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A Computational package to aid the design and to evaluate centrifugal turbopumps

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A Computational Package To Aid the Design and to Evaluate Centrifugal Turbopumps

by

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ABSTRACT

The CPAC(Centrifugal Pump Analysis Code) is a one-dimensional meanline pump analysis code which predicts performances of centrifugal pumps at design and off-design conditions based on pump geometries and operating conditions. The PC version of the CPAC is based on Loss Isolation Code (LSISO) which was written in the early 1970s for NASA Lewis Research Center and the code developed previously at RIT which runs on VAX/VMS environment. This new version of CPAC is written with Visual Basic Programming language to work on personal computers. CPAC is a menu-driven and user-friendly code with online help manual. The following enhancements were made over previously existing codes.

Additional features:

* Additional pump elements
* Nodes based modeling scheme
* Individual or multiple elements analysis
* Constants or variable fluid properties
* English or SI unit input/output
* User-friendly interface incorporating
    - various input options
    - on-screen input editing
    - graphical and tabular output displays
    - graphical and tabular print-outs
* Personal computer based software
* Reusability of the code

Along with online help and the user's manual for program usage make the PC version CPAC a versatile tool for centrifugal turbopump design performance prediction and evaluation. It also offers the capability of predicting other pump configurations such as vaneless diffuser pumps, vaned diffuser pumps, volute pumps, single and multistage pumps, including the crossover elements (turning channel and downcomer).

Comparisons of the CPAC predictions to experimental test data for several turbopumps and industrial pumps over a wide range of pump operating speed and flow rates were made, and the results were acceptable as a performance prediction code.

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List of Symbols

Symbols	Definitions
A	Area
B	Blockage
C	Absolute Fluid Velocity
C_m	Absolute Meridional Fluid Velocity
C_u	Absolute Tangential Fluid Velocity
W	Relative Fluid Velocity
U	Tangential Tip Speed
V_t	Impeller Tip Speed
D	Diameter
D_h	Hydraulic Diameter
F	Function
K	Empirical Correction Coefficient
L	Length
N	Impeller Speed (rpm)
P	Perimeter
Q	Flow Rate (gpm)
Q_{cbft}	Flow Rate (ft^3/s)
W_t	Weight Flow (lb/s)
Re	Reynolds Number
S_I	Incidence Loss
Tn	Normal Thickness
w	Passage Width
Z	Number of Blades(vanes)
α	Absolute Fluid Flow Angle
β	Blade Angle
β_f	Flow Angle Relative to Blade
η	Efficiency
ϕ	Flow Coefficient
ν	Kinematic Viscosity
π	pi (3.141593)
ρ	Density (lb/ft^3)
f	Friction Coefficient
g	Gravity
σ	Solidity

Subscripts

1	Inlet
2	Discharge
b	Blade
i	i th element
f	fluid
rms	Root Mean Square
cbft	Cubic Feet
inc	Incidence
dif	Diffusion
skf	Skin Friction
scm	Scroll Momentum
throat	Volute Throat

wr	Wear Ring
des	Design
Act	Actual
Euler	Euler or Theoretic
th	Theoretic
b1	Inlet Blade
b2	Discharge Blade
f1	Inlet Flow
f2	Discharge Flow
hyd	Hydraulic

1. INTRODUCTION

1-1.0 Justification of Work

Accurate assessment of proposed centrifugal turbopump designs is needed for design and off-design operating conditions due to the necessity in developing advanced turbopump technology. This assessment can be made with an easy-to-use pump performance prediction code which has to be versatile enough to handle various pump elements, including multistage pump handling and various working fluids. Development of accurate prediction code would enable the evaluation of proposed turbopump designs as well as a design tool. These capabilities would shorten the time required to develop new pumps and improve existing pumps as well as to reduce development costs. The goal of this project is to develop a user-friendly pump performance prediction code, to expand the capabilities and to add more features over existing prediction codes:

- personal computer based software
- intuitive menu-driven interface
- on-line help manual
- on-screen editing features
- variable fluid properties capability
- on-screen graphical and tabular output display capability
- addition of crossover elements for multistage pumps

A more versatile programming language such as Visual Basic Programming language is necessary to handle above features. Good documentation is required so that future experimental and empirical information gained from testing can be incorporated into the program easily to further improve prediction performance of the code.

1-2.0 Goal of Work

The goal of this work was to develop a PC version of CPAC which is user friendly, menu-driven with greater geometry flexibility and easier use. This was accomplished along with several other enhancements: on-screen input editing, greater output capability including on-screen output, file output, graphical output, variable fluid properties, and English or SI unit capability. In addition, the code has been well documented with on-line help and a user's manual which covers all the theoretical and empirical equations and coefficients.

The performance prediction capabilities of the program are also investigated by several case studies of actual centrifugal turbopumps and industrial centrifugal pumps with comparison to test data.

2. ONE-DIMENSIONAL TURBOMACHINERY THEORY

2-1.0 Conservation of Angular Momentum and the Continuity Equations

One-dimensional turbomachinery theory describes the relations of the operating conditions(Operating speed, Torque, Flow rates, Heads) to the average fluid velocities at the inlet and discharge at pump elements. The 'average' fluid velocity means the average in a particular region of the turbomachine over cross-section of a fluid passage. The cross-sections of the fluid passages are related to the average fluid velocity by condition of continuity (Eq.2.1). The average fluid velocities are assumed to be steady; they do not change as a function of time. The flow can be assumed to proceed along a prescribed path of known cross-sections where uniform velocity distributions exist. Therefore, only one point in the path is necessary to determine the flow conditions. With one dimensional considerations applied to incompressible fluids, the velocity is determined from the cross-section geometry by the continuity equations:

$$V = \frac{\dot{Q}}{A} \tag{2.1}$$

where V = average fluid velocity

$\dot{Q}$ = volumetric flow rate

A = cross-sectional area normal to V

Rotor

i) Continuity Equation

From continuity equation, velocities(V_m-meridional velocity) at the inlet and the discharge section of impeller can be determined.

$$V_{mi} = \frac{\dot{m}_i}{\rho_i A} = \frac{\dot{Q}_i}{2\pi r_i b_i} \tag{2.2}$$

where r = radius of the rotor, b = blade width, and i denotes 1 and 2 for inlet and discharge

ii) Momentum Equation

To determine the flow conditions, the forces from the impeller and pump casing acting on the fluid as it travels through the pump have to be determined. The relationship between the fluid velocity and the forces can be determined from the momentum equation (Eq. 2.3):

$$T = \frac{d(m v_u r)}{dt} \tag{2.3}$$

where T is torque and V_u is tangential velocity of the fluid and m is mass. Equation 2.3 states that the moment(torque) acting on the fluid is change in momentum over time dt. Change in momentum can be written as Equation 2.4. Figure 2.1 shows the fluid path from point 1 to point 2 and the fluid moves from r_1 to r_1` over time dt.

$$d(mv_ur) = (2\pi r_2 v_{m2} dt \rho_2) v_{u2} r_2 - (2\pi r_1 v_{m1} dt \rho_1) v_{u1} r_1 \quad (2.4)$$

Substituting Eq.2.4 into Eq. 2.3,

$$T = \frac{d(mv_u r)}{dt} = \frac{(2\pi r_2 v_{m2} dt \rho_2) v_{u2} r_2 - (2\pi r_1 v_{m1} dt \rho_1) v_{u1} r_1}{dt} \quad (2.5)$$

Hence $\dot{Q}_1 = 2\pi r_1 v_{m1}$ and $\dot{Q}_2 = 2\pi r_1 v_{m1}$. Eq. 2.5 becomes

$$T = \rho_2 \dot{Q}_2 v_{u2} r_2 - \rho_1 \dot{Q}_1 v_{u1} r_1 \quad (2.6a)$$

$$T = \dot{m}(v_{u2} r_2 - v_{u1} r_1) \quad (2.6b)$$

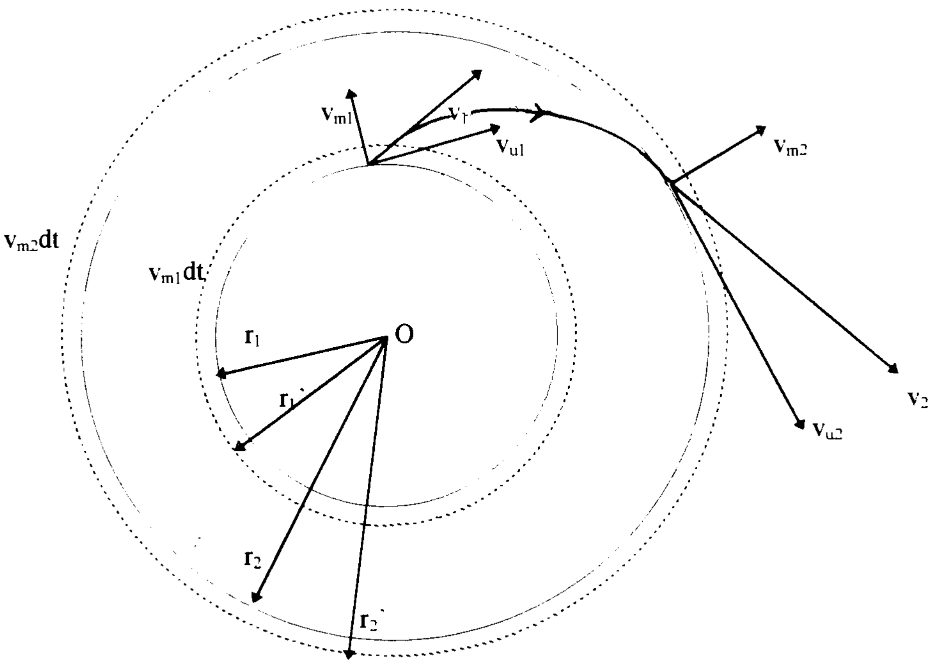

Figure 2.1 Space of revolution

iii) Energy Equation

The constant angular momentum law is an important consideration in examining the one-dimensional fluid flow through a turbomachine, but there is a limitation to examine interaction between the impeller and fluid. An additional relationship is necessary to determine the energy transfer to the fluid from the impeller. the conservation of angular momentum. Eq. 2.6b can be used in describing the angular momentum applied to the fluid entering and leaving the impeller.

The above derivations lead to the relationship between the energy(head) and the momentum of the fluid. The power input from the impeller is equal to the product of the angular velocity(ω) and the torque(T). This power must be equivalent to the power output of the pump which is equal to the product of the flow rate($\dot{Q}$) and pump head(H_E)

$$\omega T = \gamma \dot{Q} H_E \tag{2.7}$$

where γ is the specific weight of the fluid, H_E is the total change in energy per unit weight of fluid excluding losses, thus the 'ideal' head. Substituting equation 2.6 into 2.7 with $\rho = \gamma / g$.

$$\omega T = \omega \frac{\gamma}{g} \dot{Q}(V_{u2} r_2 - V_{u1} r_1) = \gamma \dot{Q} H_E \tag{2.8}$$

which becomes

$$H_E = \frac{V_{u2} U_2 - V_{u1} U_1}{g} \tag{2.9}$$

where $U_i = \omega r_i$ (2.10)

This equation thus relates the Euler head(H_E) of a pump to the circumferential velocities. To further examine this relationship, it is convenient to look at the well-known velocity diagrams.

Diffusers

I) Continuity Equation

From continuity equation, velocities(V_m-meridional velocity) at the inlet and the discharge section of impeller can be calculated.

$$V_{mi} = \frac{\dot{m}_i}{\rho_i A_i} = \frac{\dot{Q}_i}{2\pi r_i w_i} \tag{2.11}$$

where r = radius, w = diffuser width and i denotes 1 and 2 for inlet and discharge

ii) Momentum Equation

Between r1 and r2 from Figure 2.1, there are no external forces present(i.e no blades), thus T = 0 in Eq. 2.5b, and the equation becomes:

$$v_{u1}\, r_1 = v_{u2}\, r_2 \tag{2.12}$$

In general, $$v_u r = \text{const.} \tag{2.13}$$

Equation 2.13 is the Law of constant angular momentum in a space of revolution.

Also, $$2\pi r_1 v_{m1} \rho_1 w_1 = 2\pi r_2 v_{m2} \rho_2 w_2 \tag{2.14}$$

For incompressible flow, the Eq. 2.14 becomes,

$$r_1 v_{m1} = r_2 v_{m2} \tag{2.15}$$

Then, $$r v_m = \text{const.} \tag{2.16}$$

From Eq. 2.13 and Eq. 2.16,

$$\frac{v_m}{v_u} = const. \tag{2.17}$$

To express velocities in polar cordinates which is especially useful in turbomachinery problem,

$$v_m = \frac{dr}{dt} \tag{2.18}$$

$$v_u = \frac{rd\theta}{dt} \tag{2.19}$$

Then, Eq. 2.17 can be rewritten as

$$\frac{v_m}{v_u} = \frac{\frac{dr}{dt}}{\frac{rd\theta}{dt}} = \frac{dr}{rd\theta} = const. \tag{2.20}$$

Given the above considerations, it can be shown that the law of constant angular momentum (Eq.2.13) can be used to describe the motion of a fluid in a space of revolution where no external forces are present. (i.e. no impeller vanes). Note that above equations are valid only in the absence of any circumferential force producing elements such as vanes or friction.

Volute, Exit Diffusers

i) Continuity Equation

From continuity equation, velocities(V_m-meridional velocity) at the inlet and the discharge section of impeller can be calculated.

$$V_{mi} = \frac{\dot{Q}_i}{A_i} = \frac{\dot{Q}_i}{2\pi\, r_i^2} \qquad (i = 1,2) \qquad (2.21)$$

where r = radius, 1 denotes volute tongue and 2 denotes diffuser discharge

2-2.0 Velocity Triangles

To better understand the basis of the energy transfer, one can examine the average fluid velocity vectors of an ideal fluid in the radial plane of the impeller, normal to the flow direction. These vectors can be broken down into the following components:

V: Absolute velocity

V_r: Relative fluid velocity(to rotor)

U: Linear rotor velocity

These velocity vectors form a triangle, which represents the one-dimensional state of the fluid at any section of the pump. Typically the velocity triangles are drawn at the impeller inlet and again at the impeller discharge, and are known as the impeller inlet and discharge velocity triangles, (see Figure 2.2). The absolute fluid velocity, (V) can be further decomposed into:

V_m: Meridional(radial) component

V_u: Tangential(circumferential) component.

α : Angle between absolute fluid velocity and tangential velocity

β : Angle between relative velocity and tangential component of relative velocity

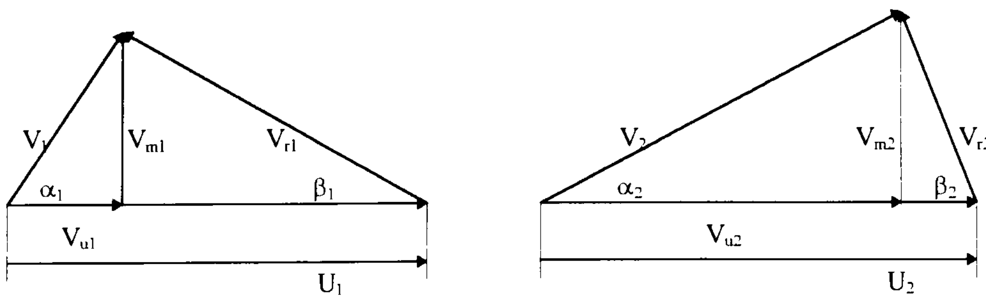

Figure 2.2 Impeller inlet and discharge velocity triangles.

In order to determine the meridional velocity component as well as other velocities, it is necessary to realize that the meridional velocity always lies in radial planes(Fig. 2.3), resulting in the flow cross-sections being normal to the radial planes, thus normal to the meridional velocity component. Since the cross-sections are normal to the radial planes, they are surfaces of revolutions, and normal to the stream surfaces since they are normal to the meridional velocity. The use of the meridional velocity Vm naturally requires a knowledge of the meridional stream lines or surfaces. Although the accurate construction of these stream lines constitutes a two or three-dimensional problem, a useful approximation can be obtained by the following one-dimensional consideration(Fig. 2.4). The space of rotation formed by the side walls is first divided by a number of cross-sections AA, BB, CC normal to the direction of the expected flow. If the revolving space is divided into various cross-sections normal to the prescribed flow

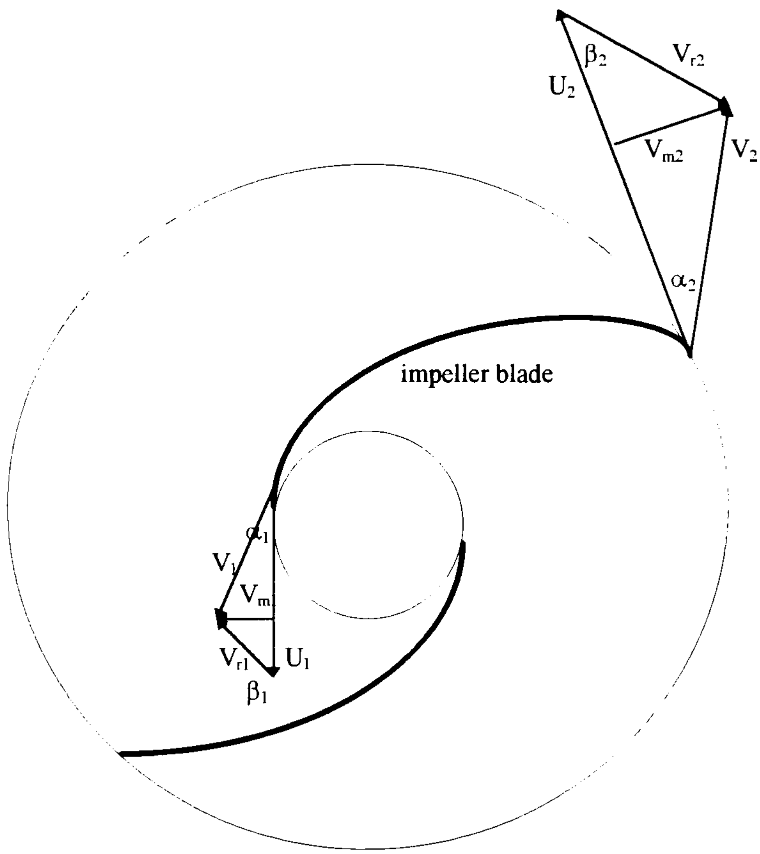

Fig 2.3 Velocity vectors in radial plane

direction. (i.e normal to the wall surfaces). the one-dimensional assumption of uniform velocity distributions states that the meridional velocity is uniformly distributed over each cross-section. If each cross-section is divided into the same number of equal parts. each section must satisfy:

$$2\pi rd = \text{const.} \tag{2.22}$$

The meridional velocity then is obtained by applying to each cross-section the condition of continuity.

The objective of the one-dimensional theory of turbomachinery then is to calculate the meridional and tangential velocity components of the fluid absolute velocity V, at the areas of energy input (inducers or impellers), by applying the energy or Euler equation. The velocity components at other pump cross sections are then determined from the continuity and momentum conservation laws. In addition, one-dimensional empirical loss mechanism equations can be formulated to better approximate the actual average fluid conditions existing in a turbomachine. The velocity triangles help visualize the fluid velocity vector components, which are determined from the momentum relationships discussed in section 2.1. These relationships constitute the ideal state of energy transfer from the impeller to the fluid in a turbomachine. Unfortunately, the ideal situation is never realized. An attempt to correlate the ideal situation to actual process must take into account the non-ideal fluid aspects, as well as the non-ideal geometry influences. These result in the following discussion concerning the turbomachine head losses.

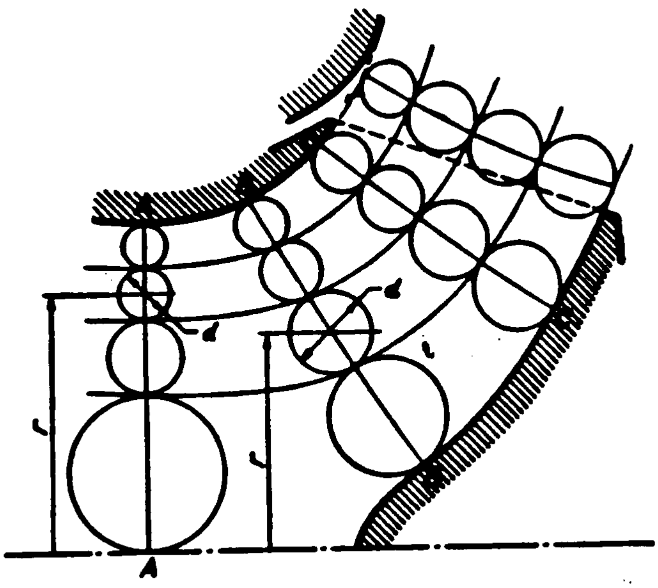

Fig. 2.4 Determination of the meridional streamlines

2 - 3.0 Head Losses

Useful formulations of pump performance characteristics can be obtained by the systematic accounting of the limitations imposed by the actual pump geometry. and the associated energy losses of the fluid passing through this geometry. The limitations imposed by the pump geometry stem from the fact that in a turbomachine, perfect guidance of the fluid through the impeller would require an infinite number of impeller vanes, which in reality is impossible; infinite blade number infers a solid disk, which would transfer little or no energy to the fluid. As a result of perfect guiding, the fluid must expend some energy to 'bend' to follow the impeller blades. This extended energy results in the fact that the head produced by the pump, neglecting losses. will never equal the Euler head expressed in equation 2.17. This expended energy is not considered a loss, in the usual sense of head losses(incidence, friction, etc.), but simply a necessary consequence of a finite number of impeller vanes. The pump output of actual head is further reduced from the Euler head by various loss mechanisms covered in the following discussions.

Fluid flow in a turbomachinery is greatly affected by several loss mechanisms. A knowledge of these mechanisms is paramount to understanding and minimizing the losses resulting in optimized designs. The loss mechanisms can be classified into several groups: Leakage, mechanical and hydraulic losses. The mechanical losses include bearing and stuffing box losses, as well as disc friction losses which primarily result in increased power requirement from the pump driver. The one-dimensional theory of loss mechanisms is mainly concerned with the hydraulic losses, which effect the pump capacity curve as shown in Figure 2.5. The CPAC code attempts to calculate the hydraulic and leakage losses, as well as the mechanical disk friction loss. The equations used in the code are presented in the later sections and appendix C.

Mechanical Losses

Disc Friction:

The major mechanical loss is that which draws input power to overcome the disc friction. The disc friction loss is a result of the spinning rotor front and/or rear shroud imparting energy to adjacent fluid in a pumping action. This pumping action serves only to expel the fluid to the periphery of the disc where it eventually leaks back to the disc hub where it is pumped out again. This loss has been shown to follow an equation of the form:

$$\text{Disc friction loss} = Kn^3D^5 \tag{2.23}$$

K is an empirical coefficient determined from experimentation, n is the rotor speed in rpm, and D is the impeller diameter. The additional mechanical losses of bearings and stuffing boxes are well known and amount to a very small percentage of the overall pump losses(typically < 1 - 2 %).

Leakage Losses

The leakage losses are primarily concerned with leakage from the impeller exit back to the impeller inlet. These losses are minimized by the use of labyrinth seals and/or wearing rings. These losses typically vary as a function of the pressure drop across the leakage path, the common form of the leakage loss equation is shown in equation 2.24.

$$\dot{Q}_L = CA\sqrt{2g\Delta H_L} \tag{2.24}$$

where C = Discharge coefficient

A = Clearance area

ΔH_L = Head drop

As a percentage of the power input, the power loss resulting from leakage effects is reduced at increased specific speeds, and typically less than 2% of the input power at specific speed(N_s) greater than 1500. Specific speed(N_s) is a non-dimensional design index used to classify pump impellers as to their type and proportions.

Hydraulic Losses

- Skin Friction Loss:

The hydraulic losses are the most important losses that should be accounted for in any type of pump analysis. Essentially the hydraulic losses can be categorized into two classifications, friction losses and turbulence losses. The friction loss results from the skin-friction affect of the internal fluid flow through the pump. The form of the skin friction loss is dependent on the friction factor which is determined from the relative roughness of the passage walls, and the Reynolds number.

$$\text{Friction Loss} = f\frac{L}{D_h}\frac{V^2}{U^2} \tag{2.25}$$

Where L is the flow path length across the surface, and is dependent on the fluid flow angle. To get an idea of how the friction loss will vary with flow rate, it is necessary to note that as the flow rate increases so does the fluid flow angle. The friction factor can be estimated from the moody diagram based on the Reynolds number and relative roughness values. In most pumping situations, the Reynolds number is high, which is characteristic of fully turbulent flow conditions resulting in the fact that the friction factor becomes independent of the Reynolds number, and is solely dependent on the relative roughness. The friction factor is thus determined from the roughness, the skin friction loss is then dependent on the fluid velocity and the path length. Therefore shorter length results in lower friction losses.

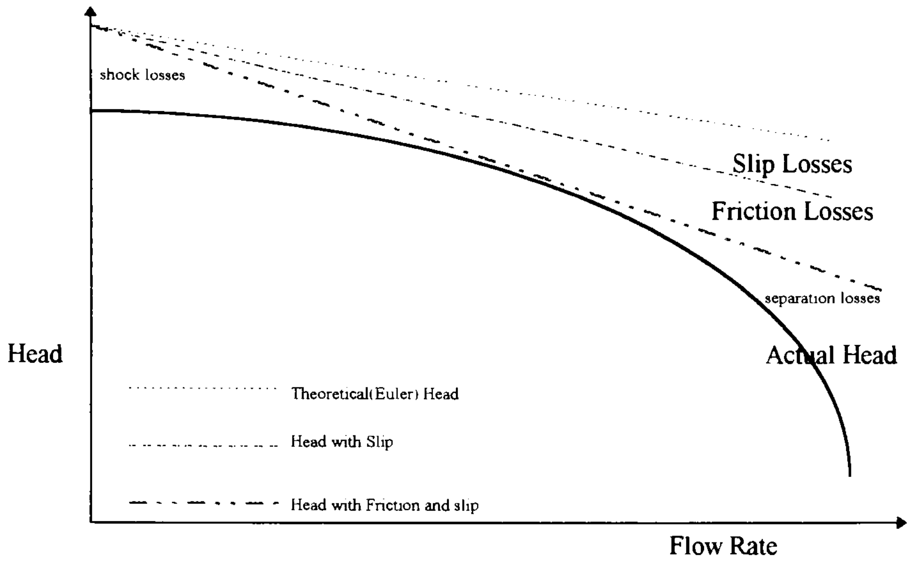

Figure 2.5 Various pump losses

- Incidence Loss

The turbulence losses consist of the incidence (shock) and diffusion losses. Any time that the fluid impinges on a blunt edge, separation is likely, resulting in flow losses. This shows the importance of proper blade angles, and how losses of this type are an important issue when concerned with off-design performance, where the fluid velocity vectors differ greatly from the blade angles. The incidence loss has been expressed as

$$\text{Shock Loss} = K\,(\dot{Q} - \dot{Q}_{shockless})^2 \qquad (2.26)$$

where K is an empirical coefficient again determined from experimentation. This equation obviously shows that at some flow rate $\dot{Q}_{shockless}$ the optimum conditions exist which minimize the incidence or shock loss, ideally there would be no incidence loss. It is usually assumed that the $\dot{Q}_{shockless}$ flow rate is the design flow rate.

- Diffusion Loss

The diffusion loss is associated with flow separation that occurs when the flow is expanded too rapidly. The form of the diffusion loss is similar to the friction loss equation, where instead of a friction factor a diffusion factor is determined empirically.

$$\text{Diffusion Loss} = K\,(\text{diffusion factor})^{N} \qquad (2.27)$$

The preceding sections discuss the one-dimensional theory of turbomachines which relate the operating conditions to the average fluid velocities resulting from the fluid traveling a prescribed path through the machine. It was shown that this path through the machine with the appropriate assumptions (uniform velocity distributions), results in the flow being uniform along the circles normal and concentric to the axis of rotation, with the exception of where the circles are intercepted by the impeller vanes. The fluid path not only revolves around the axis, (resulting in the circumferential velocity component V_u), but is also flowing through the machine, giving a meridional velocity component V_m which is normal to the circumferential direction. Therefore, the determination of pump's performance characteristics consists of following steps:

1) Determining the circumferential velocity component from the torque and head of the impeller, using the Euler equation.
2) Determining the meridional velocity component from the pumps through-flow capacity using the continuity equation.
3) Determining the actual pump output head and capacity by accounting for the head and capacity losses using the discussed empirical equations.

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3. CENTRIFUGAL TURBOPUMPS

3-1.0 Centrifugal turbopump Applications

Centrifugal turbopumps derive their name from the fact that they are driven at high speed by turbines of rocket engines and they use centrifugal forces to add energy to the fluids. The requirements of these rocket engines determine the design parameters of the pump. Centrifugal turbopumps may be single or multistage designs (Figure 3.1 and 3.2). These figures show that these types of pumps consist of many of the same elements found in other types of pumps, i.e. impellers, diffusers, and volutes. The remainder of this section discusses some of the important pump parameters that must be considered in centrifugal turbopump design. The required pump flow rate and pump head rise are the basic parameters imposed on the turbopump system from the rocket engine design thrust and combustion chamber parameters. In order for the rocket engine to achieve design thrust capability, the turbopump system must deliver the appropriate flow rate of propellant at a discharge pressure which is sufficient to overcome the hydraulic resistance (line losses), the fuel injector pressure drop, and combustion chamber pressure. Another important parameter is known as the Net Positive Suction Head.

The Net Positive Suction head, (NPSH), is the difference between the fluid head due to total fluid pressure and the head due to the fluid vapor pressure, at the pump inlet. If the NPSH is lower than a certain value, cavitation will occur at the pump impeller inlet which will lower the pump head rise below the design value. A typical critical value of the NPSH is where the head rise is 2% lower than the non-cavitating head rise value. This cavitation phenomena although prevalent at the pump impeller inlet, where the lowest absolute pressure is often encountered, can occur anywhere in the pump where the static pressure becomes less than the fluid vapor pressure. Excessive cavitation has been known to result in erratic combustion leading to excessive vibrations and even explosions.

As mentioned in the above sections, future space applications will require engine throttling capability, which result in pump operation at off-design conditions. At off-design conditions, the turbopump system encounters the most severe operating conditions. The limits imposed on throttleability, are a result of the pump becoming unstable. Centrifugal turbopumps have approximately twice the throttleability capability as axial pumps, and increased design speed improves the centrifugal turbopump throttleability. To meet these new requirements, single and multistage centrifugal pumps will be continually used in turbopump systems. For this reason, the importance of improved design methods as well as improved performance prediction capability, can not be overstated..

Engine throttling requires pump operation at off-design conditions, meaning at flow rates other than the design flow rate, as well as operating speeds at other than the design speed. Dimensional analysis and similitude has historically been applied to predict pump performance at these off-design operating points.

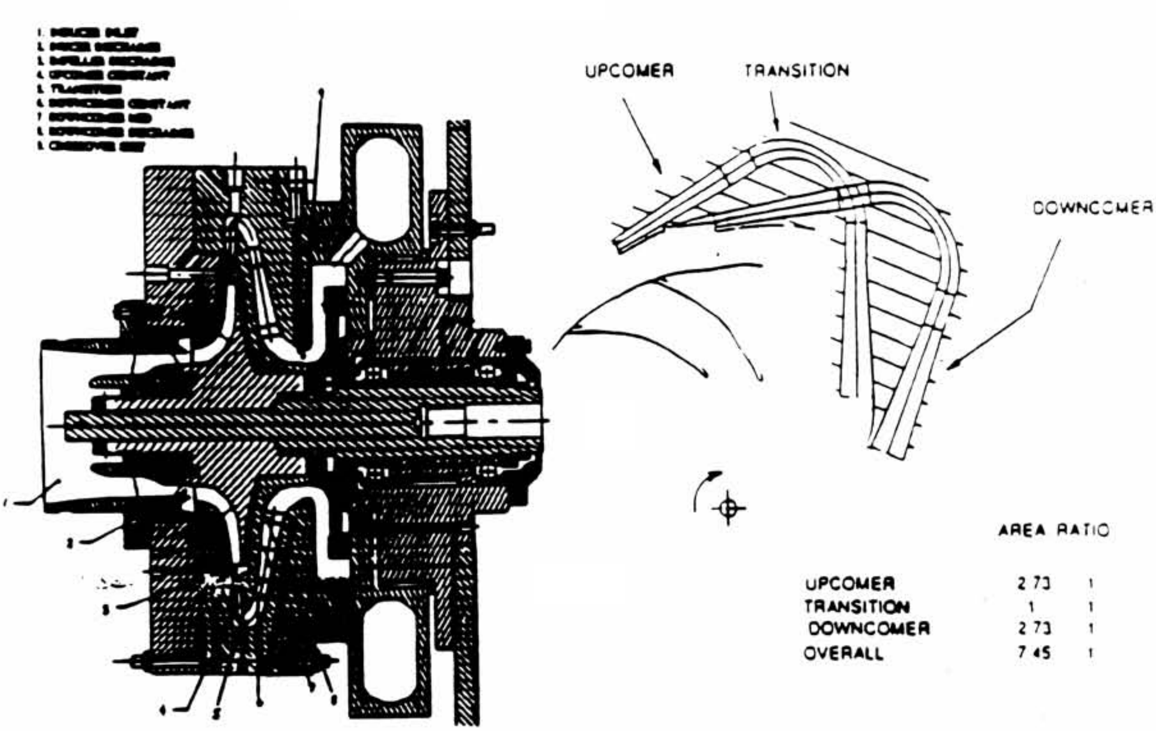


Figure 3.1 Single Stage Pump

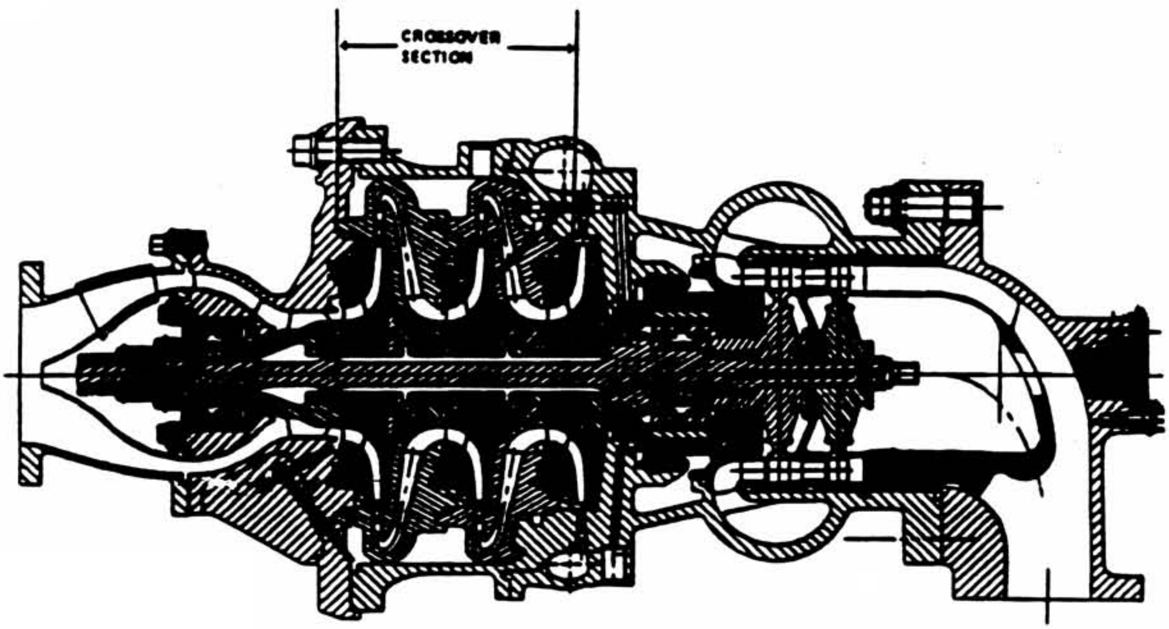


Figure 3.2 Multistage Turbopump

3-2 0 Dimensional Analysis and Scaling Laws for Turbomachinery

In plotting the results of turbomachinery tests and in the analysis of performance characteristics, it is useful to use dimensionless group of variables. Appropriate groups of variables are found by application of dimensional methodology known as Buckingham's pi theorem that the dimensionless groups so formed have a functional relationships, although the nature of the relationship is frequently unknown except by experimentation. An important benefit of dimensional analysis is that the results of the model studies so analyzed and plotted may then be used to predict full scale performance. This is important to reduce the cost of the development of turbomachines. It is also useful to use in the analysis of the data from full-sized machines, when it is desired to predict the performance of other full size machines of a different size than those tested, or to operate under different conditions.

For any turbomachine, we are interested in the relationship of flow rate, power, head, torque, size, speed, and fluid properties. Table 3.1 lists variables used in dimensional analysis of turbomachines: These variables involve 3 basic dimensions, mass M, length L and time T, as shown in Table 3.1

Parameter	**Dimensions**
Volumetric Flow Rate ($\dot{Q}$)	L^3/T
Head (H)	L^2/T^2
Power (W_s)	ML^2/T^3
Speed (N or ω)	$1/T$
Size (D)	L
Viscosity (μ)	M/LT
Density (ρ)	M/L^3

Table 3.1 Variable Dimensions

The Buckingham Pi theorem states that given a relation among n parameters of the form,

$$g(g_1, g_2, g_3, \ldots, g_n) = 0 \tag{3.1}$$

then the n parameters may be grouped into n-m independent dimensionless ratios, or Pi parameters, expressible in the functional form by:

$$G(\Pi_1, \Pi_2, \Pi_3, \ldots, \Pi_n) = 0 \tag{3.2}$$

or

$$1 = G_1(\Pi_2, \Pi_3, \ldots, \Pi_{n-m}) \tag{3.3}$$

where the number m is usually equal to the minimum number of independent primary dimensions required to specify the dimensions of all n of the parameters in equations. Since there are 7 variables and 3 primary dimensions, 4 Π parameters will characterize the turbomachines. Applying Π theorem will results the following function.

$$\Pi_1 = \frac{\dot{Q}}{\omega D^3} \propto \frac{V_m}{\omega D} \propto \frac{V_m}{U} \tag{3.4}$$

$$\Pi_2 = \frac{H}{\omega^2 D^2} \propto \frac{H}{U^2} \tag{3.5}$$

$$\Pi_3 = \frac{W_s}{\omega^3 D^5 \rho} = \frac{\rho \dot{Q} H}{\omega^3 D^5 \rho} \tag{3.6}$$

$$= (\frac{\dot{Q}}{\omega D^3})(\frac{H}{\omega^2 D^2})$$

$$= \Pi_1 \Pi_2 \propto \frac{VH}{U^3}$$

$$\Pi_4 = \frac{\mu}{\omega D^2 \rho} = \frac{\mu}{\rho D U} \tag{3.7}$$

Equation 3.4 is known as flow coefficient or capacity coefficient. For a turbomachine, this represents the fluid flow rate expressed in dimensionless form and this implies a particular relationship of fluid velocity to impeller speed. Equation 3.5 is called head coefficient and is interpreted as the ratio of the fluid head to the kinetic energy of the rotor. Equation 3.6 is known as power coefficient. W_s is the power or work added to the fluid by the rotor of a turbomachine. Equation 3.7 can be noted that this parameter is the Reynolds number. This parameter is sometimes of value in characterizing axial flow turbomachines but has little value for radial flow machines such as centrifugal pumps since machines of this type do not have a single characteristic Reynolds number throughout the machines.

If any of these parameters have equal value for two different machines, that characteristic of the two machine will be the same. If all of these parameters are the same for the two machines, then the machines will be similar in all of their performance characteristics.

Frequently, these characteristic parameters, or combinations of them, are used to characterize turbomachines of similar performance characteristics even though the physical size, design or fluid properties may be quite different. Also, these characteristic parameters are commonly used to design scale model of prototype equipment to experimentally predict the performance characteristics of prototype from a laboratory scale model.

3-3.0 Centrifugal Pump Efficiency Relations

The actual useful head of a centrifugal turbopump is always less than the head which theoretically should be produced. This phenomena is a result of the various head losses discussed in section 2-2.3. The ratio of the actual head to the theoretical head is known as the hydraulic efficiency of the pump. In addition to the hydraulic efficiency, there are several other efficiencies associated with pumps. These efficiencies are now summarized.

Hydraulic Efficiency:

$$\eta_{Hyd} = \frac{Actual\_Head}{Theoretical\_Head} = \frac{H_{Act}}{H_{th}} \tag{3.8}$$

The hydraulic efficiency is the ratio of the actual head to the theoretical or virtual head produced by the pump. It is necessary to note that the theoretical head is the head produced by a finite number of blades. The losses contributing to lower actual head are mainly the frictional and turbulence losses.

Volumetric Efficiency:

$$\eta_{vol} = \frac{weight\_flow\_delivered}{weight\_flow\_delivered + leakage\_flow} \tag{3.9}$$

The volumetric efficiency is simply a measurement of leakage flow through the machine. The higher the volumetric efficiency, the lower the leakage flow.

Mechanical Efficiency:

$$\eta_{mech} = \frac{power\_available\_at\_rotor}{power\_delivered\_to\_pump\_shaft} \tag{3.10}$$

The mechanical efficiency is the ratio of the power transmitted to the fluid from the impeller, to the power supplied to the pump shaft.

Overall Efficiency:

$$\eta_{over} = \frac{fluid\_horse\_power\_output}{brake\_horse\_power\_input} \tag{3.11}$$

The overall efficiency of the pump is the ratio of the fluid horsepower output to the brake horsepower input. The brake horsepower represents all of the power supplied to the pump unit. This power is used to increase the fluid horsepower, overcome the frictional and turbulent losses, the leakage losses, disc friction losses, and the various mechanical losses. Therefore the overall efficiency can be represented as:

$$\eta_{over} = \eta_{hyd}\ \eta_{vol}\ \eta_{mech} \tag{3.12}$$

4. CPAC (Centrifugal Pump Analysis Code)

4.1.0 Introduction to CPAC

The CPAC code is a one-dimensional meanline performance prediction code for centrifugal pumps using one-dimensional theory of turbomachinery. The code predicts performance at design and off-design conditions. A thermodynamic properties code has been integrated to the code which adds variable fluid property calculations capability for water, liquid hydrogen, liquid oxygen, and liquid nitrogen. The CPAC code is an outgrowth of the Loss Isolation Program(LSISO) developed for NASA, in the early 1970's and the previous version of CPAC which runs in a DEC VAX/VMS environment and both were written in FORTRAN-77. The new PC version of CPAC is written in Visual Basic programming language because Visual Basic has powerful window applications and visual interface applications. The new CPAC runs on any personal computer which has MS Windows on it. It is so programmed to work under MS Windows Operating System environment and it can be ported to any personal computer which is IBM compatible. The following list is the key features of the new CPAC.

1. Visual and intuitive user-interface
2. Menu driven format
3. On-line Help
4. US and SI unit for input and output
5. Constant and variable properties
6. Element and Node base modeling
7. Single or Multistage Pump Modeling Capability
8. Tabular or Graphical Output Analysis
9. Addition of Crossover and Downcomer Type Element
10. Portability to any personal computer

The CPAC has new visual user interface and simple layout of the main menu screen. The menu screen has four main sections - File(Read, New, Save As, Update), Input(Geometry, Operating Conditions), Run(Entire Pump, Single/Multiple Elements), and Output(Tabular,Graphical,Output File). Also, there is an on-Screen HELP feature that explains the required informations which are easily accessible.

The CPAC code predicts centrifugal pump performance based on the modeled pump geometry, flow rates and operating conditions using empirical equations and experimental coefficients. The code has been well documented so that new experimental data, and additional features can be added to the code for better performance prediction capability.

4.2.0 Running CPAC

There are three steps to run the program. These steps are shown in Figure 4.1. The first step is to specify the program input data-the pump configuration, element geometry, operating conditions. The input can be read in from a stored file or interactively input from a keyboard and a mouse. Once data has been read or entered, the CPAC is ready to run for calculations for the entire pump model or single/multiple elements. After the calculations are completed, outputs can be viewed in a tabular form, prints, or as a file. A user, then, can change some of the input values and run again to see what effects the change makes.

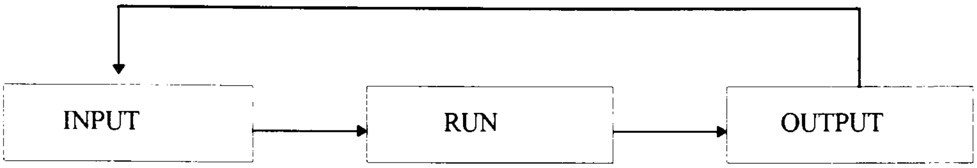


Figure 4.1 Simplified CPAC sequence

There are several types of output a user can examine: on-screen output, printed tabular output, graphical output, and storing to an output file which a user specifies. On screen output is a feature that a user can view output on the screen. Printed output is an output which will be printed as a hard copy. A graphical output is to view a data set displayed on a screen where a user can type in the name of graph and labels. Graphs can also be printed out. Output can also be stored in a file which a user specifies. Once output has been viewed and analyzed, one could modify the input data and rerun the CPAC program, which leads to design optimization.

4.3.0 Main Menu Screen

The CPAC code is structured in a menu driven and intuitive format so that a user can go from input menu to output menu easily. The Figure 4.2 is a menu screen where a user selects types of input and output options. Each square box is called a '**button**' and a user clicks to pop a menu screen open to enter input data or to view outputs. There is also a feature that a user selects either SI unit system or US customary unit system. This button is called 'radio button'. Default unit system is the US customary unit system and calculations are based on USCS system. If a user wants to use SI unit system, clicking SI button with a mouse will set all units and calculations are done accordingly. On this main menu screen, a user is required to use a mouse to select buttons to input except entering actual data.

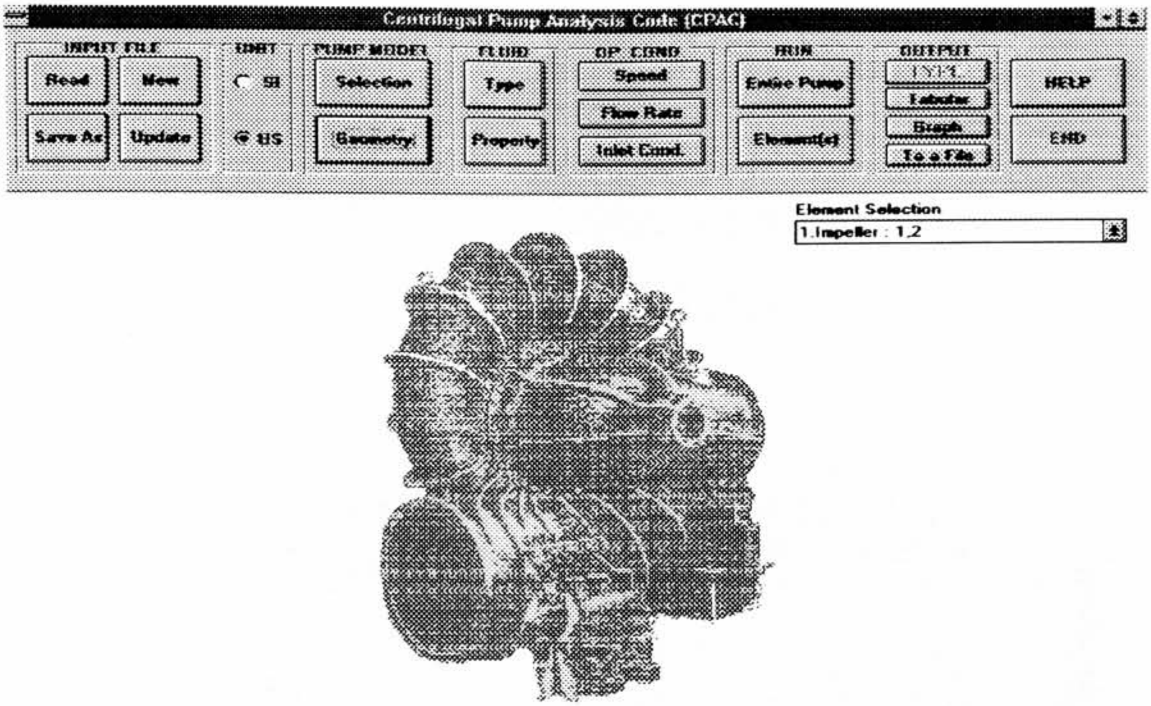


Figure 4.2 Main Menu Screen

Input File

Input file section is where a user specifies a input file name where data are read from. The Figure 4.3 is a screen which pops up when a user clicks the **READ** button. **Update** button is used when a user modifies part of data to a different values, and it will store updated data set to an original file. A message will be shown and says that the file has been updated. **Save As** button is used when a user wants to save current file to another file and when a user first creates a file.

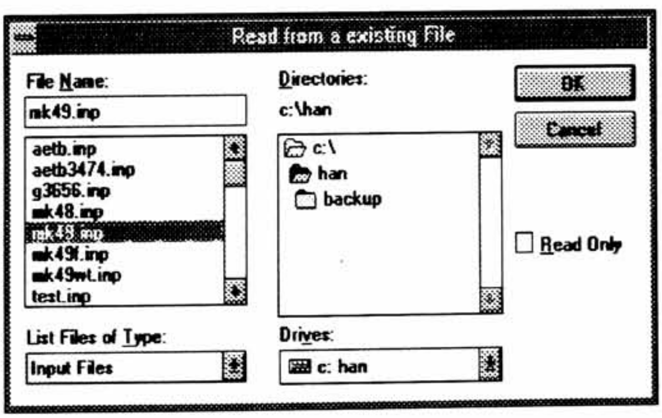


Figure 4.3 Read from an Existing File Screen

This action will pop a screen similar to Figure 4.3 except that a user has to enter a new file name. **New** button is used when a user creates a new pump model and it prompts a pump name. Figure 4.4 is the typical screen when this button is clicked.

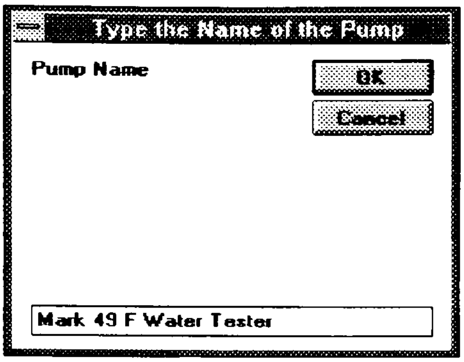


Figure 4.4 Pump Name Screen

Pump Model

Selection Button is clicked when a user wants to compose a pump with pump elements such as inducer, impeller, diffusers., and so on. The Figure 4.5 is typical screen which a user defines a pump. This particular figure is taken from composing a XLR134 turbopump model to analyze.

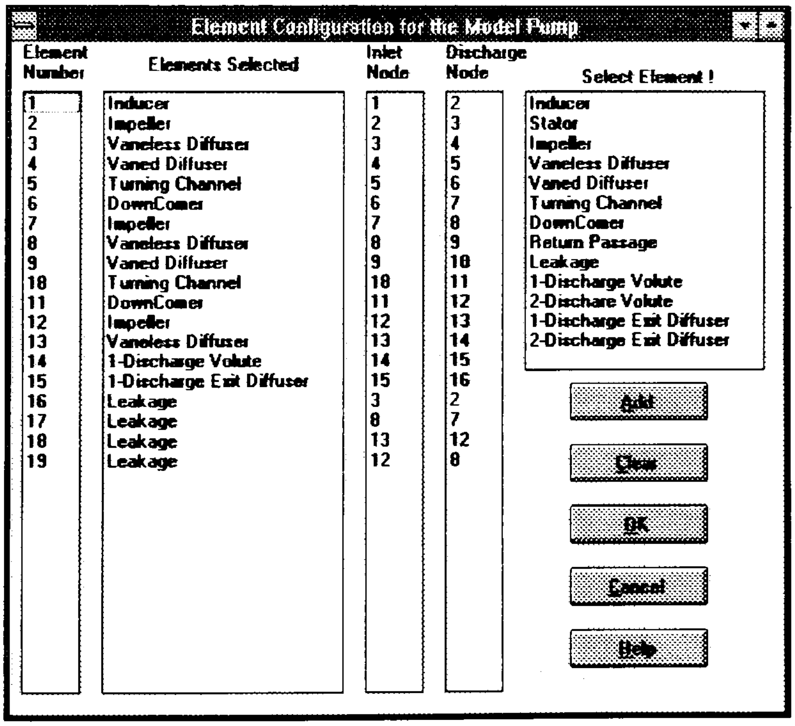


Figure 4.5 Model Configuration Screen

In Figure 4.5, a user can select an element in two different ways. One way of doing it is to select an element from a box where 'Select Element!' label is written and click **ADD** button. Another way is by double clicking a desired element a user wants to add to a model. Element number and nodes are given automatically as a user selects an element and nodes can be altered by double clicking Inlet Node or Discharge Node boxes. This action will open a small box where a user enters a new node. Node numbers can be changed in later stage of input process where geometries are entered. **Clear** button will clear up elements selected. **Cancel** button will cancel configuring modeling a pump and returns to main menu screen. Figure 4.6 is a typical screen for impeller geometry inputs. Note that blade loading coefficients are not available for input since these coefficients are used only for open impellers. The new CPAC only deals with closed type of impeller because modern turbopumps are built with closed type of impellers.

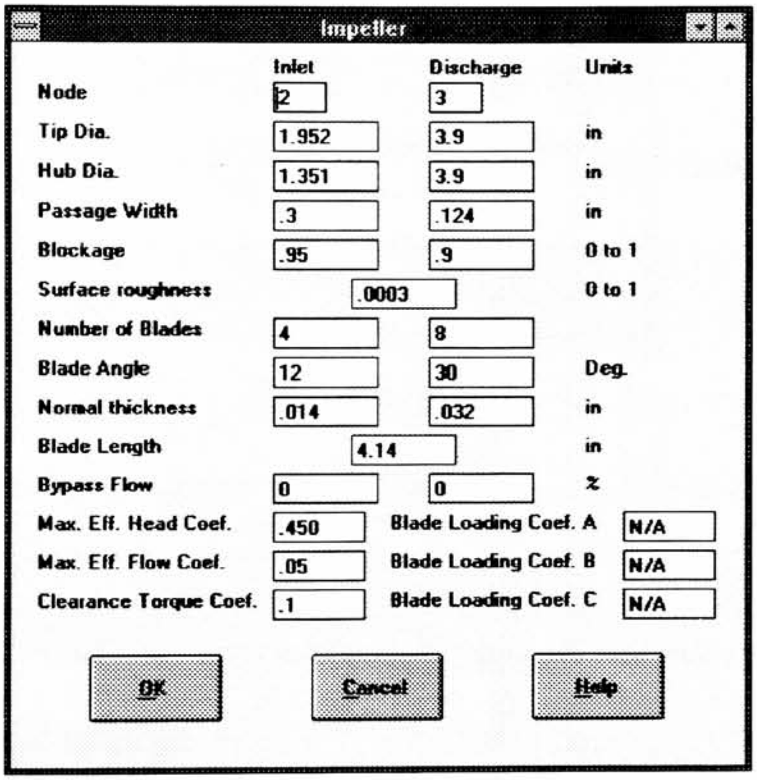


Figure 4.6 Impeller Geometry Input Screen

Geometry

Geometry input screens are for a user to specify geometry input for selected element. These screens differ a little by each element, but they are in the similar format. First, a user is required to specify tip and hub diameters. Then, passwidth, normal thickness, surface roughness, number of blades, blade angles, and so on. Once a user finishes entering required data, **Ok** button will save these data into global array for calculation and storing for later use. Also, **Ok** button will enable a user to go to another element for geometry inputs.

Fluid Type

This process can be done before or after configuring a pump or entering geometries of selected elements. Figure 4.6 is typical screen of selecting type of fluid a pump will handle. CPAC can handle 4 fluids and a user defined type of fluid. The fluids that can be handled are water, liquid hydrogen, liquid oxygen, liquid nitrogen, and a user defined type of fluid. A user defined fluid handling enable CPAC to handle any type of fluid provided that the properties of the fluid remain constant. Figure 4.7 is for viewing or changing fluid's properties. **Ok** button changes to type or properties a user specifies.

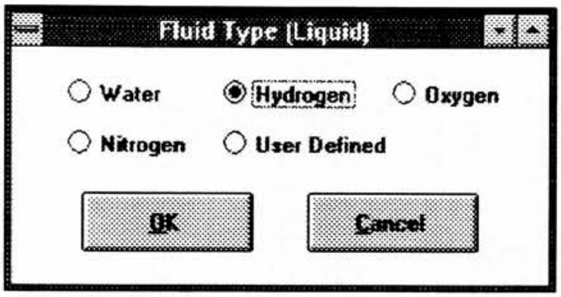


Figure 4.7 Fluid Type Screen

Fluid Property

Fluid properties vary upon operating temperature and pressure. In CPAC, there are two modes-constant and variable fluid properties. Constant property is that the properties of the selected fluid remain constant throughout as a user specifies. Water can be handled with constant property since the values do not vary much. Water can also be handled with variable property. However, other types of fluids such as liquid hydrogen is very sensitive to temperature and pressure. CPAC incorporates a subroutine called GasPlus which will calculate density, viscosity, and specific heat given temperature and pressure at nodes. The values calculated are within a percent off from the property tables.

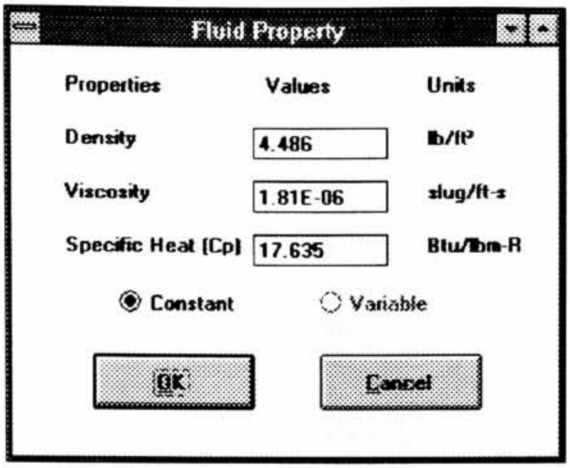


Figure 4.8 Fluid Property Screen

Operating Conditions

Operating conditions are divided into three sections-**Flow Rates**, Pump Operating **Speed**, and **Inlet Conditions**. Figure 4.9 is a screen a user enters a flow rates and Figure 4.10 is a screen where pump operating speeds are entered. Figure 4.11 is an Inlet Condition screen where inlet conditions are specified.

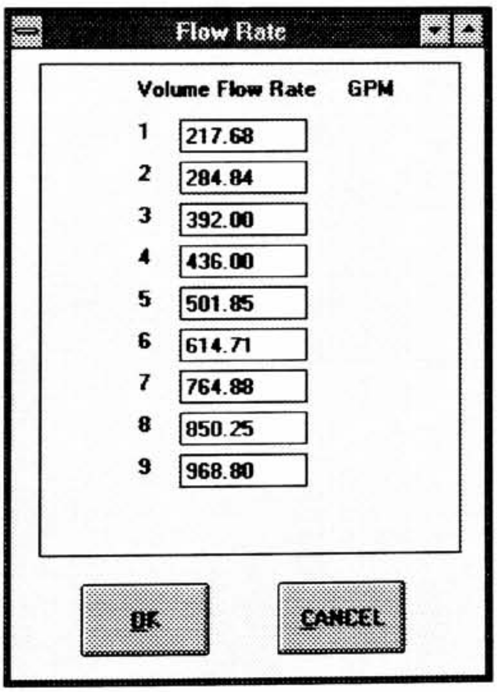


Figure 4.9 Flow Rate Screen

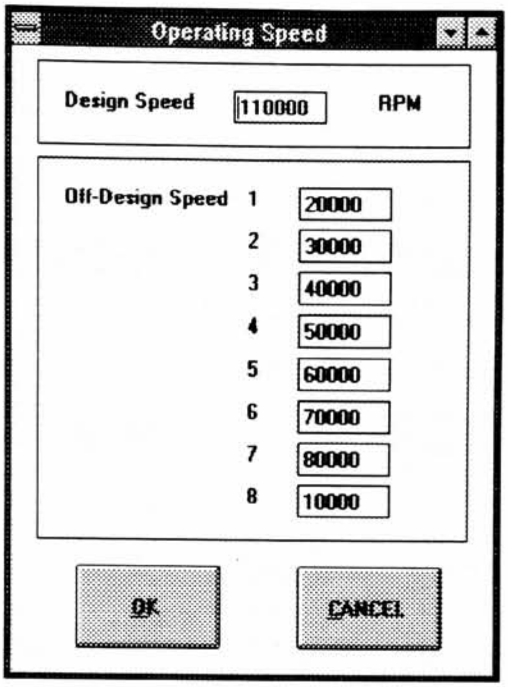


Figure 4.10 Operating Speed Screen

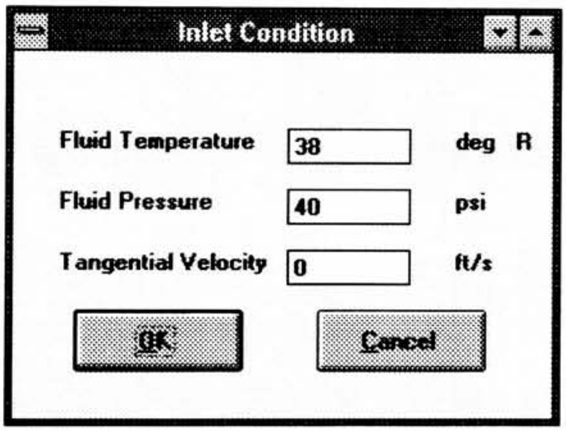


Figure 4.11 Inlet Condition Screen

Run

There are two types of running calculations for selected pump model. Normally, **Entire** button is selected to analyze the model pump. Clicking this button will start calculating from the first element to the last element of the pump. Second type of running CPAC calculations is to click **Element(s)** button which will show a screen where a user must specify the starting element and ending element. If a single element is to be analyzed, a user has to enter, for example, 2 for starting element and 2 for the ending element. If two elements are chosen, then, 2 and 3 have to be entered. Figure 4.12 shows the screen when latter type of Run is chosen. The screen is similar to Element Configuration screen except that a user has to select a starting and ending element number.

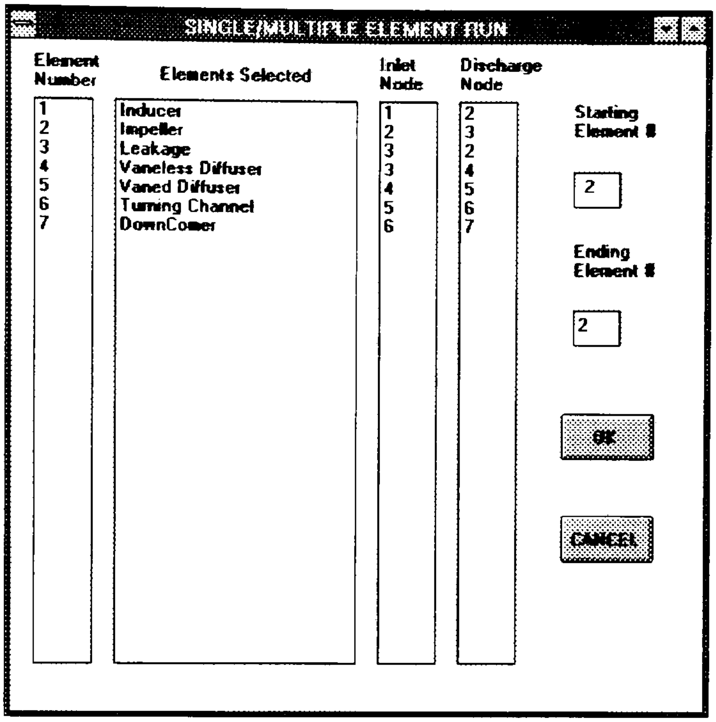


Figure 4.12 Single/Multiple Element Run Screen

Output Type

Once calculations are done, a message will be given for completion of calculations. Then, a user can browse through the types of output. A user can view results in tabular form and graphical form on screen, in the printed form, or as a text file if a user wishes so. However, a user must select types of output data - Geometries of each element, Velocity triangle and fluid angles, Element losses, Element Performances, Overall Performance, or all of these. Figure 4.12 is a screen for a user to select output data types. In this particular figure, all types of output data are selected.

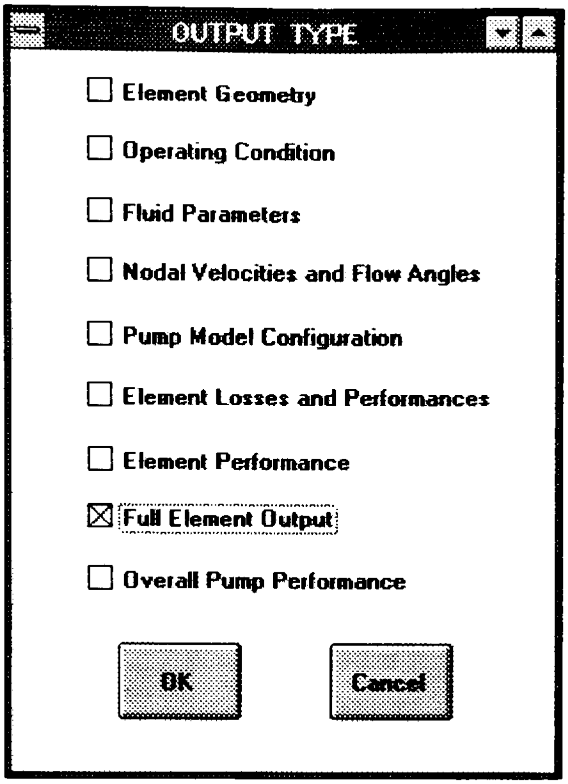


Figure 4.13 Output Data Type Selection Screen

Tabular

Once output types are selected, a user can choose **Tabular** or **Graph** button for tabular, graphical form, or storing data to a file if a user selects **To a File** button. If a user wants to see data in tabular form, **Tabular** button needs to be clicked. Figure 4.14 is a typical screen for viewing in tabular form. This particular screen shows velocity triangles and fluid flow angles. A user can choose another Operating Speed, Element, or data type such as Element Losses. If a user wants to print the current data type, there is a **Print** button which will send the data to a printer. Appendix C includes printed outputs. The data is shown for all flow rates. The tabular form is designed in a way that a user can click to view different sets of data, with ease. There are three selection bars a user can pick -Output Type, Element Selection, and Operating Speed. Figure 4.14 is an example of tabular output when a user selects Nodal Velocity and Flow Angles, Inducer, 74000 rpm. A user can select other set of data by clicking arrows in the selection bar, then a list will come out for a user can select. **Cancel** button will return to main menu screen.

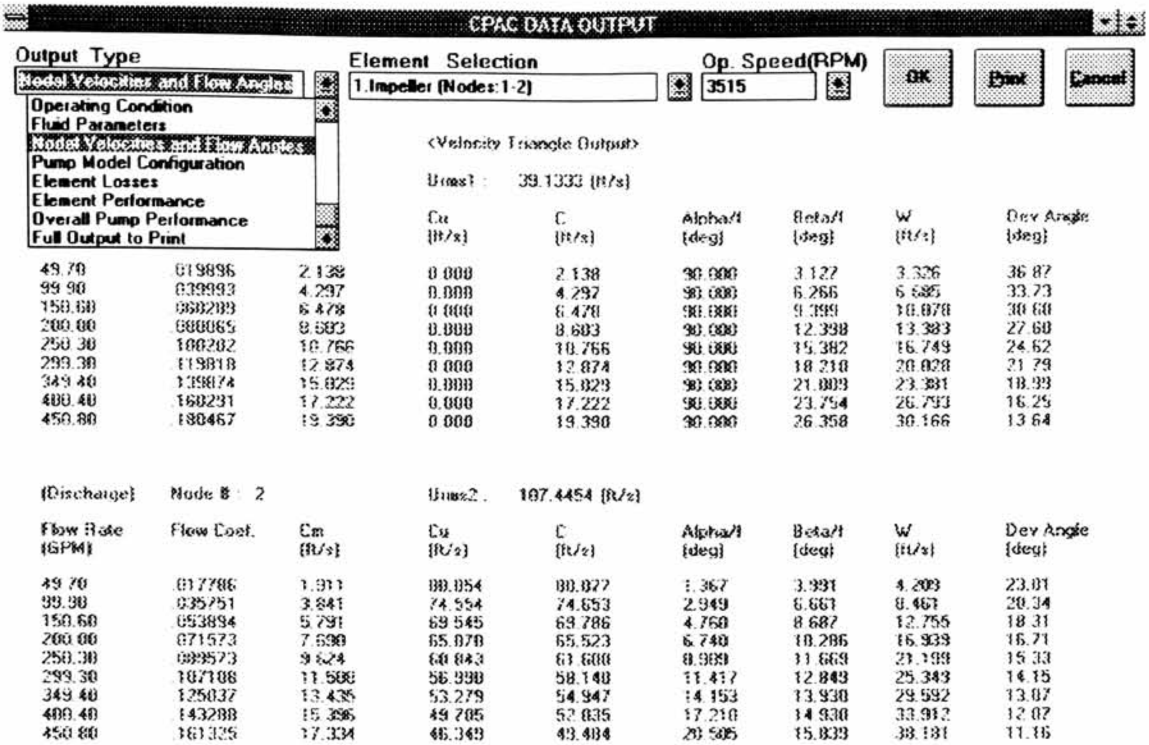


Figure 4.14 Tabular Output Screen

In Figure 4.14, notations are:

C_m = meridional fluid velocity

C_u = tangential fluid velocity

C = absolute fluid velocity

Alpha/f = angle between C and Cu

Beta/f = relative angle of the fluid

W = relative velocity

Dev Angle = angle between the blade and the Beta/f

Graph

When a user wants to see output in a graphical form, **Graph** button will open a screen where he/she can choose types of data sets available. Data can be represented as lines and marks, marks only, and curve fit(only straight line available). A user can also name a graph title, x-axis, and y-axis. Selection bars are also available for viewing different sets of data. **Graph** button will graph on screen, and **Print** button will print the graph that a user sees on the screen. **End Graph** button will return to main menu screen. Figure 4.15 is a typical screen when a user selects to view in a graphical form of data.

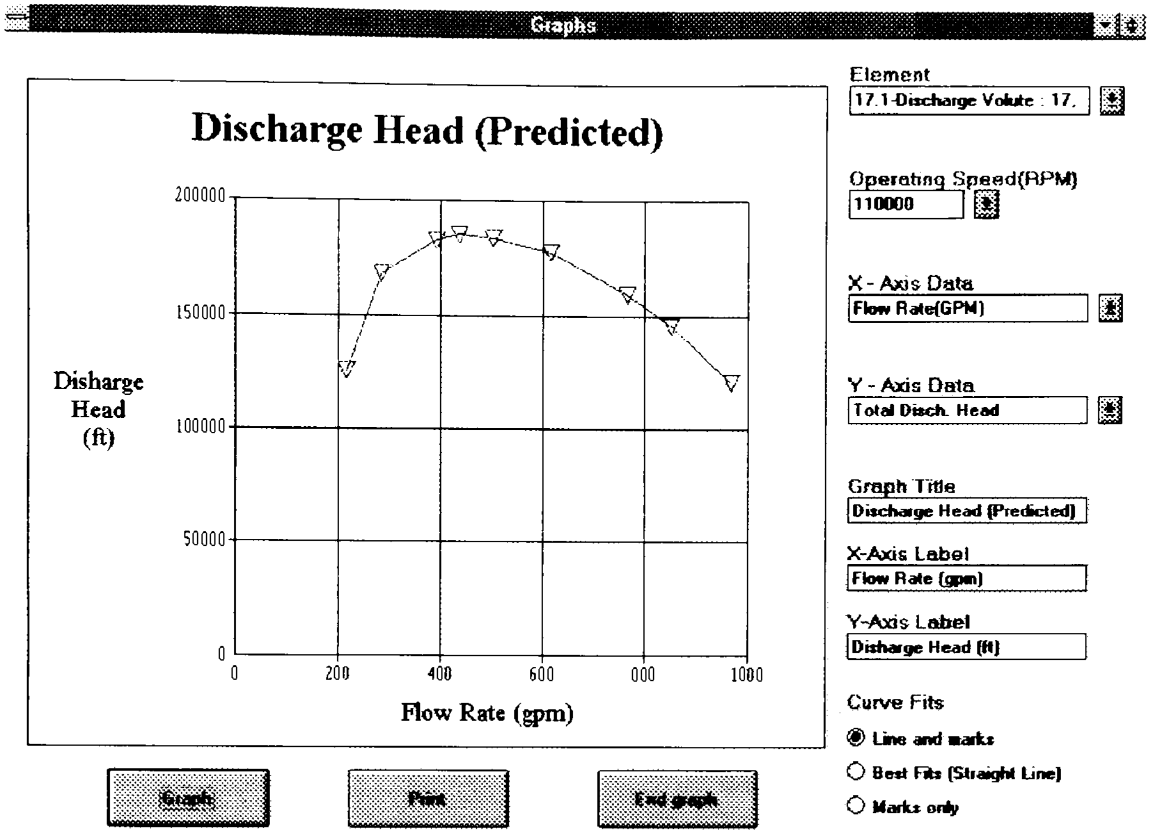


Figure 4.15 Graphical Output Screen

Help

On screen help is available when a user clicks a Help button. Figure 4. 16 is a help screen that a user sees when Help button is clicked. Help menu is in the same format as any other MS Windows applications. A user can browse back and forth through the Help screen and a hand will be shown for a user to jump to another menu. CPAC manual will be available as a part of this program so that a user can read the manual before he/she runs the CPAC program. Also, CPAC manual is included in Appendix D.

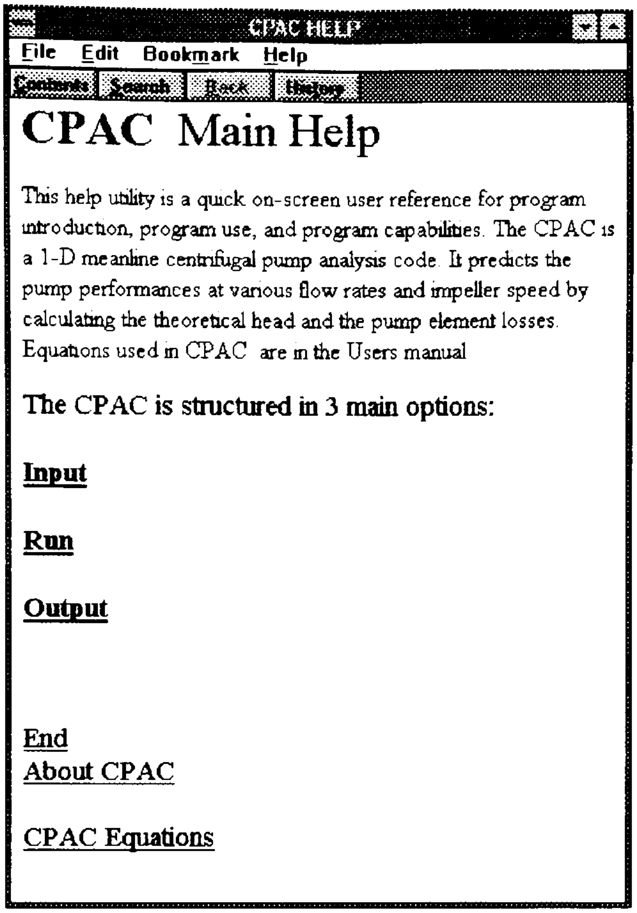


Figure 4.16 Help Screen

4.4.0 Examples of Centrifugal Pump Modeling

To model a centrifugal pump in CPAC is relatively simple. The CPAC code calculates the theoretical head input from the pump impellers, then analyzes the head and capacity losses associated with the modeled pump. These losses are dependent on the pump geometry and operating conditions. Therefore to correctly predict the pump performance, the pump must be correctly modeled. This is accomplished by configuring the model with the appropriate pump elements, and operating conditions.

A pump is modeled as a series of pump elements connected to each other at nodes. A list of currently available element types is shown in Table 4.1. These elements figuratively represent the major geometry sections of a centrifugal turbopump. Under the Leakage element there are several different leakage configurations, such as front or rear shroud leakage, front or rear balance ribs, and etc. these are shown in Table 4.2.

Available Pump Elements	
Inducer	Turning Channel
Stator	DownComer
Impeller	Return Channel
Vaneless Diffuser	Vaneless Diffuser
1-Discharge Volute	1-Discharge Exit Diffuser
2-Discharge Volute	2-Discharge Exit Diffuser
Leakage(NFS,FS,NRS,RS,FWR,RWR,FBR,RBR)	

Table 4.1 Element Types

Front Face of Impeller	**Rear Face of Impeller**
No Front Shroud(NFS)	No Rear Shroud(NRS)
Front Shroud(FS)	Rear Shroud(RS)
Front wear Ring(FWR)	Rear Wear Ring(RWR)
Front Balance Rib(FBR)	Rear Balance Rib(RBR)

Table 4.2 Leakage Element Types

In order to model a pump correctly, one should break up the actual pump geometry into the appropriate pump elements listed in Table 4.1. When the pump elements have been selected, they must be connected in the proper order through the element node numbers which correctly traces the fluid path through the pump. This process is accomplished easily through an interactive process. Once the pump geometry has been correctly modeled, the required parameters must be entered into the program file, this is also done interactively. An example of a pump modeling session is discussed in section 4-3.4. When these steps have been completed, the pump model is ready to run computations through the CPAC code which will predict the pump performance.

4-4.1 Model Example3: Gould's 3656 S 2 1/2 x 3-7 pump

The Gould's 3656 series pump which was a general purpose pump was tested to see how CPAC predicts the industrial centrifugal pumps. This pump was modeled as having three elements(Table 4.3) and the model diagram is shown in Figure 4.17.

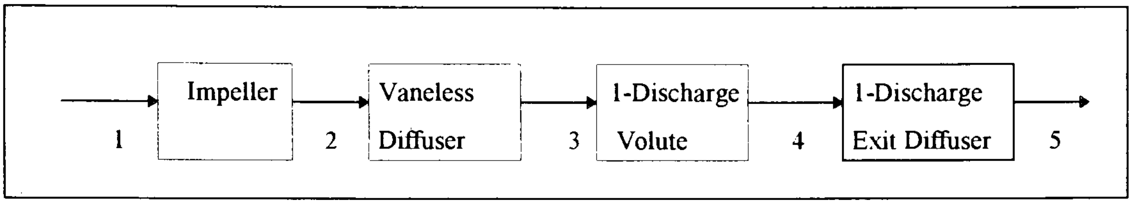


Figure 4.17 Model Diagram of Gould's 3656 pump

Element Number	Element Type	Inlet Node	Disch. Node
1	Impeller	1	2
2	Vaneless Diffuser	2	3
3	1-Discharge Volute	3	4
4	1-Disch Exit Diffuser	4	5

Table 4.3 Model Configuration (Gould's 3656)

4-4.2 Model Example 2: MK49-F Water Tester

The MK49-F Water Tester is a scaled-up single stage pump used during the development of the 3 stage Mark 49-F liquid hydrogen turbopump. This water test program provides test data with the CPAC program can be evaluated. This test pump model is consisted of Inducer, Impeller, Vaneless Diffuser, Vanded Diffuser, Turning Channel,' DownComer, and Leakage element which accounts for impeller shroud and wear ring leakage effects. Thus, CPAC models the tester pump accordingly with elements mentioned. Figure 4.18 is a simple schematic diagram of the pump model. The Model configuration of this pump follows in the Table 4.4.

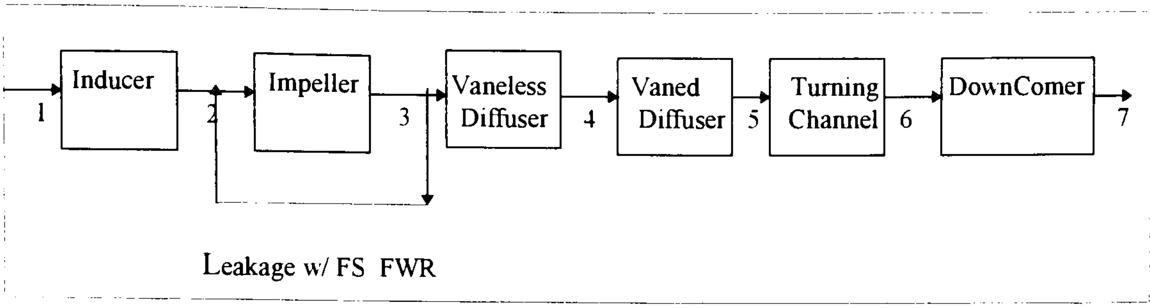


Figure 4.18 MK49-F Water Tester Model Diagram

Element Number	Option1			Option2		
	Element Type	inlet	Outlet	Element type	Inlet	Outlet
1	Inducer	1	2	Inducer	1	2
2	Impeller	2	3	Impeller	2	3
3	Leakage /FS FWR	3	2	Vaneless Diffuser	3	4
4	Vaneless Diffuser	3	4	Vaned Diffuser	4	5
5	Vaned Diffuser	4	5	Turning Channel	5	6
6	Turning Channel	5	6	DownComer	6	7
7	DownComer	6	7	Leakage /FS FWR	3	2

Table 4.4 Element sequence options

It can be noted that there are two options available to model the pump being the leakage element can go next to the impeller or at the end. The option2 is recommended for every modeling scheme. The leakage can be placed anywhere in a single stage pump or when there is only one leakage involved in the pump in multistage pumps. However, if there are more than 2 leakage elements throughout the pump, they have to be placed at the end like shown in Table 4.5.

4.4.3 Model Example 1: MK 49-F Turbopump

This section discusses a typical CPAC modeling session. Figure 4.19 shows a model diagram which has pump elements connected by nodes and fluid paths. This model schematic of the MK 49-F Centrifugal Turbopump depicts spool 1 of the actual turbopump consisting of 3 stages separated by crossover assemblies. Further investigation into the reference material resulted in the first stage consisting of an inducer followed by impeller with associated leakage, leading to a vaneless diffusing section and a vaned diffuser.

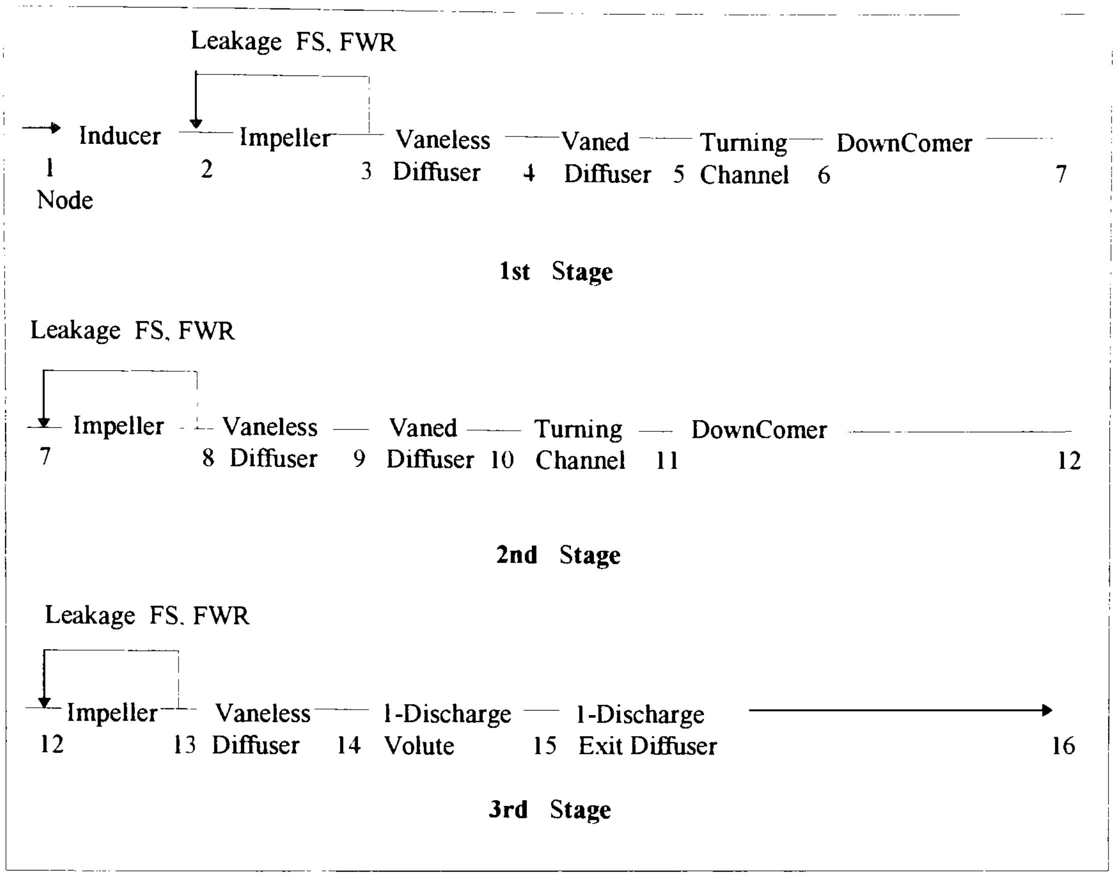


Figure 4.19 Schematic Diagram of a CPAC Model (MK 49-F)

The crossover assembly is modeled as a turning channel and a downcomer which in turn leads to the second stage impeller. The second stage impeller is followed by a vaneless diffuser and vaned diffuser and second stage crossover assembly of a turning channel and a downcomer. The third stage impeller leads to a vaneless diffuser followed by a single discharge volute and a single discharge exit diffuser. This configuration of the particular pump is shown in the Table 4.5. This assembly of elements is connected via inlet and discharge nodes which constitute the flow path through the pump.

Once a model pump has been configured, a user is ready to input geometry for each element starting by inducer element in this case. Figure 4.6 shown previously is a sample example of entering geometries for impeller element. Figure 4.20 is a Leakage element geometry input screen. Note that a user can select a type of leakage by clicking a check box on the right side of the screen, and a small star mark comes on which values are required for a user to enter. Impeller geometry values are automatically shown in the screen. A user has to change inlet node and discharge node to which the leakage flows.

Element Number	Element Type	Inlet Node	Discharge Node
1	Inducer	1	2
2	Impeller	2	3
3	Vaneless Diffuser	3	4
4	Vaned Diffuser	4	5
5	Turning Channel	5	6
6	Downcomer	6	7
7	Impeller	7	8
8	Vaneless Diffuser	8	9
9	Vaned Diffuser	9	10
10	Turning Channel	10	11
11	Downcomer	11	12
12	Impeller	12	13
13	Vaneless Diffuser	13	14
14	1-Discharge Volute	14	15
15	1-Disch. Exit Diffuser	15	16
16	Leakage /w FS FWR	3	2
18	Leakage /w FS FWR	8	7
20	Leakage /w FS FWR	13	12

Table 4.5 MK 49-F LH2 Model Configuration

This process can be also done in the model configuring step. In this particular model pump, four types of leakages are modeled - FS(Front Shroud) Leakage, FWR(Front Wear Ring) Leakage, RS(Rear Shroud) Leakage, and RWR(Rear Wear Ring) Leakage. FS and FWR types of leakages are going from impeller discharge to impeller inlet. RS and RWR types of leakages are going from impeller inlet to previous impeller discharge. The program calculates a new flow rate for each element associated with and calculates again accordingly.

The type of fluid used in this model pump was liquid hydrogen and constant properties were used. It's inlet conditions, operating speed, and flow rates are given in appendix. The design operating speed used was 110000 rpm. The whole pump was calculated by clicking Entire button which allows entire pump element calculations. Once calculations were done, both tabular and graphical output were analyzed to compare with test data. If a user wants to get a results based on another set of operating speeds and flow rates, a user just has to change values and press **Entire** button again and view results upon new input data. Also, for example, if a user wants to know what effects on overall performance of the pump as a discharge blade angle of impeller changes, a user only has to open a geometry screen for mpeller and change blade angle and run the CPAC again. This process is simple enough that designing a new pump or redesigning is changing a few numbers away.

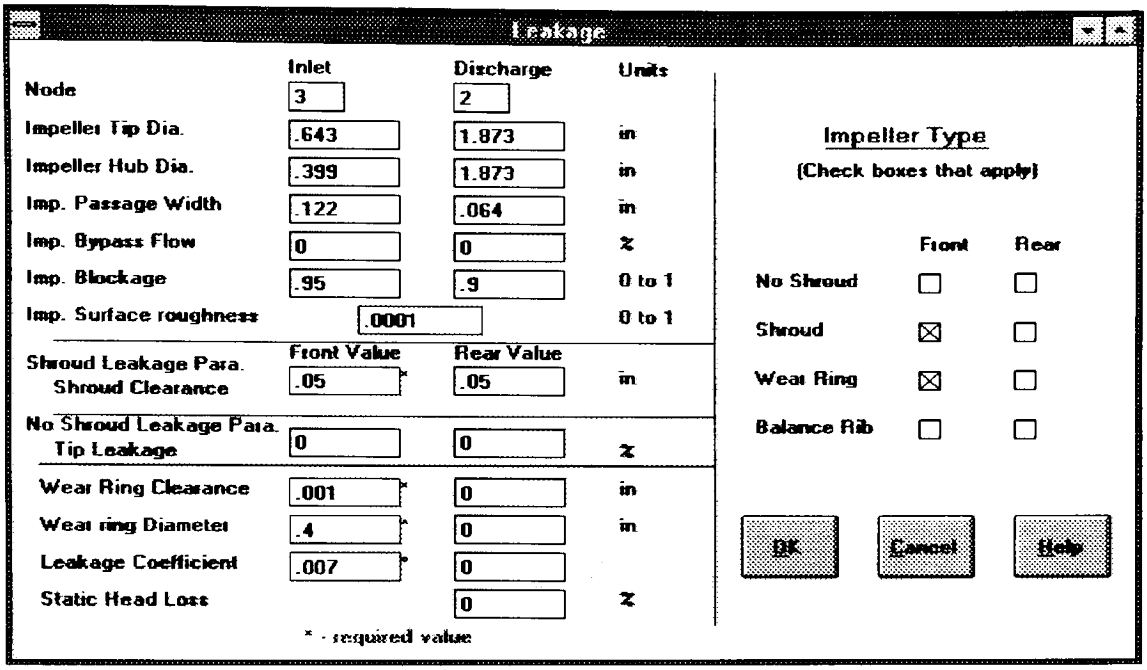


Figure 4.20 Leakage Type Element Geometry Input Screen

5. CPAC EQUATIONS

5-1.0 Introduction

The CPAC code calculation method is to solve for the velocity triangles at each element node based on the modeled pump geometry, flow rates and operating conditions.
Once the velocity triangle components are known, the theoretical or Euler Head is calculated followed by the associated element losses at design and off-design conditions.
The theoretical input head and the predicted losses thus provide the predicted output head, therefore the element efficiencies can be calculated. This information serves as the performance prediction output of the program. The major calculation equations are resented in the next sections while a detailed equations are presented in appendix C.

5-2.0 General Equations

The CPAC code performs the required calculations for each element in the following order:

1. Element area calculations
2. Element diameter (rms) calculations
3. Element velocity calculations
4. Element flow calculations
5. Element flow coefficient calculations
6. Element fluid velocity triangle (rms) calculations.

Area Calculations:

$$A = \frac{1}{2}\,\pi\,\,w\,\,(D_{tip} + D_{hub}) \qquad (5.1)$$

RMS Diameter Calculation:

$$D_{rms} = \sqrt{\frac{D_{tip}^{\,2} + D_{hub}^{\,2}}{2}} \qquad (5.2)$$

RMS Velocity Calculation:

$$Urms = \frac{D_{rms}\,N}{229.0} \qquad (5.3)$$

Weight Flow Calculation: $$WT = \frac{\dot{Q}\,\rho}{448.765} \tag{5.4}$$

Flow Rate Calculation: $$\dot{Q} = \frac{WT}{\rho} \qquad (\dot{Q} \text{ in ft}^3/\text{s}) \tag{5.5}$$

Flow Coefficient Calculation: $$\phi = \frac{144\dot{Q}}{V_{tip} A_{flow}} \tag{5.6}$$

where $$A_{flow} = AB - \frac{Z T_n w}{\sin(\beta_{rms})} \tag{5.7}$$

A = Area , B = blockage

5-2.1 Velocity Triangle Calculations

The following equations present ways that the various velocity triangle components are calculated for the pump elements. These are the general equations and it is necessary to note that various elements may have slight differences in the equations.

Fluid Meridional Velocity Calculation: $$C_{m\ rms} = \phi\, V_{tip} \tag{5.8}$$

substituting ϕ $$C_{m\ rms} = \frac{144\dot{Q}}{A_{flow}} \tag{5.9}$$

Once these independent values are calculated, the dependent values are then calculated using the previous elements parameters. The next calculations are the absolute rms(root mean square) fluid velocity and the absolute rms fluid tangential velocity components. The tangential component is calculated using a conservation of angular momentum approach:

Fluid Tangential Velocity Component: $$C_{ui\ rms} = \frac{C_{ui-1\ rms}\, D_{i-1\ rms}}{D_{i\ rms}} \tag{5.10}$$

Absolute Fluid Velocity: $$C_{rms} = \frac{C_{m\ rms}}{\sin(\alpha)} \tag{5.11}$$

When these parameters have been calculated, the element losses and other performance parameters can be calculated.

5-2.2 Loss Equations

The following sections present the various loss equations which are incorporated into the CPAC code. Each equation has been researched to a referenced theoretical base.

Incidence Loss Equation

The incidence loss or "shock loss" is calculated using the following empirical equations. Note that this form takes the relative angle of the blades and fluid into account to determine the correlation coefficient K_{inc}.

Incidence Loss:

$$\phi_{inc} = \frac{K_{inc}}{2}\left(\frac{S_1}{V_{tip}}\right)^2 \tag{5.12}$$

where

$$\frac{S_1}{V_{tip}} = \frac{C_{mrms}}{V_{tip}}\left|\cot\beta_{b1} - \cot\beta_{f1}\right| \tag{5.13}$$

with

$$K_{inc} = 0 \quad \text{for } \left|\beta_{b1} - \beta_{f1}\right| \le 2 \tag{5.14a}$$

$$K_{inc} = 0.3 \quad \text{for } \left|\beta_{b1} - \beta_{f1}\right| > 2 \tag{5.15b}$$

In these equations, the subscript 1 denotes the inlet to the element.

Diffusion Loss Calculations

The diffusion losses are estimated by the calculation of a diffusion factor D, modified by a correction factor determined from the type of pump element under evaluation. The diffusion factor is determined from

$$D = 1 - \frac{W_2}{W_1} + \frac{W_1 - W_2}{2\sigma W_1} \tag{5.15}$$

The diffusion loss coefficient then is calculated empirically by

$$\phi_{dif} = K_{dif} D^{N} \tag{5.16}$$

The values for K and N are element dependent and are listed in Table 5.2. It should be noted that the diffusion loss calculated for the volute, and downcomer has been added to the code at R.I.T. The correction factors K and N have been selected based on experience, however, they may be modified depending on further investigation.

Element	K	N
Inducer	0.05	2
Stator	0.03	3
Impeller	0.03	3
Diffuser	0.03	3
Volute	0.02	2
Downcomer	0.03	3

Table 5.1 Diffusion Loss Empirical Parameters

Skin Friction Loss Calculations

The final major pump loss calculated is the skin friction loss. This loss is calculated for the element types: inducer,stator, impeller, vaned diffuser, single and double volutes, turning channel, downcomer, and return passage. The loss calculation is strongly dependent on the friction loss coefficient, which is calculated by determining Reynolds number and the hydraulic diameter, then incorporating the Moody Diagram to select the appropriate friction coefficient. The following equations are used in the program to calculate the element skin friction loss coefficients:

$$\phi_{dif} = \frac{fL}{4D_h}\left[\frac{W_1^2 + W_2^2}{V_{tip}^2}\right] \tag{5.17}$$

The friction coefficient is then a function of the Reynolds number and roughness as noted above.

$$f = F(\mathrm{Re}, \frac{e}{D_h}) \tag{5.18}$$

where

$$\mathrm{Re} = \left[\frac{W_1^2 + W_2^2}{V_{tip}^2}\right]\frac{D_h V_{tip}}{2\nu} \tag{5.19}$$

where the hydraulic diameter, $D_h = \frac{4}{2}\left[\frac{A_1}{P_1} + \frac{A_2}{P_2}\right]$ (5.20)

and

$$A_i = \left[\frac{\pi}{Z_i} D_{irms} \sin\beta_{bi}(B_i - Tn_i)\right](D_{tipi} - D_{hubi}) \tag{5.21a}$$

$$P_i = \left[2(D_{tipi} - D_{hubi}) + \frac{\pi}{Z_1}(D_{tipi} + D_{hubi})\sin\beta_{bi} - 2Tn_i\right] \tag{5.21b}$$

i = 1,2

Incorporating Moody Diagram is done with an equation by Colebrook.

$$\frac{1}{f^{0.5}} = -2.0\log(\frac{e/D}{3.7} + \frac{2.51}{\mathrm{Re} f^{0.5}}) \tag{5.22}$$

The friction factor equation is transcendental so that it has to be iterated with initial estimate by Miller.

$$f_0 = 0.25\left[\log(\frac{e/D}{3.7} + \frac{5.74}{\mathrm{Re}^{0.9}})\right]^{-2} \tag{5.23}$$

Volute Momentum Loss Calculation

The scroll momentum loss is determined from the following equations:

$$\phi_{scm} = K_{scm}\left[\frac{C_{u\,rmsi}}{V_{tip}}\right]^2\left[\frac{A_{throat} - A_{scm}}{A_{throat}}\right]^2 \tag{5.24}$$

where A_{scm} is the area determined from D_{scm} given below, and K_{scm}=0.5.

$$D_{scm} = 2\sqrt{D_{throat} w_i \tan\alpha_i} \qquad \text{i=inlet} \tag{5.25}$$

Mechanical Loss Calculations

The program calculates a variety of mechanical losses associated with the closed type of impellers. where as old version of CPAC has ability to calculate open face type impellers. This new version of CPAC discarded the option to calculate open face type of impellers because in practice where high speed turbopumps are used. open face type of impellers are rarely in use. The mechanical losses include disc friction losses. wear ring losses. leakage losses. and recirculation losses.

The horsepower loss due to disc friction. and the capacity losses due to leakage flow rate through the impeller affect the incidence. skin friction and diffusion losses due to new flow rate which is the sum of the initial flow rate and leakage flow rate. These losses are modeled with leakage elements. The loss coefficients are calculated from the following equations:

The horsepower losses are of the form: $$Hp_d = KD^2 \rho U_{rms}^3 \quad (5.26)$$

where K = correction coefficient

D = impeller diameter

ρ = fluid density

U = impeller peripheral velocity

In CPAC. $$U_{rms} = V_{tip} \quad (5.27a)$$

$$D = \frac{\left(D_{rms2}^5 - D_{rms1}^5\right)}{D_{rms2}^3} \quad (5.27b)$$

where $$K = \frac{[9\rho][0.5][24][12^5]}{550g} \quad (5.27c)$$

The leakage losses are of the following form:

$$\dot{Q}_{leakage} = C_{wr} A_{wr} \sqrt{2gH_{wr}} \quad (5.28)$$

where A_{wr} = Leakage flow area

C_{wr} = Wear ring loss coefficient

H_{wr} = Head drop across wear ring

Once these losses have been computed, the subroutine modifies the flow rate, and other flow rate dependent parameters, due to the losses and leakages of the impeller. These modifications are as follows:

Flow Rate Modification: $$\dot{Q}_{delivered} = \dot{Q}_{delivered} + \dot{Q}_{leakage\ rear} + \dot{Q}_{leakage\ front} \quad (5.29)$$

Flow Coefficient Calculation: $$\phi = \frac{144\dot{Q}_{delivered}}{V_{tip} A_{flow}} \quad (5.30)$$

where $$A_{throat} = AB - \frac{ZTnw}{\sin\beta_{rms}} \quad (5.31)$$

Recirculation Loss Calculations

An empirical equation has been developed based on test data that gives the flow coefficient of a pump at the maximum efficiency point and is a function of the head coefficient at the maximum efficiency ϕ_{des} and blade angle at discharge of impeller,
β_{b2} and minimum blade number for maximum efficiency Z2. This equations is:

$$\phi_{2des} = \frac{K\phi_{des}\sin\beta_{b2}}{Z_2} \quad (5.32)$$

where K = 7.03 empirically.

The recirculation loss is considered to be zero at the maximum efficiency point. At zero flow, the required pump horsepower due to recirculation is a constant G times the design pump power required.

$$\Delta P_{rec} = 0.0 \qquad \text{at } \phi_2 = \phi_{des2} \quad (5.33a)$$

$$\Delta P_{rec} = G\ Hp_{[at\ max\ \eta]} \qquad \text{at } \phi_2 = 0.0 \quad (5.33b)$$

An empirical equation is then given as :

$$\Delta P_{rec} = \frac{G\phi_{des}\left[\phi_{des2} - \phi_2\right]^{3\eta}}{\phi\phi_{des2\,2}^{2\eta}} \quad (5.34)$$

where η defines the amount of power loss with ϕ and could possibly be correlated with impeller discharge blade angle. The value G has been found from test data at shutoff or zero flow to be in the range of 0.3 to 0.5.

Impeller Theoretical Head Calculations

In order to correctly evaluate pump performance, the theoretical head input by the impeller needs to be calculated. This input head by the impeller is calculated from the velocities.

Theoretical Head Equation:

$$H_{input} = \frac{C_{rms2}^2 - C_{rms1}^2}{2g} + \frac{U_{rms2}^2 - U_{rms1}^2}{2g} + \frac{W_2^2 - W_1^2}{2g} \qquad (5.35)$$

In the CPAC code, the theoretical head coefficient is calculated:

$$\psi_{theory} = \frac{U_{rms2}C_{u2} - U_{rms1}C_{u1}}{V_{tip}^2} \qquad (5.37)$$

from which the theoretical head is calculated:

$$Head_{theory} = \frac{\psi_{theory}U_{rms2}^2}{g} \qquad (5.38)$$

5-2.3 Performance Equations

It is important to note that for each element, once all of the losses for that element are calculated, the individual element performance is evaluated.

Total Element Loss : Total Loss = Σ all Element Losses (5.39)

Element Euler Head Coefficient:

$$H_{Euler} = \frac{U_{rms2}C_{u2} - U_{rms1}C_{u1}}{U_{rms2}^2} \qquad (5.40)$$

Element Actual Head Coefficient: $H_{Actual} = H_{Euler}$ - Total Losses (5.41)

Element Efficiency: $$\eta_{Element} = \frac{H_{Actual}}{H_{Euler}} \tag{5.42}$$

5.3.0 Programming CPAC in Visual Basic

5.3.1 Proram Structure

CPAC was written in Visual Basic programming language. Visual Basic was chosen since it has a good user interface capabilities on MicroSoft Windows operating system and powerful windows applications. Since CPAC is based on one-dimensional theory of turbomachinery, the programming was done accordingly. First, the CPAC calculates the areas of inlet and discharge of each element to determine the meridional velocity, given flow rates which is in the form of flow coefficients. With operating speeds, CPAC calculates the tip speeds of the impeller. With meridional velocity, tip speed and input geometric data supplied by a user, other velocities such as absolute velocity, tangential velocity, and relative velocity, and fluid angles such as relative and absolute fluid angles are determined. With velocities and fluid angles determined, losses such incidence, skin friction, and diffusion losses and other minor losses can be determined with user supplied geometric data which are required for loss calculations. The next step is to calculate the performances of the pump with information supplied and determined. Heads, pressures, and temperatures are determined in performance procedure. If the element is a Leakage type, then, leakage subroutine is called to calculate leakage flow and new flow rate based on the leakage, and power losses due to the increased flow rate. Then, the procedures to calculate flow coefficients, velocities, and losses are called again upon new flow rates. Next step is to calculate the overall performance of the pump, where power coefficients, total losses, total head, and efficiencies are calculated. If variable properties mode was selected, the subroutine 'gasplus' is called upon temperature and pressure. Properties were calculated by equations which were interpolated from the property table. Data calculated from procedures are stored in the global data arrays listed in Appendix A. These global data will be used in the output stage. The figure 5.1 shows the sequence of the CPAC calculations.

5.3.2 Programming a user interface with Visual Basic

Designing an interface is a more appropriate term for writing or programming in Visual Basic. In Visual Basic, forms are used; forms are like windows. Forms contain buttons that can be clicked to activate commands. Commands are subroutines that are written in Basic language. Forms can contain pictures or command buttons, or graphical forms. In main menu screen of CPAC, there are many buttons and a picture which were added from the tool box. Tool box is one of the features that Visual Basic offers. From the tool box, command buttons, labels, pictures, graphs, links between MicroSoft Windows, scroll bars, check boxes, and etc are available for the interfaces. Command buttons, a picture, and a scroll bar picture make up the main menu screen. Each button are controlled by a feature called 'Properties'. Properties control the position of the buttons, captions, colors, attributes, and so on. Each button calls a subroutine. For example, Run button calls the subroutine that carries out calculations (steps shown in Figure 5.1). Tabular button creates a full size form that shows output values in tabular form. In tabular form, there are scroll bars placed where a user can select a type of output. Graph button creates a full size form in which graph box is placed. The graph box is a very convenient tool that can display data in the form of lines and marks. Help button calls a help file that was compiled by Borland C help compiler program, and the help file is in standard windows help format. Files for storing input data and output data are in text file format, so that they can be modified by text editor if a user wants to. File reading or writing procedures are linked to windows application; thus, if a user clicks a read button, the screen that appears will be the same screen that are seen in other MicroSoft Windows program to open a file. The files used in CPAC program are listed below.

Input forms files

Inducer.frm, Impeller.frm, Stator.frm,Vanediff.frm, Vlessdif.frm, Turnchan.frm, Downcome.frm
Leakage.frm, Sdvolute.frm, Ddvolute.frm, Sdexdiff.frm, Ddexdiff.frm, Retpass.frm
Flowrate.frm, Speed.frm, Inletcon.frm, Elconfig.frm, Fluidtyp.frm, Fluidpro.frm

Menu forms files

Title.frm, Newform.frm, Graphs.frm, Dataout.frm, Multirun.frm

Calculations files

Engine.bas, global.bas

Notice files

Cpacrun.frm, Printing.frm

Graphic files

Appolo.bmp, Pump.bmp

Help file

Cpachelp.hlp

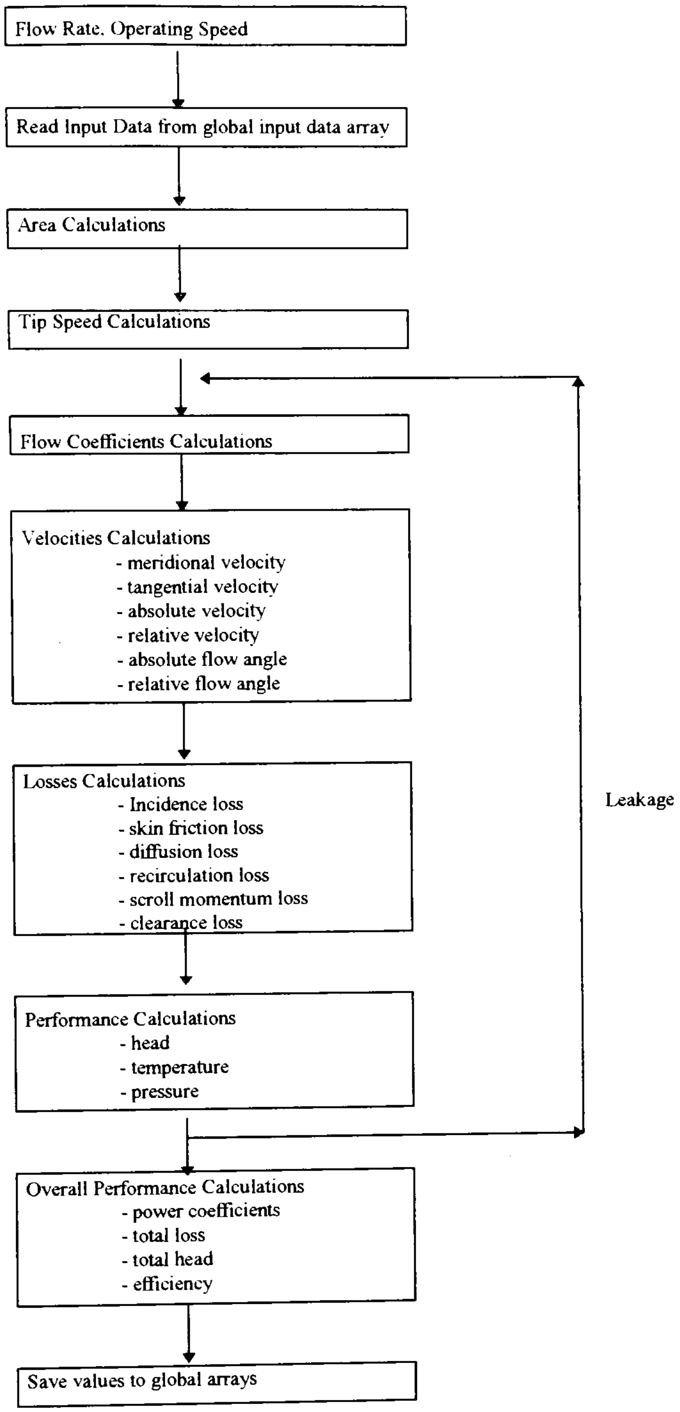


Figure 5.1 CPAC programming sequence

6. Results and Discussions

Several different types of pumps have been modeled to demonstrate the predictive capabilities and to show the versatility of the CPAC code, and comparisons between the predicted performance values and the available actual test data were made. The various type of the pumps from the scaled-up test pump to actual cryogenic turbopumps used in the rocket engines, also including an industrial general purpose pump, were modeled. Two cases of the five pumps tested were run with variable property to show one of the unique features of the CPAC. Various operating speeds as well as flow rates were used to demonstrate the capabilities of performance predictions at off-design operating conditions. Table 6.1 shows the types of pumps modeled. Each model is represented with the configuration and predicted performances. Full CPAC output summaries for the first two are included in Appendix D.

Pump Type	Fluid Type	Stages	Property
1. A scaled up Mark 49-F water tester	Water	1	Constant
2. The Mark 49-F high pressure 3-stage turbopump with high velocity ratio crossover elements	LH2	3	Variable
3. The Mark 48-F turbopump high pressure low capacity 3-stage turbopump	LH2	3	Variable
4. The Pratt & Whitney Advanced Engine Test Bed (AETB)	LH2	1	Constant
5. Gould's 3656 (2x1/2 3-7) general purpose pump	Water	1	Constant

Table 6.1 Pump models for CPAC case studies

6.1.0 Mark 49-F Water Tester

Mark 49-F Water Tester is the scaled-up first stage of Mark 49F 3 stage LH2 turbopump and it was developed as a part of an extensive test program. This test program provided data including required input geometric data as well as the operating conditions so that the CPAC program can be evaluated. The CPAC model configuration for this pump is shown in Table 6.2. The model consists of an inducer, impeller, vaneless diffuser, vaned diffuser, crossover(turning channel and downcomer) as well as a leakage element to account for impeller shroud and wear ring leakage effects. Static head rises of inducer alone with both inducer and impeller were compared, as well as overall head rise and the efficiency of the pump, shown in Figure 6.1-4.

Element Number	Element Type	Inlet Node	Discharge Node
1	Inducer	1	2
2	Impeller	2	3
3	Vaneless Diffuser	3	4
4	Vaned Diffuser	4	5
5	Turning Channel	5	6
6	DownComer	6	7
7	Leakage w/ FS FWR	3	2

Table 6.2 Model Configuration of MK49 Water Tester Pump

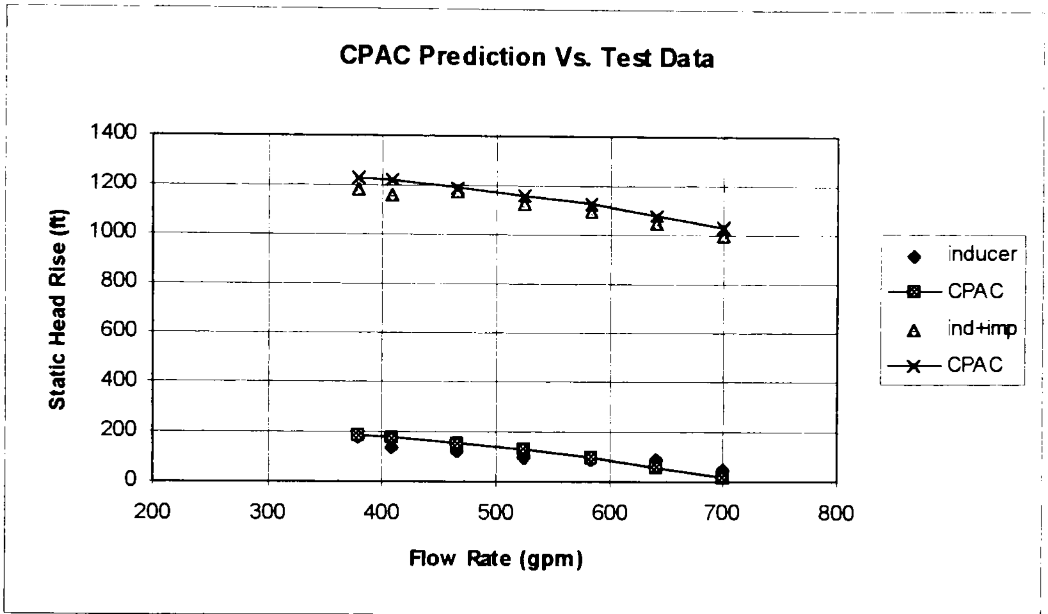


Figure 6.1 Head Rise of Inducer and Impeller elements (Test Data vs. CPAC output)

The CPAC program predicts the static head rise for the inducer and impeller elements to within 5% of the available test data over entire flow rate range and 2% at the design flow rate(Q_d=583 gpm) as shown in Figure 6.1. The Figure 6.2 shows the overall stage head rise over flow rates from 380 gpm(65% of Q_d) to 700 gpm(120% of Q_d). The attempt to compare the overall stage head rise was made, but it seems that CPAC underpredicted the head rise. Upon investigating the head rises of inducer and impeller being very close to the test data, another CPAC calculations were made without crossover elements, that is without turning channel and downcomer(Fig. 6.2). With the crossover elements, the CPAC predicted 11% lower than the test data at Q_d. Without crossover elements, it predicted 4.8% lower. Loss data on crossover elements were not available to justify the assumption. Head drops by the crossover elements were 25 ft to 105 ft over the range of flow rates. Hence, another attempt to predict the overall stage head was made with lower surface roughnesses for the vaneless diffuser(50% and 10% of data originally 0.0086 used) since vaneless diffuser is where major portion of the frictional head loss is produced; These attempts included crossover elements(Fig. 6.3). With 50% of the surface roughness, the overall head was under 6 % for the whole flow rates. With 10% of the roughness, the prediction was within 4% over the entire flow rates and 0.5% off at the design flow rate. It seems that frictional loss may be the problem. This again could not been verified, but it suggests that more studies on the vaneless diffuser can be done in the future. The overall stage efficiency is predicted within 6 % at the lowest flow rate tested and 2 % at the design condition from the test data as shown in Figure 6.4.

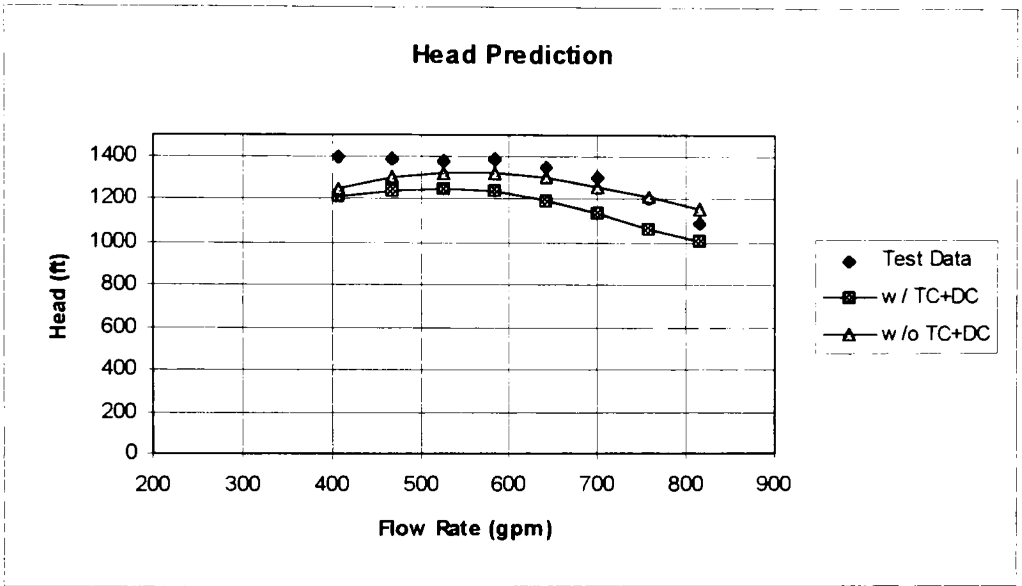


Figure 6.2 Overall Head Prediction vs. Test Data w/ or w/o crossover elements

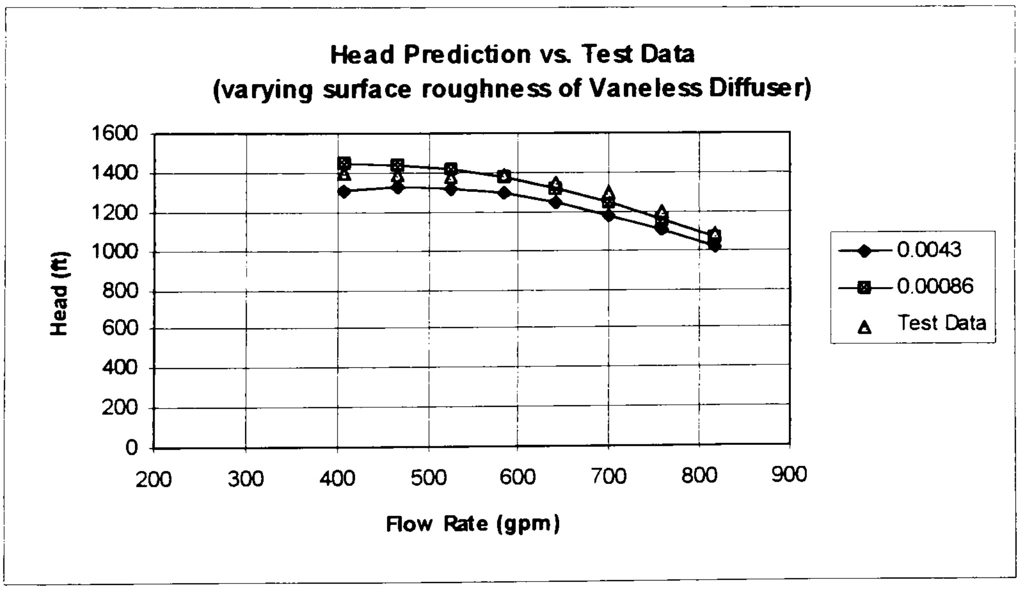


Figure 6.3 Overall Head Prediction vs. Test Data with lower surface roughnesses

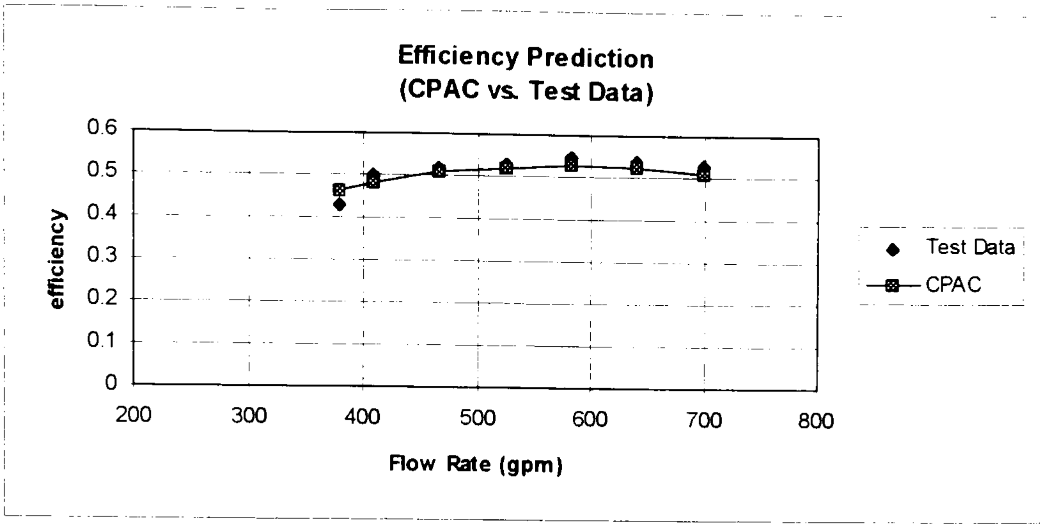


Figure 6.4 Efficiency prediction vs. Test Data

Although some deviations in the performance prediction exist due to the nature of one dimensional assumption, the usefulness of CPAC program is evident in that it serves to identify inefficiencies in the pump on an individual element basis and acceptably predicts overall performance.

6.2.0 Mark 49-F 3-Stage Liquid Hydrogen turbopump

The Mark 49-F 3-Stage Turbopump was developed for use on the RS-44 Orbital Transfer Vehicle rocket engine. This pump features the use of high velocity ratio diffusing crossovers between stages. The Table 6.3 shows the configuration of the CPAC pump model. The first stage is modeled with inducer, impeller, vaneless diffuser, and vaned diffuser. The crossover elements between the first stage and the second stage are turning channel and downcomer, and also used between the second stage and the third stage. The second stage starts with impeller, followed by vaneless diffuser, and vaned diffuser. The third stage also starts with impeller, followed by vanelss diffuser, a single discharge volute, and a single discharge exit diffuser.. Leakage elements are also associated with impellers in each stage and were modeled to account for front shroud leakage effects.

This model was to predict the performance of the Mark 49-F turbopump for which the scaled-up Mark 49 water tester was built and tested. Unfortunately, the test data was not available to justify this model, but CPAC predictions over several operating speeds and flow rates were made and it shows well of the characteristics of the head(Figure 6.5). This model was run with variable properties which was incorporated into the CPAC. The design speed of the Mark 49-F was known to be at 110,000 rpm.

Element Number	Element Type	Inlet Node	Discharge Node
1	Inducer	1	2
2	Impeller	2	3
3	Vaneless Diffuser	3	4
4	Vaned Diffuser	4	5
5	Turning Channel	5	6
6	DownComer	6	7
7	Impeller	7	8
8	Vaneless Diffuser	8	9
9	Vaned Diffuser	9	10
10	Turning Channel	10	11
11	DownComer	11	12
12	Impeller	12	13
13	Vaneless Diffuser	13	14
14	1-Disch Volute	14	15
15	1-Disch Exit Diffuser	15	16
16	Leakage w/ FS FWR	3	2
17	Leakage w/ FS FWR	8	7
18	Leakage w/ FS FWR	13	12

Table 6.3 Mark 49-F LH2 Pump model configuration

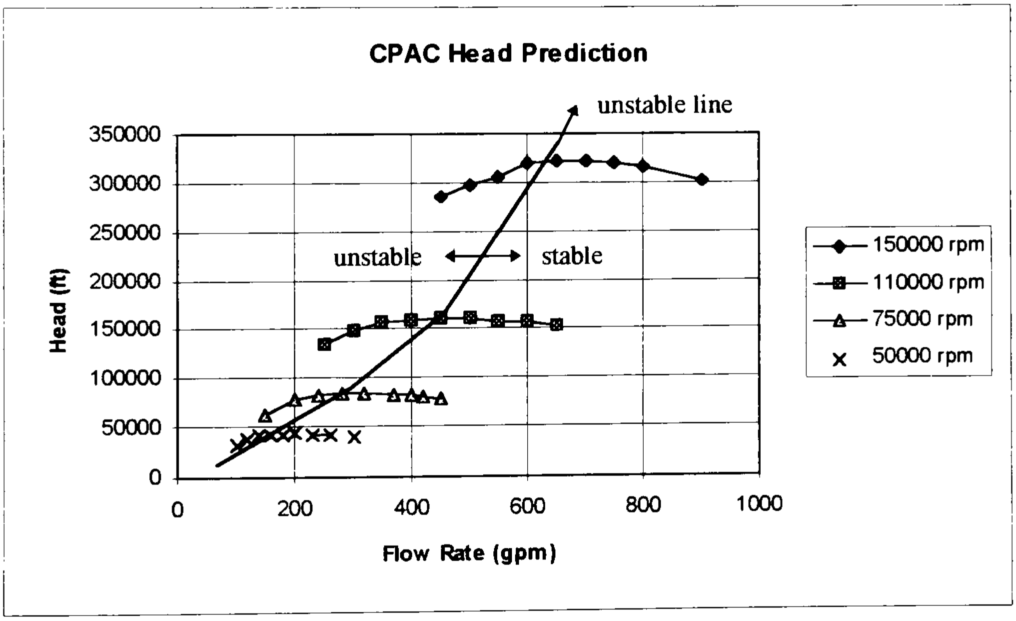


Figure 6.5 Overall Head prediction of the Mark49-F at the various operating speed.

6.3.0 Mark 48-F Small high-pressure 3 stage turbopump

The Mark 48-F is an earlier version of the Mark 49-F and is a high pressure, low capacity liquid hydrogen 3-stage turbopump designed by the Rocketdyne Division of Rockwell International. This pump was intended to be in use for small, high performance, reusable, versatile, staged combustion and expander cycle rocket engine applications. The design speed for this pump is 95000 rpm with mass flow rate of 6.04 lb/s (620 gpm). This turbopump is required to operate for a long duration and coasting flight with multiple starts including off-design operations. Performance analysis at off-design conditions becomes necessary with reliable predictive methods which may be very expensive and time consuming in testings, and CPAC can be an inexpensive and quick method for performance analysis.

The Mark 48-F turbopump was modeled as shown in Table 6.4. The crossover elements are modeled with 2 turning channels and a downcomer. The crossover elements connects between stages.

Element Number	Element Type	Inlet Node	Discharge Node
1	Inducer	1	2
2	Impeller	2	3
3	Vaneless Diffuser	3	4
4	Vaned Diffuser	4	5
5	Turning Channel	5	6
6	DownComer	6	7
7	Turning Channel	7	8
8	Impeller	8	9
9	Vaneless Diffuser	9	10
10	Vaned Diffuser	10	11
11	Turning Channel	11	12
12	DownComer	12	13
13	Turning Channel	13	14
14	Impeller	14	15
15	Vaned Diffuser	15	16
16	Vaneless Diffuser	16	17
17	1-Disch Volute	17	18
18	Leakage w/ FS FWR	3	2
19	Leakage w/ FS FWR	9	8
20	Leakage w/ FS FWR	15	14

Table 6.4 Mark 48-F model configuration

Overall discharge head was compared to the available test data. Table 6.5 is tabularized to compare values tested and predicted, and the Figure 6.6 graphically shows the test data and the results from the CPAC calculations. The Figure 6.7 is supplied with test data and the prediction of unknown code. In this case study, calculations were done in both variable property and constant property modes. It seems that, at the higher operating speeds, constant property calculations predict better, and at the lower operating speeds the variable property calculations predicted better.

Speed = 95000 rpm				Speed = 75000 rpm			
mass	Pressure(psi)			mass	Pressure(psi)		
rate (lb/s)	Test Data	VP(%diff)	CP(%diff)	rate (lb/s)	Test Data	VP(%diff)	CP(%diff)
4.0	5070	5171(2.0)	5310(4.7)	3.3	3150	3144(-0.2)	3310(5.1)
4.3	5100	5100(0.0)	5307(4.0)	4.0	3250	3110(-4.3)	3280(0.9)
4.5	5220	5090(-2.5)	5300(1.5)	4.8	3100	3048(-1.7)	3218(3.8)
5.0	5250	5054(-3.8)	5271(0.4)	5.8	2950	2752(-6.7)	2955(0.2)
5.3	5200	5020(-3.5)	5247(0.9)	5.9	2900	2720(-6.2)	2925(0.9)
6.0	5050	4953(-1.9)	5174(2.5)				

Speed = 60000 rpm				Speed =45000 rpm			
mass	Pressure(psi)			mass	Pressure(psi)		
rate (lb/s)	Test Data	VP(%diff)	CP(%diff)	rate (lb/s)	Test Data	VP(%diff)	CP(%diff)
2.8	2050	2003(-2.3)	2115(3.2)	2.3	1150	1124(-2.3)	1184(3.0)
3.4	2000	1978(-1.1)	2090(4.5)	2.8	1100	1102(0.2)	1163(5.7)
3.8	1900	1948(2.5)	2062(8.5)	3.2	1050	1046(-0.4)	1105(5.2)
4.0	1850	1930(4.3)	2046(10.4)	3.5	1000	1000(0.0)	1060(6.0)
4.5	1800	1805(0.3)	1920(6.7)	-	-	-	-

Table 6.5 Mark 48-F CPAC prediction vs. Test Data(VP-Variable Property, CP-Constant Property)

The CPAC performance prediction is very close at the design operating speed (95000 rpm) and design mass rate(6.04 lb/s): variable property calculation predicts -1.9% and 2.5% for the constant property. Generally at the design speed, the CPAC predicts very well within 4%. At 75000 rpm and design mass rate(4.8 lb/s), it predicts -1.7% and 3.8% for variable and constant property calculations. For operating speeds of 60000 rpm and 45000 rpm, variable property calculations predict better over constant property. At 60000 rpm and the design mass rate(3.8 lb/s), variable property mode predicts 2.5 % off from the test data and 8.5 % when constant property was used. At 45000 rpm with 2.8 lb/s(design mass rate), variable property predicts 0.2% and 5.7% for the constant property.

Generally, the variable property calculations predict better over the constant property calculations, and it makes sense that as temperature and pressure change at each node in the pump, the properties change accordingly. CPAC performance predicts satisfactorily, and does appear to perform much better than the unknown predictive code used during the actual testing (Figure 6.7).

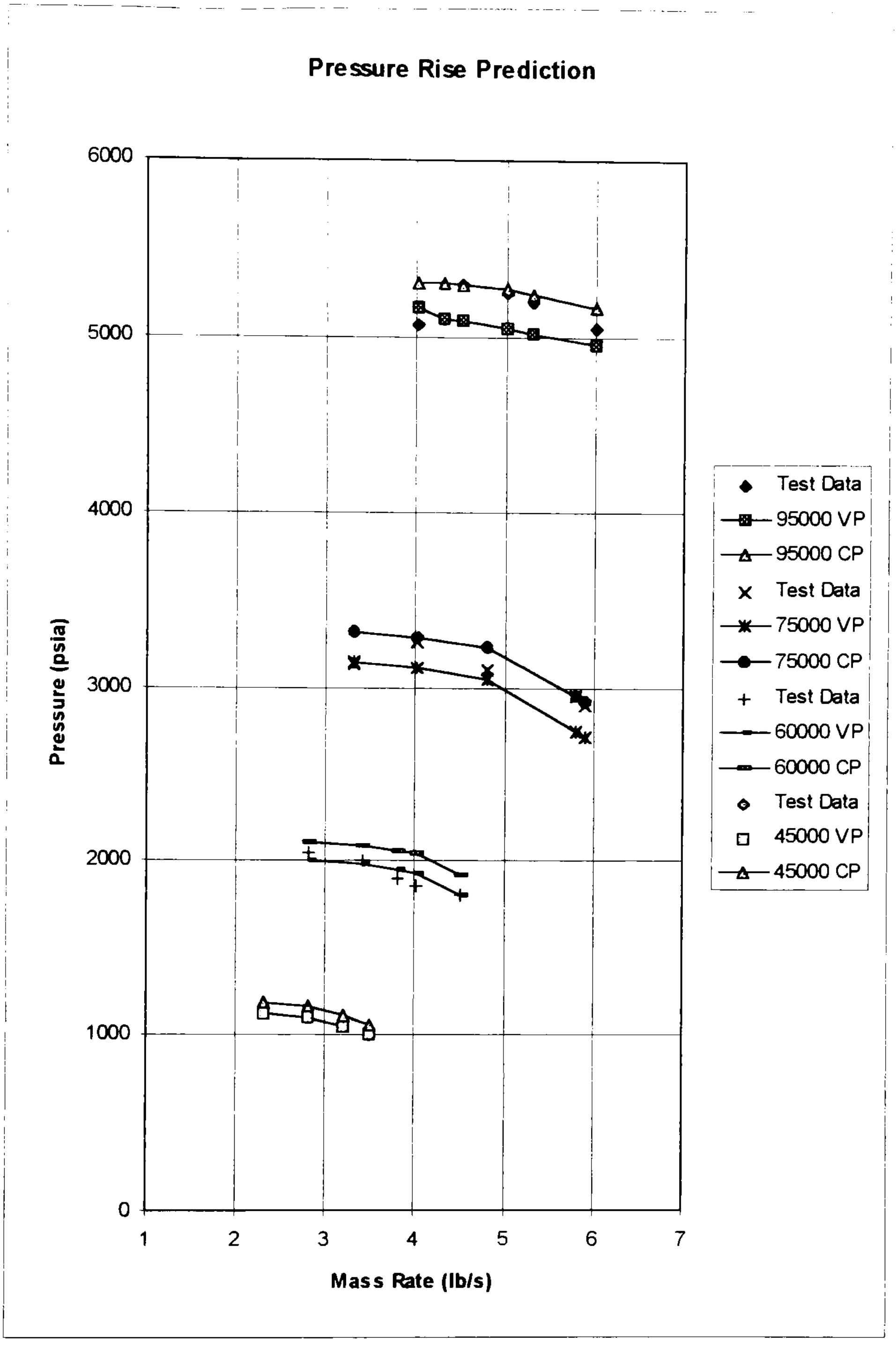


Figure 6.6 Mark 48-F overall Head prediction at various operating speed
(VP stands for variable property and CP for constant property)

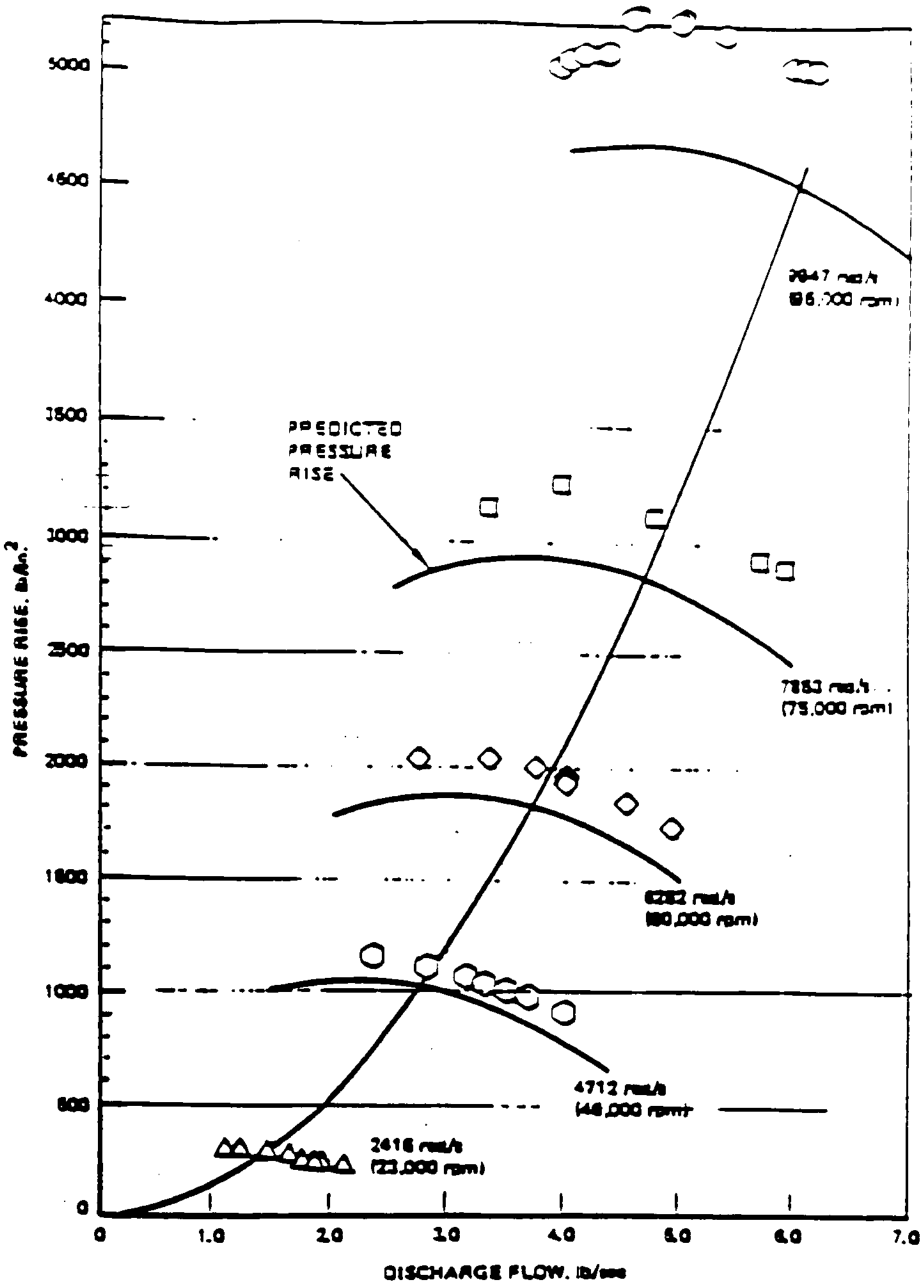


Figure 6.7 Test Data with prediction by unknown code

6.4.0 Advanced Engine Test Bed (AETB) Turbopump

The AETB turbopump is a volute type turbopump developed at Pratt and Whitney. This pump was developed for deep throttling capabilities like the Mark 49-F Turbopump. The CPAC pump model configuration. models a single stage and is presented in Table 6.6. Figure 6.8 shows the overall head predictions at various operating speeds. This case considers only the first stage of the AETB pump. The actual pump consists of 2 stages and unfortunately no test data was available for comparison.

Element Number	Element Type	Inlet Node	Discharge Node
1	Inducer	1	2
2	Impeller	2	3
3	Vaneless Diffuser	3	4
4	1-Discharge Volute	5	6
5	Leakage w/ FS_FWR	3	2

Table 6.6 AETB model configuration.

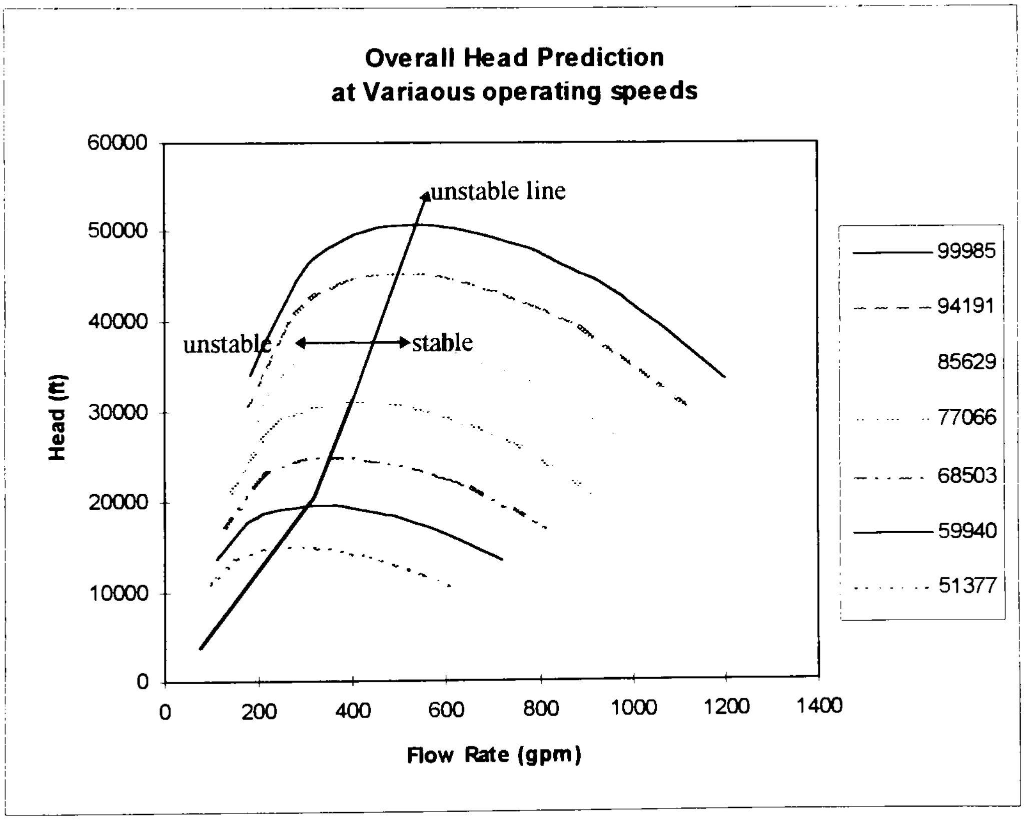


Figure 6.8 Head predictions of various operating speeds

6.5.0 Gould's 3656 General Purpose pump

This pump is an industrial centrifugal pump specially designed for water circulation, booster service, spraying system, and irrigation system, driven by a motor. CPAC attempts to predict this industrial centrifugal pump to see how it performs on the general purpose pump so that in the future modifications can be made to better predict. The pump is designed to operate at 3500 rpm over a wide range of flow rate(50 to 450 gpm). Table 6.7 is the model configuration of the pump. Notice that the pump has vaneless diffuser after impeller. The reason of having vaneless diffuser is that the space between the impeller and the volute casing is considerably large compared to other pumps studied previously. It turned out that vaneless diffuser did not play a big part lowering the total head of the pump. The loss produced by vaneless diffuser is shown in Figure 6.11 with other elements, and the figure shows almost no head was lost at the design flow rate(250 gpm).

Element Number	Element Type	Inlet Node	Discharge Node
1	Impeller	1	2
2	Vaneless Diffuser	2	3
3	1-Discharge Volute	3	4
4	1-Discharge Exit Diffuser	4	5

Table 6.7 Model configuration for Gould's 3656

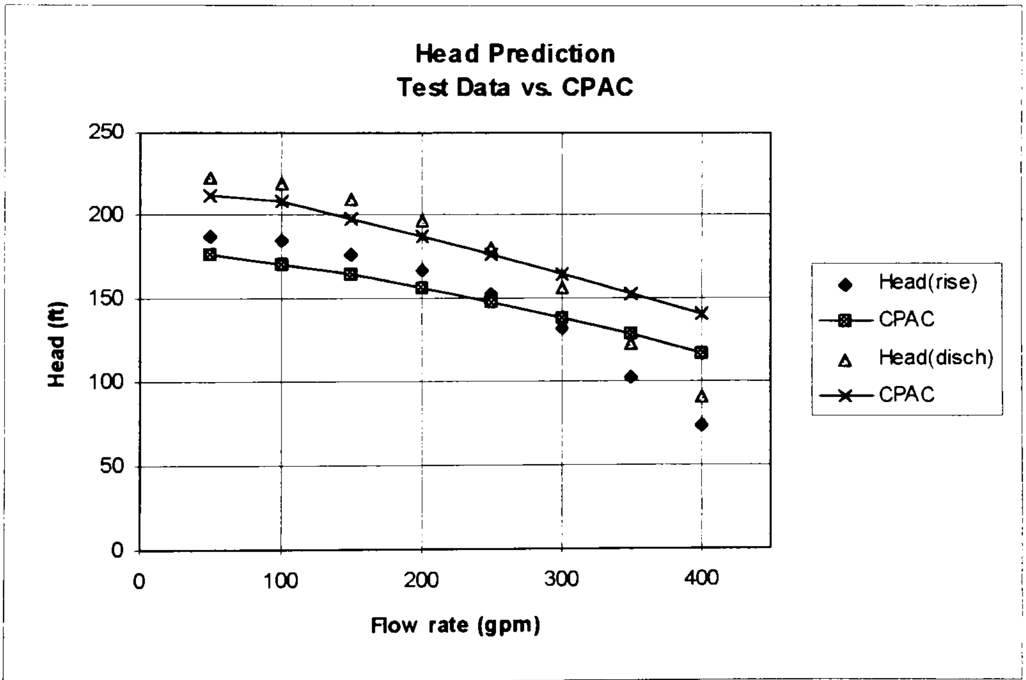


Figure 6.9 Head prediction vs Test Data

CPAC seems to underpredict below design flow rate(250 gpm) and overpredict over the design flow rate. However, at the design flow rate, it predicts very well within 4%. Figure 6.10 shows the discharge pressure compared to the test data. The shape of the pressure curve resembles the head curve since it reflects the head of the pump produces. Though the CPAC code was written for turbopumps, it predicts the performance of the general purpose pump acceptably.

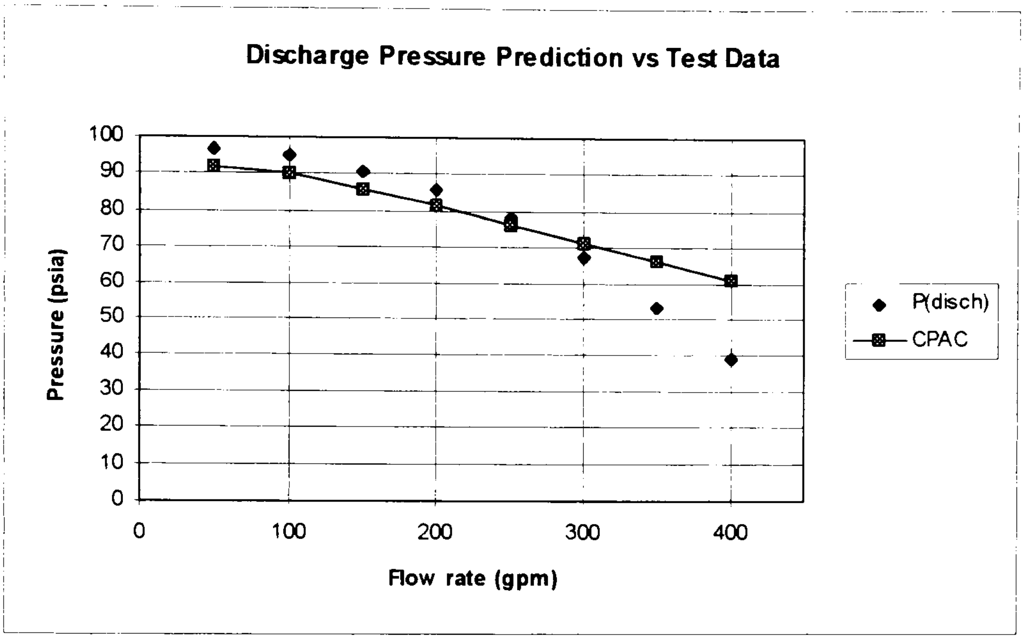


Figure 6.10 Discharge Pressure prediction vs Test Data

The geometric data of the impeller used in this model was taken from the drawing of the pump. Once the impeller is molded and cooled, it has some shrinkage effects and the dimensions of the impeller can be different from the drawing. These factors should be taken into account for any discrepancies.

To investigate the under-predictiveness and over-predictiveness of the CPAC on the general purpose of the pump, losses of each element were scrutinized as shown in Figures 6.11-13, since all loss equations and slip factor equation for impeller were written for highspeed turbopumps. From Figure 6.11 and 6.12, it can be noted that head losses in vaneless diffuser and exit diffuser are minor and major losses are due to 1-Discharge volute. Losses associated with the 1-Discharge volute is shown in Figure 6.13. From Figure 6.13, it can also be noted that scroll momentum loss is major to other losses mechanisms. Though losses are also associated with impeller, further studies can be done to verify losses in the volute element which industries call a casing.

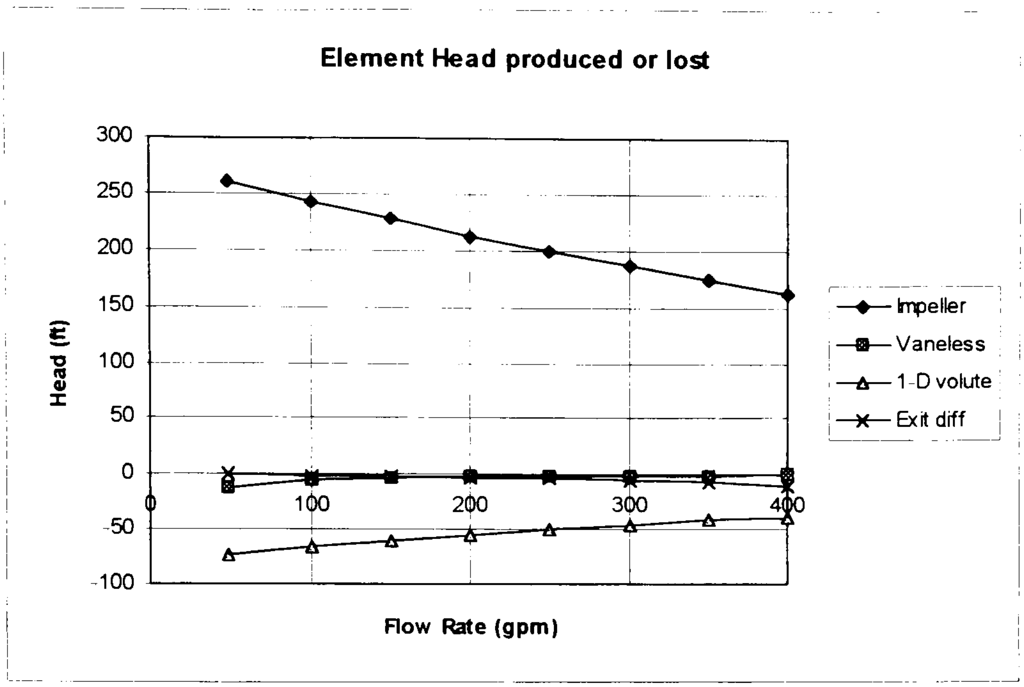


Figure 6.11 Element Head produced or lost

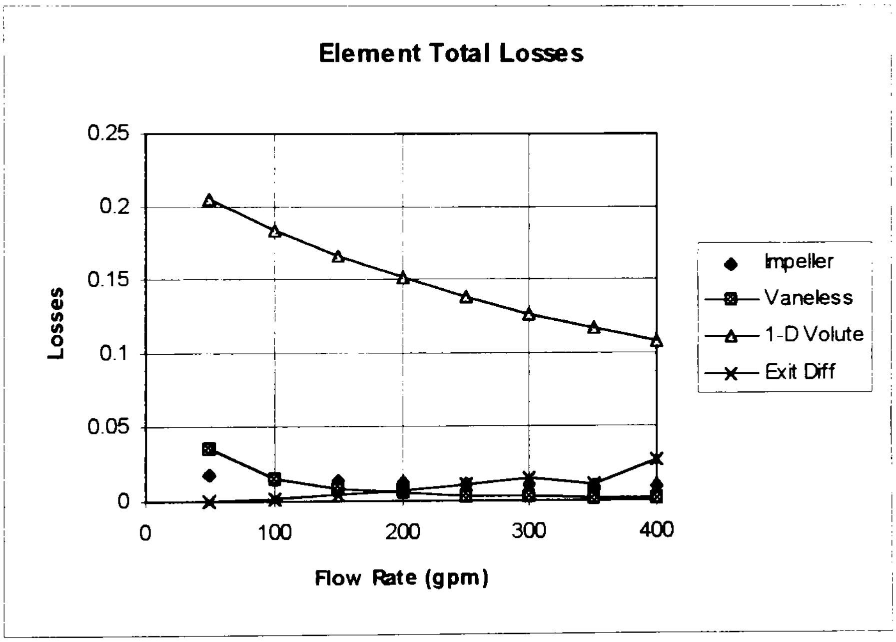


Figure 6.12 Element Total Losses

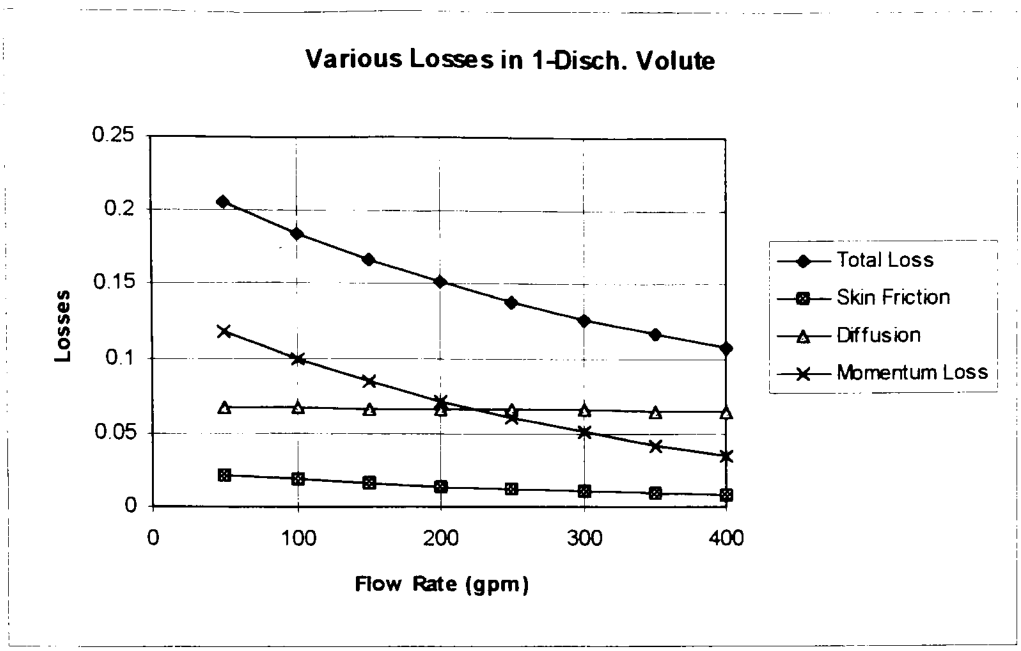


Figure 6.13 Various Losses in 1-Discharge Volute

6.6.0 Effects of some design variables on performances

To study how some of the impeller geometric data affect the total performance of the pump, different values of blockage, surface roughness, blade angle, and blade number, from the test data, were used for discharge section of the impeller. Figures 6. 14-17 show the effects on the total discharge head by varying geometric data of Gould's 3656 centrifugal pump.

6.6.1 Blockage Effects on Total Discharge Head

Blockage effect is like a boundary layer effect. If blockage is 0.9, then it means the flow flowing area is 90 percent of the flow passage area. Blockage ranges from 0 to 1. As blockage increases, meaning more flow flowing area, the total discharge head increases. This means that more energy is added to the fluid, thus produces more head. At low flow rate, blockage does not affect much on the head, but at higher flow rate, it makes differences. Figure 6.14 shows the effects of the blockage on the discharge head of the pump.

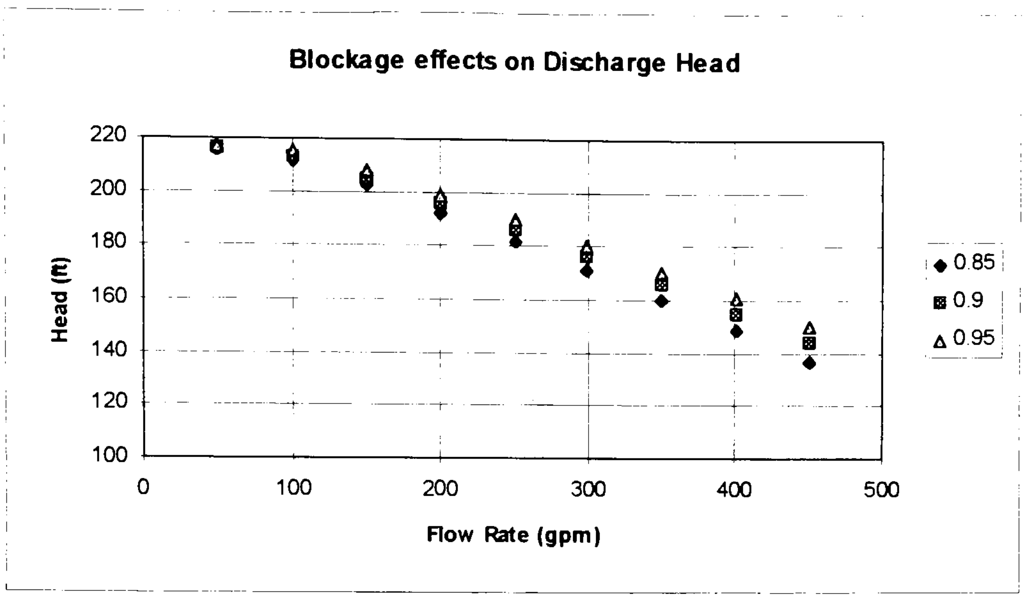


Figure 6.14 Blockage effects on the discharge head

6.6.2 Surface Roughness Effects on Total Discharge Head

Different values of surface roughness were tried to see how it affected on the total discharge head. From previous section, the surface roughness made a big difference on the performance of vaneless diffuser, but for impeller it did not create much impact on the discharge head. For impeller, surface roughness effects are very minor compared to the head produced by the impeller. Thus, as shown in Figure 6.15, impeller is less sensitive in surface roughness.

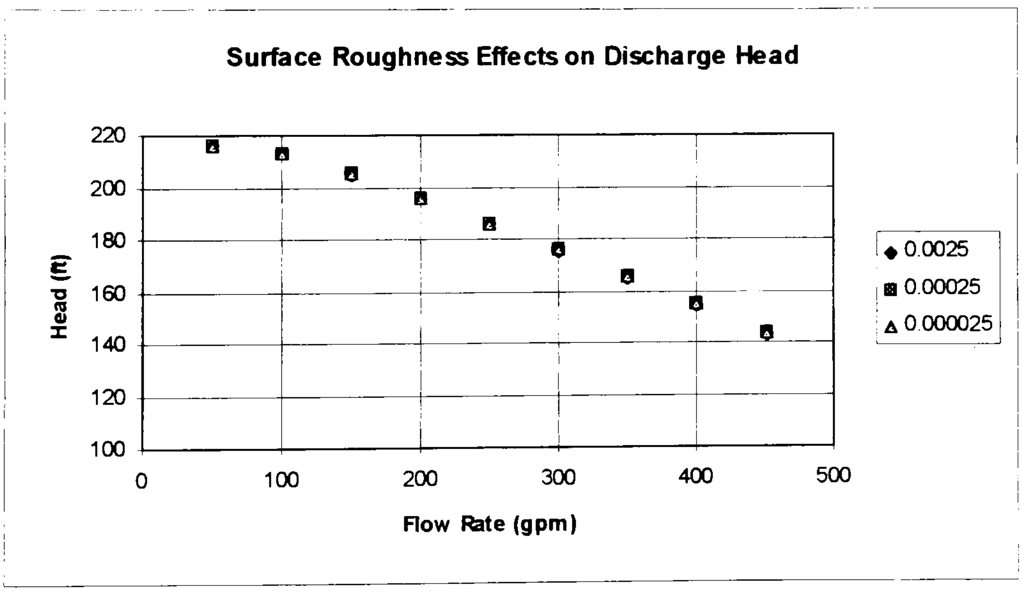


Figure 6.15 Surface roughness effects on discharge head

6.6.3 Blade Angle Effects on Total Discharge Head

Blade angle has very close relationship with fluid velocities. thus correct value for the angle must be used to predict the performance of the pump. Shown in Figure 6.16, blade angle does affect greatly on the discharge head. Higher angles produced more head. but it would require more torque to drive the impeller. It is obvious that pump manufacturer uses optimum angle compromising head and power.

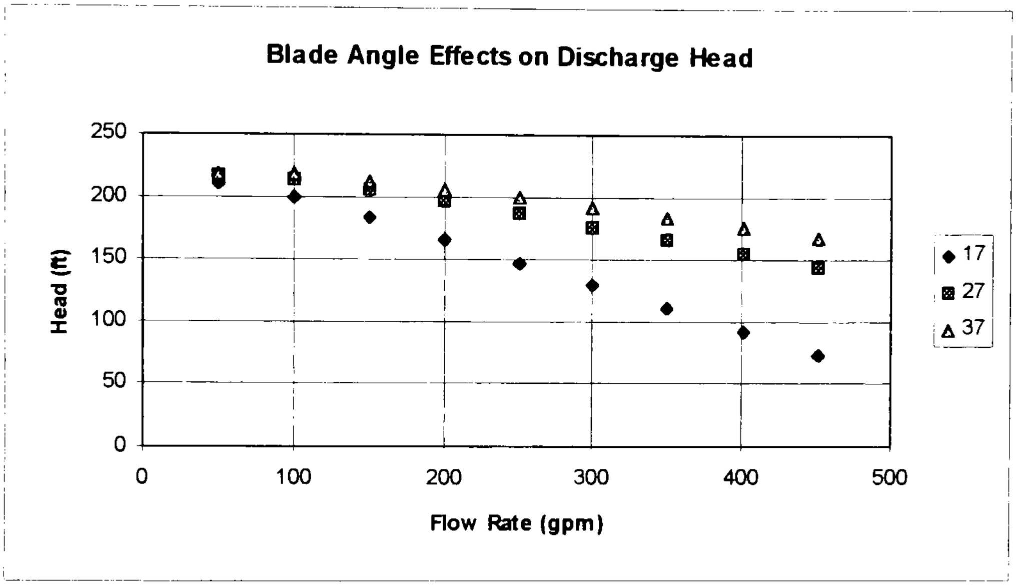


Figure 6.16 Blade angle effects on discharge head

6.6.4 Blade Number Effects on Total Discharge Head

The original design of Gould's pump used 5 blades for the impeller. To see how the number of blades affects the performance, 4,6,8, and 12 for the number of blades were used to compare to the original 5 blades. Smaller number of blades produced less head. As shown in Figure 6.17, adding one more blade from 5 to 6 did not increase as much as taking out one blade from 6. However, when the number of blades increased to 12, it made a big difference. Below design flow rate(250 gpm), the head decreased, but beyond the design flow rate the overal discharge head decreased increasingly.

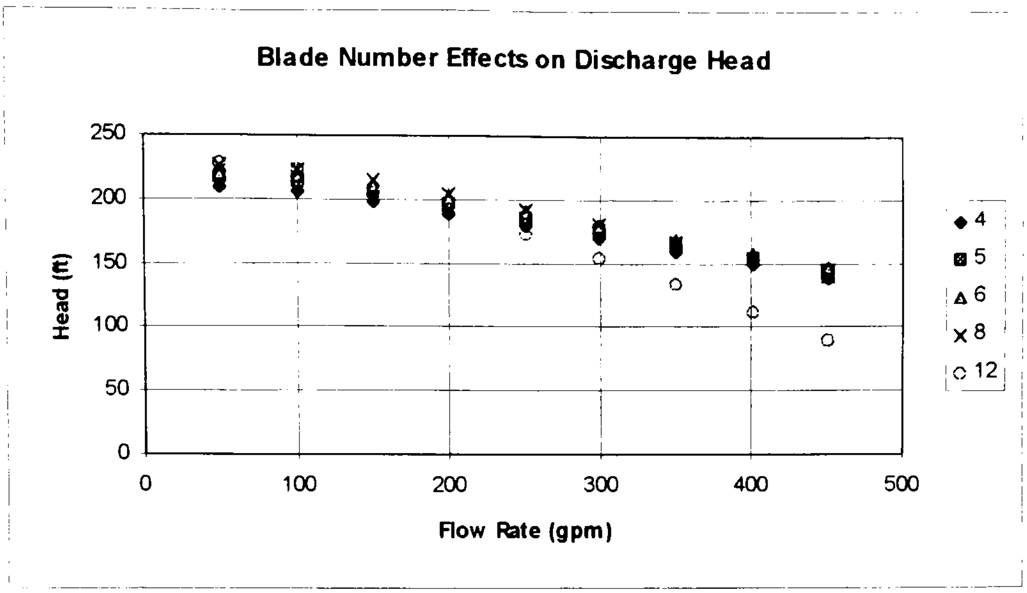


Figure 6.17 Blade number effects on discharge head

7. Conclusions and Recommendations

7.1.0 Conclusions

1. The CPAC performs successfully on a personal computer platform.
2. It has been shown that the CPAC is a user-friendly, menu driven, and easy to use program that predicts turbopump performance based on the operating conditions, fluid properties, and the pump geometries.
3. CPAC also shows that it predicts performance of general purpose process pumps, acceptably.
4. The performance prediction of the CPAC code is generally acceptable as a one-dimensional prediction code based on the average fluid flow conditions and operating conditions, comparing pump's performance outputs to the available test data.

7.2.0 Recommendations

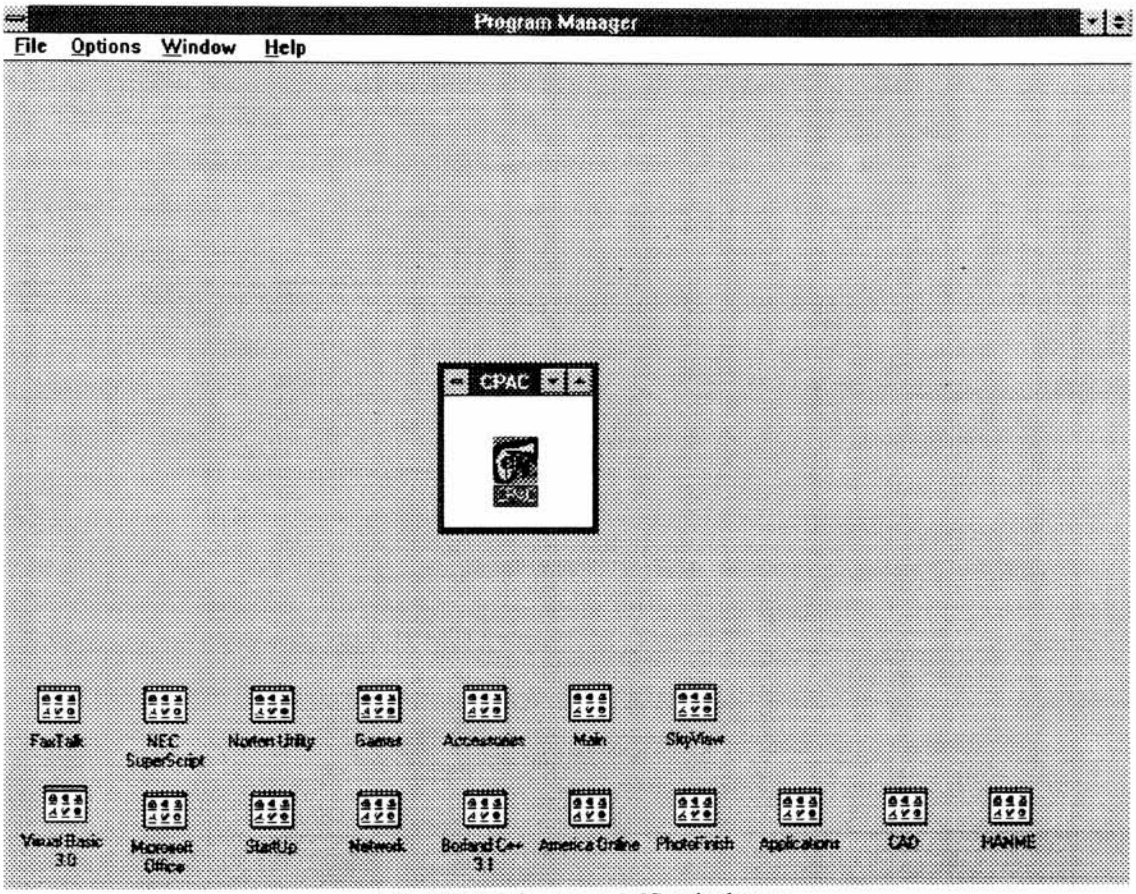
The future usage of the CPAC code is dependent on several factors and the following recommendations for the CPAC program will extend its use.

1. Evaluating different types of pump will ensure better performance predictability so that possible enhancement could be made for enabling CPAC to be a general purpose centrifugal pump analysis code.
2. Incorporation of further theoretical and empirical enhancements such as better separation loss analysis for both turbopumps and industrial pumps as they become available into the code extends the capabilities and usages of the CPAC.
3. Feedbacks from CPAC users should be incorporated for enhancing the user interface.
4. More geometric input specifications can be added for better performance predictabilities of the code. For example, there are some impellers where discharge blade angles at the pressure side and suction side of the blade are different.
5. On-screen diagrams of entire pump and each element can be added for clarity of the geometric data.
6. On-screen geometrical modification can be done via place-and-click feature as well as tabular input format.

APPENDIX A CPAC MANUAL

A.0 Executing CPAC

Executing the CPAC from MS Windows is to double-click the CPAC icon from the windows screen with a mouse. The figure A.0 is the typical Windows screen which has a CPAC icon on it. Double-clicking CPAC icon will execute CPAC program and pop a title form (Figure A.1). Clicking **OK** button will open the main menu screen(Figure A.2).



A.0 CPAC icon on MS windows

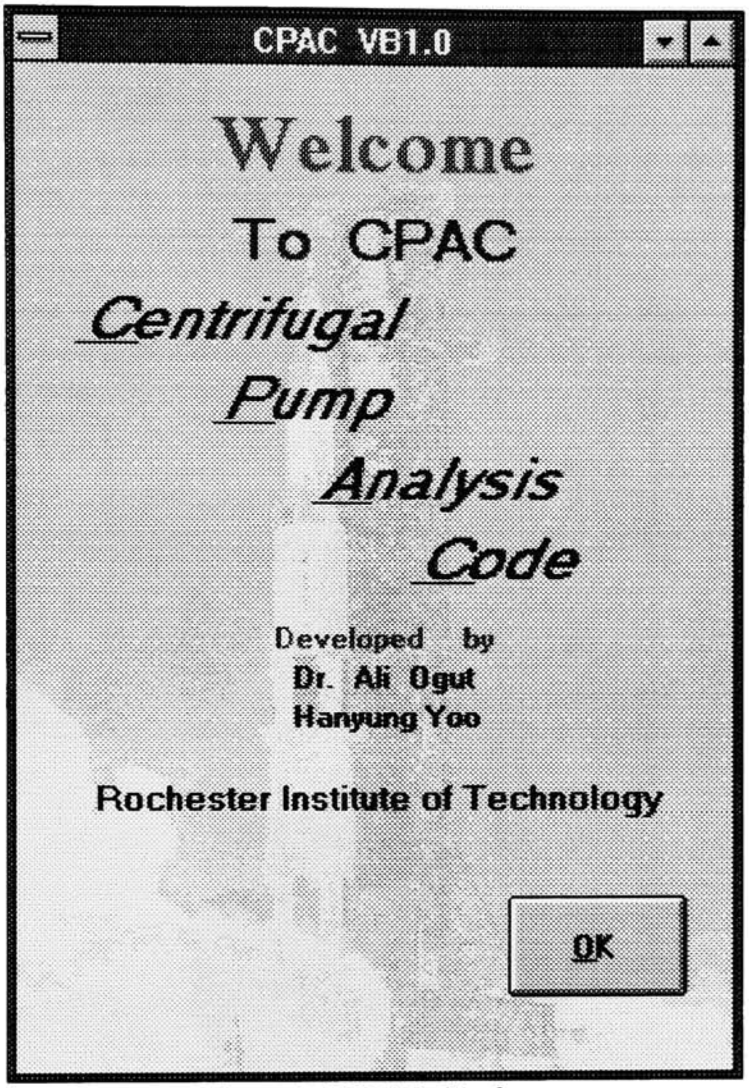


Figure A.1 CPAC title form

A.1 Main Menu Screen

The CPAC code is structured in a menu driven and intuitive format so that a user can go from input stage to output stage as he or she wishes to. The Figure A.2 is a main menu screen where a user select types of input and output options. Each square box is called a '**button**' and a user clicks to pop a menu screen open to enter input data or to view outputs. There is also a feature that a user selects whether SI unit system or US customary unit system. This button is called 'radio button' Default unit system is the US customary unit system and units are set in USCS system and calculations are based on USCS system. Thus, **US** button is the default button. If a user wants to use SI unit system, clicking **SI** button with a mouse will set all units and calculations are done accordingly. On this main menu screen, a user is required to use a mouse to select buttons to input except entering actual data.

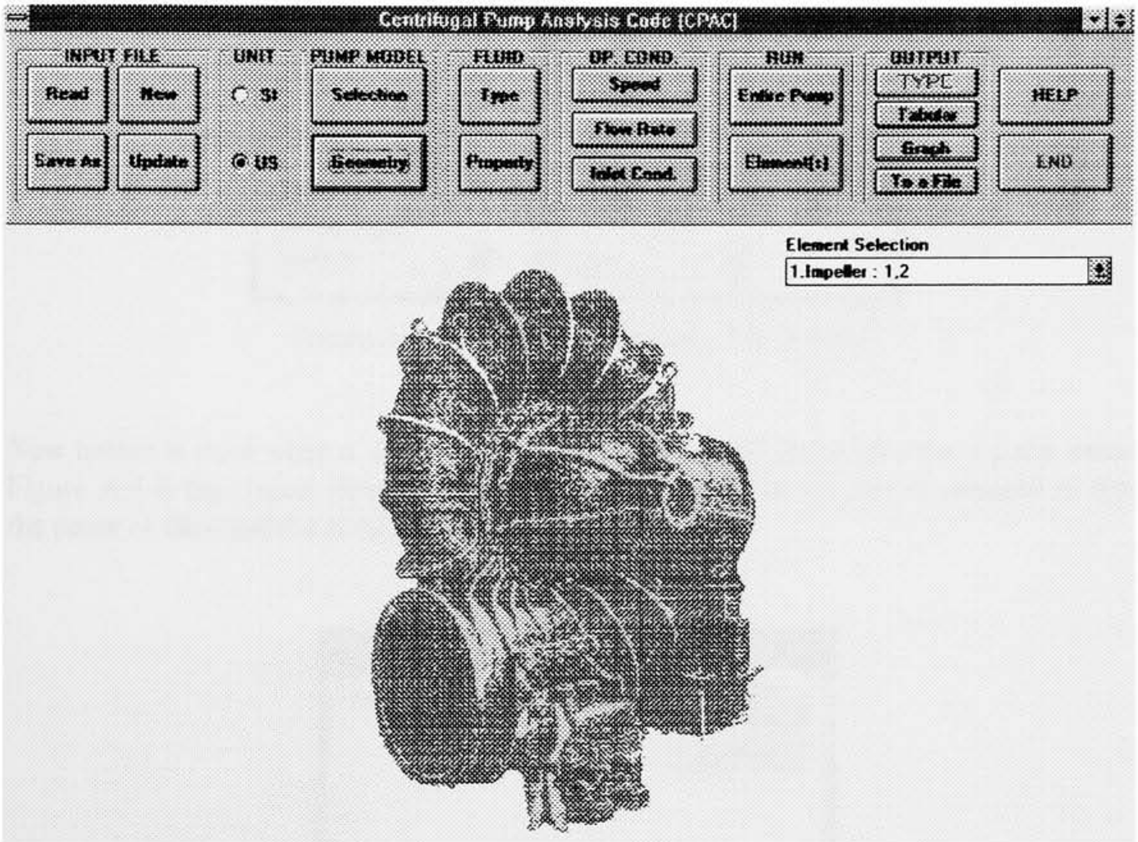


Figure A.2 Main Menu Screen

A.2 Input File

Input file section is where a user specifies a input file name where data are read from. The Figure A.3 is a screen which pops up when a user clicks the **READ** button. Once a user types in a file name and clicks **Ok** button, a message will given that the data has been read. **Update** button is used when a user modifies part of data to different values, and it will store updated data set to an original file. A message will be shown and say that the file has been updated. **Save As** button is used when a user wants to save current file to another file and when a user first creates a file. This will also open a window similar to Figure A.3 and a user has to specify a name for a file in which the data is saved.

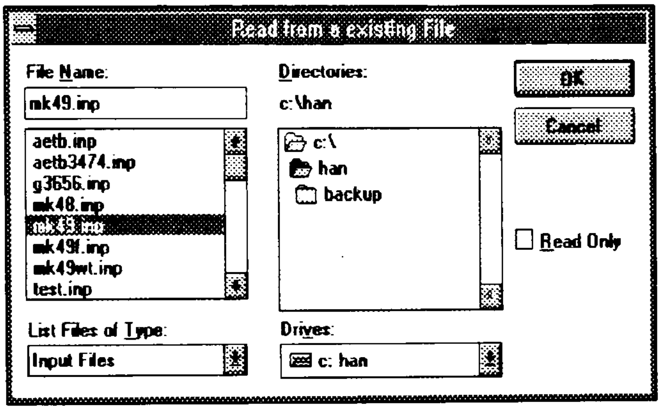


Figure A.3 Read from an Existing File Screen

New button is used when a user creates a new pump model and it prompts a pump name. Figure A.4 is the typical screen when this button is clicked and a user is required to type the name of the modeled pump.

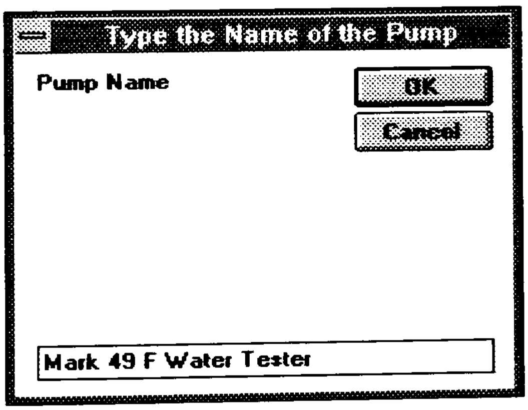


Figure A.4 Pump Name Screen

A.3 Pump Model

A.3.0 Selection

Selection Button is clicked when a user wants to compose a pump with pump elements such as inducer, impeller, diffusers..,etc. The Figure A.5 is typical screen which a user defines a pump. This particular figure is taken from composing a XLR134 turbopump model to analyze.

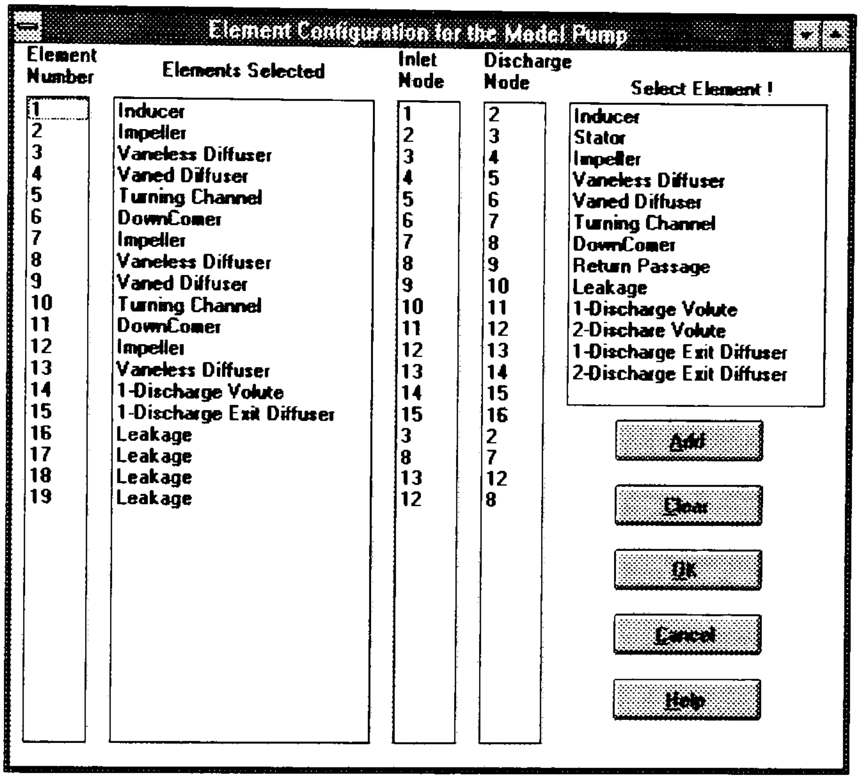


Figure A.5 Model Configuration Screen

In Figure A.5, a user can select element in two different ways. One way of doing it is to select an element from a box where 'Select Element!' label is written and click **ADD** button. Another way is by double clicking a desired element a user wants to add to a model. Element number and nodes are given automatically as a user selects an element and nodes for leakage element can be altered by double clicking Inlet Node or Discharge Node boxes. This action will open a small box where a user enters a new node. Node numbers can be changed in later stage of input process where geometries are entered. **Clear** button will clear up elements selected. **Cancel** button will cancel configuring modeling a pump and returns to main menu screen. When configuring a pump model is completed, a user can specify geometry for elements which comprises the pump by clicking **Geometry** button. The Figure A.6 is a typical screen for impeller geometry inputs. Other elements are in similar format, but differs by elements. Note that blade loading coefficients are not available for input since these coefficients are used only for open impellers. The new

CPAC only deals closed type of impeller because modern turbopumps are built with closed type of impellers.

A.3.1 Geometry

Geometry input screens are for a user to specify geometry input for selected element. These screen differs a little by each element, but they are in the similar format. First, a user is required to specify tip and hub diameters. Then, passwidth, normal thickness, surface roughness, number of blades, blade angles, and so on. Once a user finishes entering required data, **Ok** button will save these data into global array for calculation and storing for later use. Also, **Ok** button will enable a user to go to another element for geometry inputs. Specifying input values for leakage element will be discussed in the later chapter where a modeling technique is discussed.

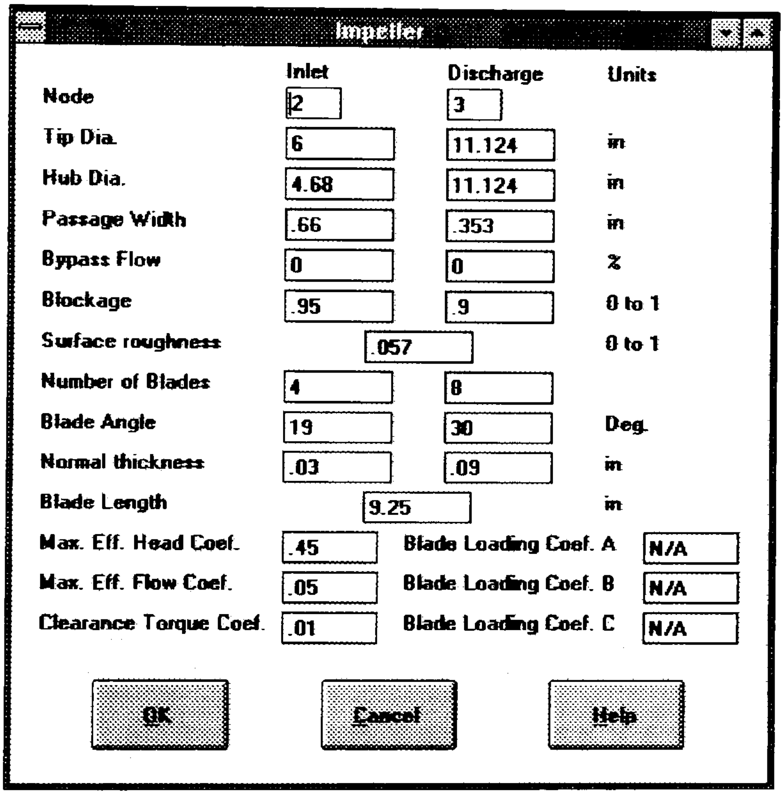


Figure A.6 Impeller Geometry Input Screen

A.4 Fluid

A.4.0 Type

This process can be done before or after configuring a pump or entering geometries of selected elements. Figure A.7 is typical screen of selecting type of fluid a pump will handle. CPAC can handle 4 fluids and a user defined type of fluid. The fluids that can be handled are water, liquid hydrogen, liquid oxygen, liquid nitrogen, and a user defined type of fluid. A user defined fluid handling enable CPAC to handle any type of fluid provided that the properties of the fluid remain constant. Figure A.8 is for viewing or changing fluid's properties. **Ok** button changes to type or properties a user specifies. A default type of fluid is water.

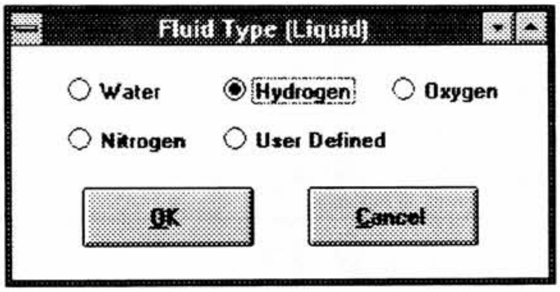


Figure A.7 Fluid Type Screen

A.4.1 Property

Fluid properties vary upon operating temperature and pressure. In CPAC, there are two modes-constant and variable fluid properties. Constant property is that the properties of the selected fluid remains constant throughout as a user specifies. Water can be handled with constant property since the values do not vary much. Water can also be handled with variable property. However, other types of fluids such as liquid hydrogen is very sensitive to temperature and pressure. CPAC incorporates a subroutine called GasPlus which will calculate density, viscosity, and specific heat given temperature and pressure at nodes. The values calculated by the subroutine are within a percent from the property tables. Constant property is a default mode.

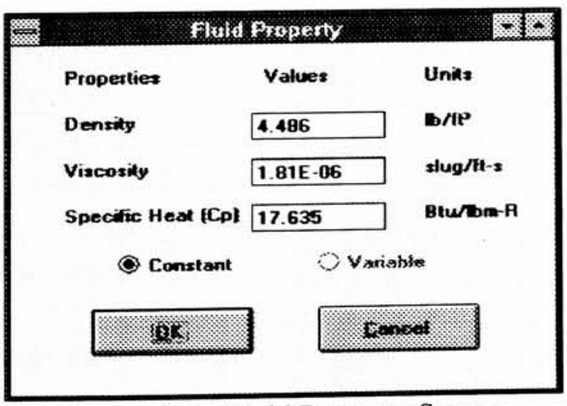


Figure A.8 Fluid Property Screen

A.5 Operating Conditions

A.5.0 Operating Speed

Operating conditions are divided into three sections-**Speed**, **Flow Rate**, and **Inlet Conditions**. The Figure A.9 is a screen a user enters a pump operating speed. A user can enter 9 different pump operating speeds.

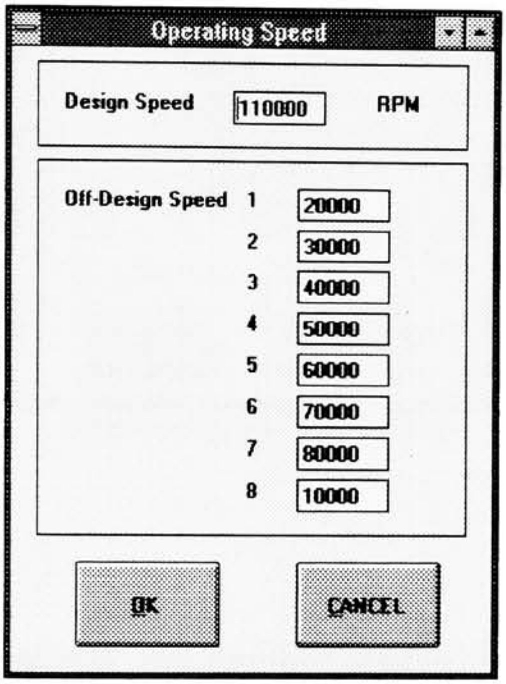


Figure A.9 Operating Speed screen

A.5.1 Flow Rates

Like Operating speeds, a user can specify 9 different flow rates, thus, when a user specifies 9 operating speeds and 9 flow rates, a total of 81 cases of calculations will be done at run command. US conventional unit system uses gpm(gallons per minute) and SI system uses m^3/s. The Figure A.10 is a screen where flow rates are entered.

A.5.2 Inlet Conditions

Inlet condition is where a user has to enter the temperature and pressure(suction pressure) at the inlet of the pump. Also, the tangential velocity is required. Default value is 0. The Figure A.11 is an Inlet Condition screen where inlet conditions are specified.

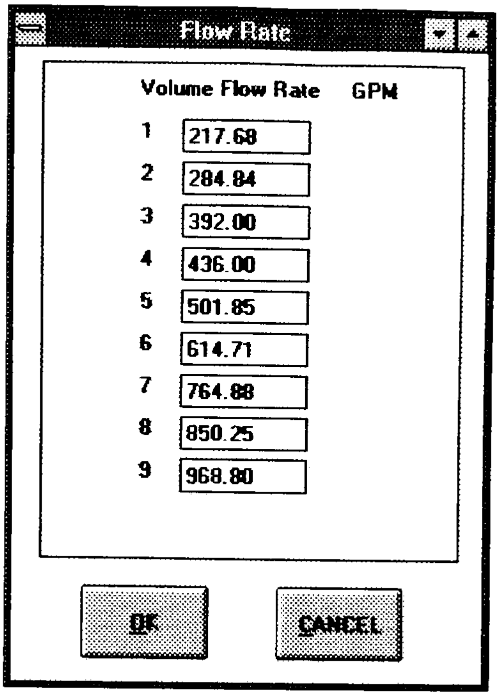


Figure A.10 Flow Rate Screen

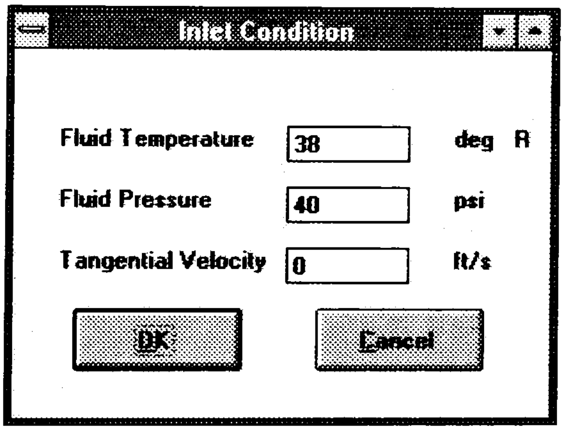


Figure A.11 Inlet Condition Screen

A.6 Run

A.6.01 Entire

There are two types of running calculations for selected pump model. Normally, **Entire** button is selected to analyze the whole model pump. Clicking this button will start calculating from the first element to the last element of the pump.

A.6.12 Element(s)

Second type of running CPAC calculations is by clicking **Element(s)** button which will show a screen where a user must specify the starting element and ending element. If a single element is to be analyzed, a user has to enter, for example, 2 for starting element and 2 for the ending element. If two elements are chosen, then, 2 and 3 have to be entered. Figure A.12 shows the screen when latter type of Run is chosen. The screen is similar to Element Configuration screen except that a user has to select a starting and ending element number. The Figure A.12 is a case for running impeller alone.

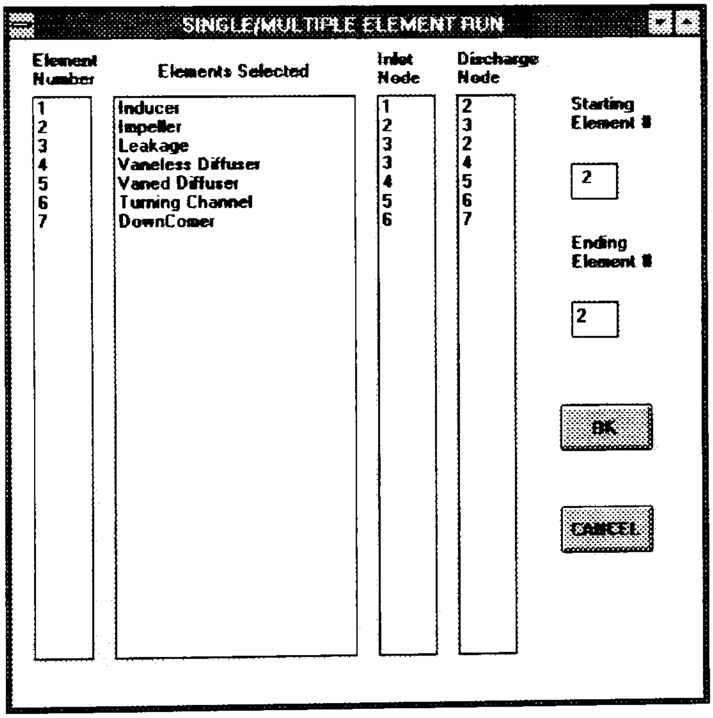


Figure A.12 Single/Multiple Element Run Screen

A.7 Output

A.7.0 Type

Once calculations are done, a message will be given for completion of calculations. Then, a user can browse through the output. A user can view results in tabular form and graphical form on screen, in the printed form, or as a text file if a user wishes so. However, a user must select types of output data - Geometries of each element, Velocity triangle and fluid angles, Element losses, Element Performances, Overall Performance, or all of these. Then, a user can go to **Tabular** for tabular output on the screen or **To a File** to save selected output to a user specified file.Figure A.13 is a screen for a user to select output data types. In this particular figure, all types of output data are selected.

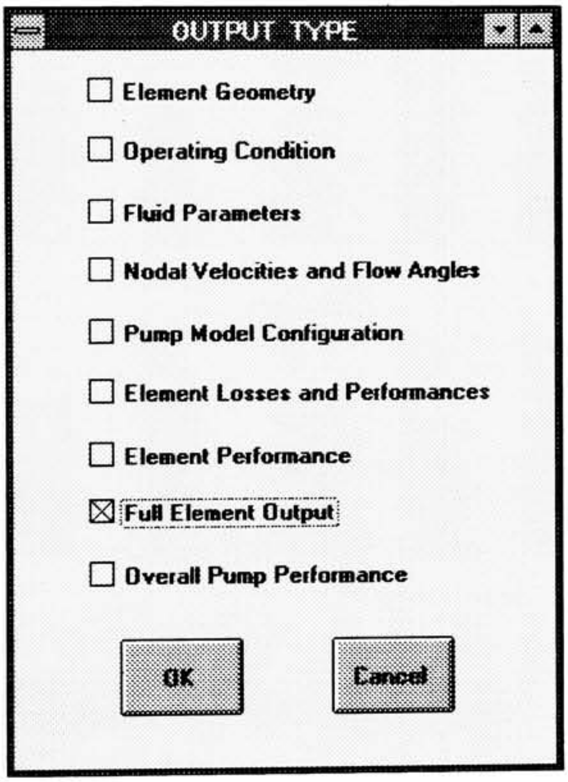
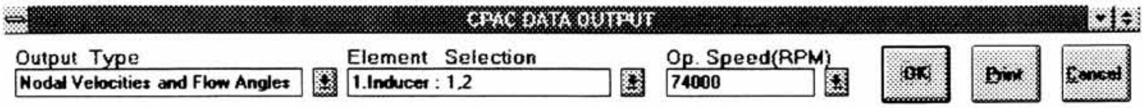


Figure A.13 Output Data Type Selection Screen

A.7.1 Tabular

Once types of data are selected, a user can choose **Tabular** or **Graph** button for tabular, graphical form, or storing data to a file if a user selects a a **To a File** button. If a user wants to see data in tabular form, **Tabular** button needs to be clicked. Figure A.14 is a typical screen for viewing in tabular form. This particular screen shows velocity triangles and fluid flow angles. A user can choose another Operating Speed, Element, or data type such as Element Losses. If a user wants to print the current data type, there is a **Print** button which will send the data to a printer. Sample printed outputs are in later chapter.. The data is shown for all flow rates. The tabular form is designed in a way that a user can click to view different set of data, with ease. There are three selection bars a user can pick -Output Type, Element Selection, and Operating Speed. Figure A.14 is an example of tabular output when a user selects Nodal Velocity and Flow Angles, Inducer, 74000 rpm. A user can select other set of data by clicking arrows in the selection bar, then a list will come out for a user can select. **Cancel** button will return to main menu screen.



<Velocity Triangle Output>

{Inlet} Node # : 1 Urms1 : 164.317 {ft/s}

Flow Rate {GPM}	Flow Coef.	Cm {ft/s}	Cu {ft/s}	C {ft/s}	Alpha/f {deg}	Beta/f {deg}	W {ft/s}	Dev Angle {deg}
9.28	.027348	16.552	0.000	16.552	90.000	5.752	132.066	1.45
11.12	.032770	19.834	0.000	19.834	90.000	6.883	158.252	0.32
12.96	.038193	23.116	0.000	23.116	90.000	8.008	184.437	-0.81
14.79	.043586	26.380	0.000	26.380	90.000	9.121	210.430	-1.92
17.08	.050334	30.465	0.000	30.465	90.000	10.504	243.070	-3.30
18.46	.054401	32.926	0.000	32.926	90.000	11.331	262.709	-4.13
20.29	.059794	36.190	0.000	36.190	90.000	12.421	288.752	-5.22
22.13	.065216	39.472	0.000	39.472	90.000	13.508	314.938	-6.31
25.88	.076032	46.018	0.000	46.018	90.000	15.645	367.167	-8.45

{Discharge} Node # : 2 Urms2 : 172.9123 {ft/s}

Flow Rate {GPM}	Flow Coef.	Cm {ft/s}	Cu {ft/s}	C {ft/s}	Alpha/f {deg}	Beta/f {deg}	W {ft/s}	Dev Angle {deg}
9.28	.031375	18.990	80.463	82.673	13.279	11.607	89.141	0.69
11.12	.037596	22.755	62.132	66.168	20.114	11.607	106.815	0.69
12.96	.043817	26.520	43.801	51.204	31.193	11.607	124.490	0.69
14.79	.050004	30.265	25.571	39.621	49.806	11.607	142.068	0.69
17.08	.057746	34.951	2.757	35.059	85.490	11.607	164.065	0.69
18.46	.062412	37.775	-10.991	-39.341	-73.777	11.607	177.321	0.69
20.29	.068599	41.520	-29.222	-50.772	-54.862	11.607	194.900	0.69
22.13	.074820	45.285	-47.552	-65.665	-43.601	11.607	212.574	0.69
25.88	.087228	52.795	-84.114	-99.310	-32.115	11.607	247.027	0.69

Figure A.14 Tabular Output Screen

A.7.2 Graphs

When a user wants to see output in a graphical form, **Graph** button will open a screen where he/she can choose types of data sets available. Data can be represents as lines and marks, marks only, and curve fit(only straight line available). A user can also label a graph title, x-axis, and y-axis. Selection bars are also available for viewing different set of data. **Graph** button will graph on screen, and **Print** button will print the graph that a user sees on the screen. **End Graph** button will return to main menu screen. FigureA.15 is a typical screen when a user selects to view in a graphical form of data.

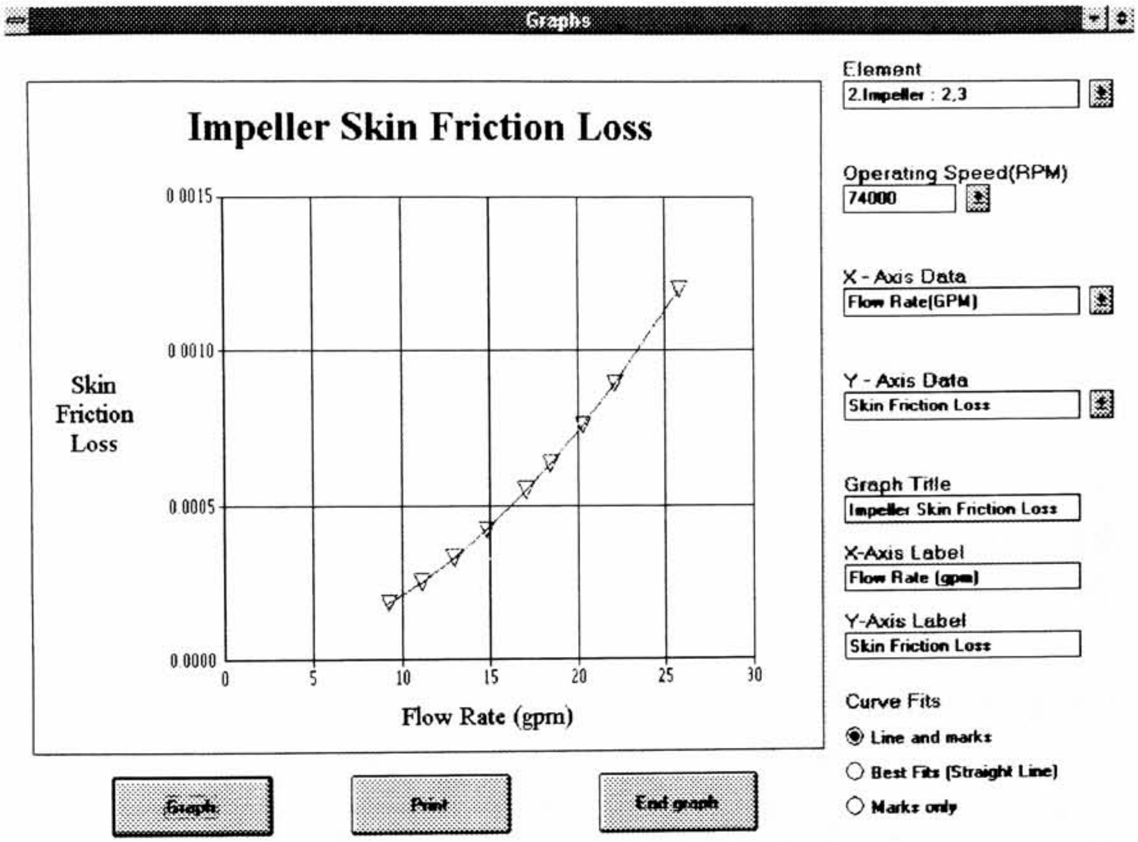


Figure A.15 Graphical Output Screen

A.8 Help

On screen help is available when a user clicks a Help button. Figure A.16 is a help screen that a user sees when Help button is clicked. Help menu is in the same format as any other MS Windows applications. A user can browse back and forth through the Help screen and a hand will be shown for a user to jump to another menu. Also, CPAC manual will be available as a part of this program so that a user can read the manual before he/she runs the CPAC program.

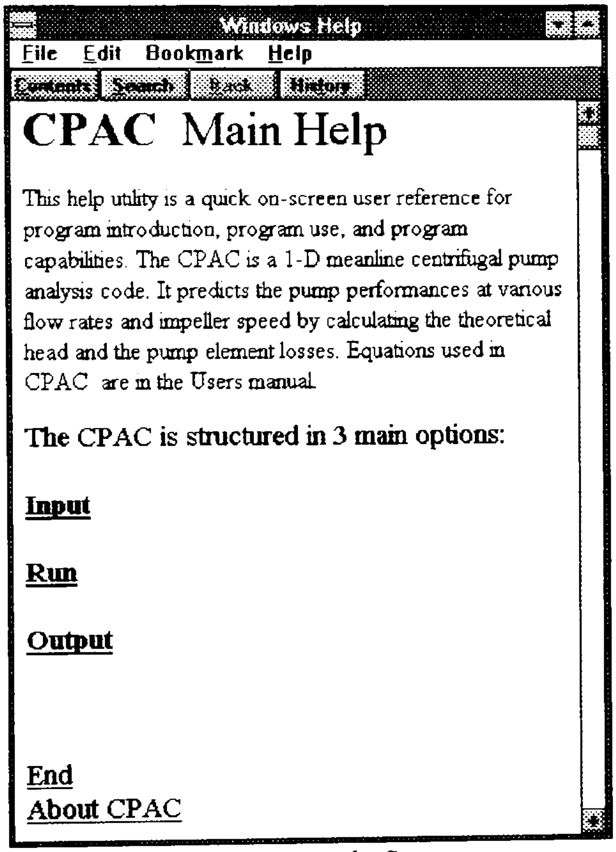


Figure A.16 Help Screen

APPENDIX B

Data Structure

This section attempts to explain the data storage and retrieval array system and some other global variables. Gloabl data scheme for storage enables fast retrieval of data for tabular and graphical output and also for calculating purpose.

Data Type	Variable Name/Dimension	Data Description
Global	rho_Prev(50)	Density at Discharge of previous element
Global	Visc_Prev(50)	Viscosity "
Global	Cp_Prev(50)	Specific Heat "
Global	Head_Prev(50)	Head "
Global	Temp_Prev(50)	Temperature "
Global	Press_Prev(50)	Pressure "
Global	C_Prev(50)	Absolute fluid Velocity "
Global	Cu_Prev(50)	Tangential fluid Velocity "
Global	Arms_Prev(50)	Absolute fluid angle "
Global	Drms2_Prev(50)	Rms Diameter "
Global	Area2_Prev(50)	Area "
Global	STATHD_Prev(50)	Static Head "
Global	PWDF(50, 10, 10)	Power coefficient
Global	XLEAK(50, 10, 10)	Leakage power coefficient
Global	TOHP(50, 10, 10)	Total leakage horse power loss
Global	FHP1(50, 10, 10)	Leakage power loss
Global	FHP2(50, 10, 10)	"
Global	RHP1(50, 10, 10)	"
Global	RHP2(50, 10, 10)	"
Global	TotalLeak(50, 10, 10)	Total leakage flow rate
Global	LeakF1(50, 10, 10)	Leakage flow rate at front
Global	LeakF2(50, 10, 10)	"
Global	LeakR1(50, 10, 10)	Leakage flow rate at rear
Global	LeakR2(50, 10, 10)	"
Global	Geom(50, 30)	Geometry data array
Global	No_Element	Number of Element of the pump
Global	Fluid_Option	Fluid type
Global	Speed(10)	Operating Speed
Global	FRate(10)	Flow rate
Global	MassRate(10)	Mass flow Rate
Global	MRate(100, 10, 10)	Mass flow rate at each node
Global	VRate(100, 10, 10)	Volume flow rate at each node
Global	Hed(100, 10, 10)	Head at each node
Global	Pump_Name	Name of the pump
Global	Urm1(50, 10)	Tip Speed of each element at inlet
Global	Urm2(50, 10)	" at discharge
Global	Fi_Eff(50, 10, 10)	Finite to infinite number impeller efficiency
Global	Tem(100, 10, 10)	
Global	InTemp	Inlet Temperature
Global	InPressure	Inlet Pressure
Global	DisTemp(10, 10)	Discharge Temperature
Global	DisPress(10, 10)	Discharge Pressure
Global	Disrho(10, 10)	Density at discharge
Global	DisVisc(10, 10)	Viscosity at discharge

Global	DisCp(10, 10)	Specific heat at discharge
Global	DisHead(10, 10)	Discharge head
Global	Pre(100, 10, 10)	Pressure at each node
Global	Den(100, 10, 10)	Density at each node
Global	Vis(100, 10, 10)	Viscosity at each node
Global	Cpp(100, 10, 10)	Specific heat at each node
Global	Density	inlet density
Global	Viscosity	inlet Viscosity
Global	Cp	Inlet specific heat
Global	Cu_Inlet	inlet tangential velocity
Global	Area(100)	area at each node
Global	Drms(100)	Rms diameter at each node
Global	sol(100)	solidity at each node
Global	Cm(100, 10, 10)	Meridional velocity at each node
Global	Cu(100, 10, 10)	Tangential velocity at each node
Global	Ca(100, 10, 10)	Absolute velocity at each node
Global	Wp(100, 10, 10)	Relative velocity at each node
Global	Alpha(100, 10, 10)	Absolute fluid angle at each node
Global	Beta(100, 10, 10)	Relative fluid angle at each node
Global	Delta(100, 10, 10)	Difference in fluid angle at each node
Global	Phit(10, 10)	Impeller flow coefficient at impeller discharge
Global	Phi(100, 10, 10)	Flow coefficient at each node
Global	Suct_SS(50, 10, 10)	Suction specific speed
Global	In_Loss(50, 10, 10)	Incidence loss at each element
Global	SF_Loss(50, 10, 10)	Skin friction loss at each element
Global	Di_Loss(50, 10, 10)	Diffusion loss at each element
Global	To_Loss(50, 10, 10)	Total loss at each element
Global	Eu_Head(50, 10, 10)	Euler head at each element
Global	Eu_Coef(50, 10, 10)	Euler coefficient at each node
Global	Ac_head(50, 10, 10)	Actual head at each node
Global	Ac_Coef(50, 10, 10)	Actual coefficient at each node
Global	Th_head(50, 10, 10)	Theoretical head at each node
Global	Th_Coef(50, 10, 10)	Theoretical coefficient at each node
Global	Re_Coef(50, 10, 10)	Recirculation coefficient
Global	Cl_Coef(50, 10, 10)	Clearance coefficient
Global	Scr_Mom(50, 10, 10)	Scroll momentum loss at volute element
Global	He_Rise(50, 10, 10)	Head rise at each element
Global	T_Rise(50, 10, 10)	Temperature rise at each element
Global	P_Rise(50, 10, 10)	Pressure rise at each element
Global	Ele_Eff(50, 10, 10)	Element efficiency
Global	Fri_Fac(50, 10, 10)	Friction loss at each element
Global	Re(50, 10, 10)	Reynolds number at each element
Global	Pmp_Head(10, 10)	Pump head
Global	Pmp_Coef(10, 10)	Total actual coefficient
Global	Pow_Coef(10, 10)	Overall power coefficient
Global	Pmp_Eff(10, 10)	Overall pump efficiency
Global	Pmp_Loss(10, 10)	Overall pump loss
Global	SN(10, 10)	Specific speed of the pump
Global	TipSpeed	Tip Speed of impeller

Program Data Layout

1. Geom(I, J)   Type: Variant
Dimension: 50 x 30

I = Element Number

For all Elements

J = 0	Element Type
J = 1	Inlet node
J = 2	Discharge node
J = 3	Inlet tip diameter
J = 4	Discharge tip diameter
J = 5	Inlet hub diameter
J = 6	Discharge hub diameter
J = 7	Inlet passwidth
J = 8	Discharge passwidth
J = 9	Inlet bypass flow
J = 10	Discharge bypass flow
J = 11	Inlet blockage
J = 12	Discharge blockage
J = 13	Surface roughness

For Inducer, Stator, Impeller, and Vaned Diffuser

J = 14	Inlet number of blades
J = 15	Discharge Number of blades
J = 16	Inlet blade angle
J = 17	Discharge blad angle
J = 18	Inlet normal thickness
J = 19	Dischrge normal thickness
J = 20	Blad length

For Impeller

J = 21	Max. head coefficient
J = 22	Max. flow coefficient
J = 23	Clearance torque coefficient

For Turning Channel and DownComer

J = 14	Inlet hydraulic diameter
J = 15	Discharge hydraulic diameter
J = 16	Passage length
J = 17	Number of channel

For Return Passage

J = 14	Clearance
J = 15	Clearance area
J = 16	Passage length

For 1-Discharge Volute, 2-Discharge Volute

J = 14	Throat diameter
J = 15	Throat area

For 1-Discharge Exit Diffuser and 2-Discharge Exit Diffuser

J = 14 Exit diameter
J = 15 Throat area

For Leakage

J = 0 Element Type
J = 1 Inlet node
J = 2 Discharge node
J = 3 1 if Leakage type is NFS
J = 4 1 if Leakage type is NRS
J = 5 1 if Leakage type is FS
J = 6 1 if Leakage type is RS
J = 7 1 if Leakage type is FWR
J = 8 1 if Leakage type is RWR
J = 9 1 if Leakage type is FBR
J = 10 1 if Leakage type is RBR
J = 11 Not used
J = 12 Not used
J = 13 Not used
J = 14 Front shroud clearance
J = 15 Rear shroud clearance
J = 16 Front tip leakage
J = 17 Rear tip leakage
J = 18 Front wear ring clearance
J = 19 Rear wear ring clearance
J = 20 Front wear ring daimeter
J = 21 Rear wear ring daimeter
J = 22 Front leakage coefficient
J = 23 Rear leakage coefficient
J = 24 % Static head loss

2. Frate(I). Speed. MassRate. QLeak

Type: Single
Dimension: 10

3. In_Loss(I.J.K). SF_Loss. Di_Loss. To_Loss . Fri_Fac. PWDF. XLEAK. TOHP. FHP1. FHP2. RHP1. RHP2. TotalLeak. LeakF1. LeakF2. KeakR1. LeakR2. Eu_Head. Eu_Coef. Ac_Head. Ac_Coef. Th_Head. Th_Coef. Re_Coef. Cl_Coef.Scr_Mom. He_Rise. T_Rise. P_Rise. Ele_eff. Re

Type: Single
Dimension: 50 X 10 X 10

I = Element number
J = Operating speed
K = Flow rate

4. Cu(I.J.K). Cm. Ca. Wp. Pre. Den. Vis. Cpp. Mrate. Vrate. Hed. Alpha. Beta. Delta. Phi

Type: Single
Dimension: 100 X 10 X 10

I = Element number*2-1, Element Number*2
J = Operating speed
K = Flow rate

5. DisTemp(I,J), DisPress, Disrho, DisVisc, DisCp, DisHead, SN, Phit, Pmp_Head, Pmp_Coef, Pow_Coef, Pmp_Eff, Pmp_Loss

Type: Single
Dimension: 10 X 10

I = Operating speed
J = Flow rate

6. Urms1(I,J),Urms2

Type: Single
Dimension: 50 X 10

I = Element number
J = Operating speed

APPENDIX C

CPAC EQUATIONS

(i) General Equations

The CPAC code performs calculations for each element in following order.
- Equations may vary by elements

1. Read in element data (see Appendix A)

2. Element area and Root mean square (rms) diameter calculations

$$Area_i = \frac{1}{2}\pi(D_{tipi} + D_{hubi}) \qquad i=1,2$$

$$D_{rmsi} = \sqrt{\frac{D_{tipi}^2 + D_{hubi}^2}{2}}$$

3. Element tip speed calculations

$$U_{rmsi} = \frac{D_{rmsi} N}{229} \qquad i=1,2$$

4. Element flow calculations

$$\phi_i = \frac{144 Q_{cbft}}{V_{tip} A_{flowi}}$$

5. Element velocity(rms) triangle calculations

$$C_{mi} = \phi_i V_{tip} = \frac{144 Q_{cbft}}{A_{flowi}}$$

$$C_{ui} = \frac{C_{ui-1} D_{i-1}}{D_i}$$

$$C_i = \sqrt{C_{mi}^2 + C_{ui}^2}$$

$$W_i = C_{mi} / \sin(B_{bladei})$$

$$\alpha_i = \tan^{-1}\left(\frac{C_{mi}}{C_{ui}}\right)$$

$$\beta_i = \tan^{-1}\left(\frac{C_{mi}}{V_{tipi} - C_{ui}}\right)$$

6. Loss Equations

Incidence Loss:

$$\phi_{inc} = \frac{K_{inc}}{2g}\left(\frac{S_1}{V_{tip}}\right)^2$$

where

$$\frac{S_1}{V_{tip}} = \frac{C_{mrms}}{V_{tip}}\left|\cot\beta_{b1} - \cot\beta_{f1}\right|$$

with

$$K_{inc} = 0 \quad \text{for } \left|\beta_{b1} - \beta_{f1}\right| \le 2$$

$$K_{inc} = 0.3 \quad \text{for } \left|\beta_{b1} - \beta_{f1}\right| > 2$$

The subscript 1 denotes the inlet to the element.

Diffusion Loss

$$D = 1 - \frac{W_2}{W_1} + \frac{W_1 - W_2}{2\sigma W_1}$$

The empirical diffusion loss coefficient equation

$$\phi_{dif} = K_{dif} D^N$$

Element	**K**	**N**
Inducer	0.05	2
Stator	0.03	3
Impeller	0.03	3
Diffuser	0.03	3
Volute	0.02	2
Downcomer	0.03	3

Skin Friction Loss

$$\phi_{dif} = \frac{fL}{4D_h}\left[\frac{W_1^2}{V_{tip}^2} + \frac{W_2^2}{V_{tip}^2}\right]$$

The friction Loss is a function of the Reynolds number and roughness.

where

$$Re = \left[\frac{W_1^2}{V_{tip}^2} + \frac{W_2^2}{V_{tip}^2}\right]\frac{D_h V_{tip}}{2\upsilon}$$

where the hydraulic diameter. $D_h = \frac{4}{2}\left[\frac{A_1}{P_1} + \frac{A_2}{P_2}\right]$

and

$$A_i = \left[\frac{\pi}{Z_i} D_{irms} \sin\beta_{bi}(B_i - Tn_i)\right](D_{tipi} - D_{hubi})$$

$$P_i = \left[2(D_{tipi} - D_{hubi}) + \frac{\pi}{Z_1}(D_{tipi} + D_{hubi})\sin\beta_{bi} - 2Tn_i\right]$$

Incorporating Moody Diagram is done with an equation by Colebrook.

$$\frac{1}{f^{0.5}} = -2.0\log\left(\frac{e/D}{3.7} + \frac{2.51}{\mathrm{Re}\, f^{0.5}}\right)$$

The friction factor equation is transcendental so that it has to be iterated with initial estimate by Miller.

$$f_0 = 0.25\left[\log\left(\frac{e/D}{3.7} + \frac{5.74}{\mathrm{Re}^{0.9}}\right)\right]^{-2}$$ initial estimation

Volute scroll Momentum Loss

$$\phi_{scm} = K_{scm}\left[\frac{Cu_{rmsi}}{V_{tip}}\right]^2\left[\frac{A_{throat} - A_{scm}}{A_{throat}}\right]^2$$

where A_{scm} is the area determined from D_{scm} given below, and K_{scm}=0.5.

$$D_{scm} = 2\sqrt{D_{throat} w_i \tan\alpha_i}$$ i=inlet

Recirculation Loss Calculations

$$\phi_{2des} = \frac{K\phi_{des}\sin\beta_{b2}}{Z_2}$$

where K = 7.03 empirically.

$\Delta P_{rec} = 0.0$ at $\phi_2 = \phi_{des2}$

$\Delta P_{rec} = G\, Hp_{[at\ max\ \eta]}$ at $\phi_2 = 0.0$

An empirical equation is then given as :

$$\Delta P_{rec} = \frac{G\phi_{des}\left[\phi_{des2} - \phi_2\right]^{3\eta}}{\phi\phi_{des2\,2}^{2\eta}}$$

7. Impeller Theoretical Head Calculations

Theoretical Head Equation:

$$\psi_{theory} = \frac{V_{tip}C_{u2} - U_{rms1}C_{u1}}{V_{tip}^2}$$

where $V_{tip} = U_2$

$$Head_{theory} = \frac{\psi_{theory}V_{tip}^2}{g}$$

8. Performance Equations

Total Element Loss : Total Loss = Σ all Element Losses

Element Euler Head Coefficient: $H_{Euler} = \frac{U_{rms2}C_{u2} - U_{rms1}C_{u1}}{V_{tip}^2}$

Element Actual Head Coefficient: $H_{Actual} = H_{Euler}$ - Total Losses

Element Efficiency: $\eta_{Element} = \frac{H_{Actual}}{H_{Euler}}$

9. Overall pump performance equations:

$$\text{Head Coef} = \frac{Head_{actual}g}{V_{tip}^2}$$

Power Coef = $Head_{theory}$ -Σ(Losses)

$$\text{Head Loss Coef} = \frac{\Sigma(Head\_Loss)V_{tip}^2}{g}$$

$$Eff_{pump} = \frac{Head\_Loss\_Coef}{Power\_Coef}$$

(ii) Element Equations

1) Inducer

inlet

C_{u1} = inlet condition value(Inlet Tangential Velocity)

$$\beta_{fluid1} = \tan^{-1}(\frac{C_{m1}}{U_{rms1}}) \qquad \text{(absolute fluid angle)}$$

$$C_{rms1} = \sqrt{C_{u1}^2 + C_{m1}^2} \qquad \text{(absolute fluid velocity)}$$

discharge

$$\beta_{fluid2} = \beta_{blade2} - \frac{0.26[\beta_{blade2} - \beta_{blade1}]}{\sqrt{\alpha_2}}$$

$$C_{u2} = U_{rms2} - \frac{C_{m2}}{\tan\beta_2}$$

$$\alpha_2 = \tan^{-1}\frac{C_{m2}}{C_{u2}}$$

$$C_{rms2} = \frac{C_{m2}}{\sin\alpha_2}$$

Losses calculated: Incidence, Skin Friction, Diffusion

2) Stator

inlet

$$C_{u1} = \frac{C_{ui-1}D_{rmsi-1}}{D_{rms1}}$$

$$\alpha_1 = \tan^{-1}\frac{C_{m1}}{C_{u1}} = \beta_{fluid1}$$

$$C_{rms1} = \frac{C_{m1}}{\sin\alpha_1}$$

discharge

$$\alpha_2 = \beta_{blade2} - \frac{0.26(\beta_{blade2} - \beta_{blade1})}{\sqrt{\alpha_2}} = \beta_{fluid2}$$

$$C_{u2} = \frac{C_{m2}}{\tan\alpha_2}$$

$$C_{rms2} = \frac{C_{m2}}{\sin\alpha_2}$$

Losses calculated: Incidence, Skin Friction, Diffusion

3) Impeller

<u>inlet</u>

$$C_{u1} = \frac{C_{ui-1} D_{rmsi-1}}{D_{rms1}}$$

$$\alpha_1 = \tan^{-1}\frac{C_{m1}}{C_{u1}} = \beta_{fluid1}$$

$$C_{rms1} = \frac{C_{m1}}{\sin\alpha_1}$$

<u>discharge</u>

Modification to compensate the slip in the impeller

$$\Delta = \frac{D_{tip1}}{D_{rms2}}$$

$$z_2 = \frac{0.84 z_2}{1 - 0.25\Delta}$$

$$XM = 1 + \frac{\left[1.37 + 0.23\sin\beta_{blade2}\right]\left[\phi_2 + 0.05\right]^{0.6}}{z_2 (0.5)(1.1)(0.2)^{0.6}[1 - 0.12\Delta]}$$

<u>Area calculations</u>

Area$_i$ = $\pi\frac{D_{tipi} + D_{hubi}}{2} * blockage_i - \frac{z_i tn_i pw_i}{\sin\beta_{rmsi}}$

where z = number of blades
tn = normal thickness of blade
pw = passage width of the blade
i = 1, 2

<u>Theoretical head coefficient and head</u>

$$\psi_{theory} = \frac{V_{tip} C_{u2} - U_{rms1} C_{u1}}{V_{tip}^2} \qquad \text{(theoretical head coefficient)}$$

$$Head_{theory} = \frac{\psi_{theory} V_{tip}^2}{g} \qquad \text{(theoretical head)}$$

Leakage

Horsepower loss(Hp_d)

$$Hp_d = KD^2\rho U^2_{rms2}$$

where K = correlation factor = $\dfrac{[9\rho][0.5][24][12^5]}{550g}$

D = impeller diameter = $\sqrt{\dfrac{\left[D^5_{rms2} - D^5_{rms1}\right]}{D^3_{rms2}}}$

ρ = density

U^2_{rms2} = impeller peripheral tip speed(V_{tip})

Leakage flow rate

$$Q_{leakage} = C_{wr} A_{wr} \sqrt{2gH_{wr}}$$

where A_{wr} = leakage flow passage area

C_{wr} = wear ring loss coefficient

H_{wr} = head drop across wear ring

New flow rate for impeller

Q_{cbft} (new flow rate) = Q_{cbft} + $Q_{leakage\ front}$ + $Q_{leakage\ rear}$

Once new flow rate is calculated, calculates over upon new flow rate

4) Vaned Diffuser

inlet

$$C_{u1} = \frac{C_{ui-1} D_{rmsi-1}}{D_{rms1}}$$

$$\alpha_1 = \tan^{-1} \frac{C_{m1}}{C_{u1}} = \beta_{fluid1}$$

$$C_{rms1} = \frac{C_{m1}}{\sin \alpha_1}$$

discharge

$$\alpha_2 = \beta_{blade2} - \frac{0.26(\beta_{blade2} - \beta_{blade1})}{\sqrt{\alpha_2}} = \beta_{fluid2}$$

$$C_{u2} = \frac{C_{m2}}{\tan \alpha_2}$$

$$C_{rms2} = \frac{C_{m2}}{\sin \alpha_2}$$

Losses calculated: Incidence, Skin Friction, Diffusion

5) Vaneless Diffuser

inlet

$$C_{u1} = \frac{C_{ui-1} D_{rmsi-1}}{D_{rms1}}$$

$$\alpha_1 = \tan^{-1} \frac{C_{m1}}{C_{u1}} = \beta_{fluid1}$$

$$C_{rms1} = \frac{C_{m1}}{\sin \alpha_1}$$

discharge

$$C_{u2} = \frac{C_{u1} D_{rms1}}{D_{rms2}}$$

$$\beta_{fluid2} = \tan^{-1} \frac{C_{m2}}{C_{u2}} = \alpha_2$$

$$C_{rms2} = \frac{C_{m2}}{\sin \alpha_2}$$

Losses: skin friction

6) Turning Channel

inlet

$$C_{m1} = \frac{144 Q_{cbft} Area_1}{448.765 z_1} = C_{rms1} = W_1 \qquad (W_1 = \text{relative velocity})$$

discharge

$$C_{m2} = \frac{144 Q_{cbft} Area_2}{448.765 z_2} = C_{rms2} = W_2 \qquad (W_2 = \text{relative velocity})$$

z_1, z_2 - number of channels

Losses : skin friction

7) DownComer

inlet

$$C_{u1} = \frac{C_{ui-1} D_{rmsi-1}}{D_{rms1}}$$

$$\alpha_1 = \tan^{-1} \frac{C_{m1}}{C_{u1}} = \beta_{fluid1}$$

$$C_{rms1} = \frac{C_{m1}}{\sin \alpha_1}$$

discharge

$$C_{u2} = \frac{C_{u1} D_{rms1}}{D_{rms2}}$$

$$\beta_{fluid2} = \tan^{-1} \frac{C_{m2}}{C_{u2}} = \alpha_2$$

$$C_{rms2} = \frac{C_{m2}}{\sin \alpha_2}$$

Losses: skin friction , diffusion

8) Return Pass

inlet

$$C_{m1} = \frac{144 Q_{cbft} Area_1}{448.765 z_1} = C_{rms1}$$

discharge

$$C_{m2} = \frac{144 Q_{cbft} Area_2}{448.765 z_2} = C_{rms2}$$

z_1, z_2 - number of passages

losses : skin friction

9) 1, 2 -Discharge Volute

<u>volute throat</u>

$$C_{rms} = \frac{\frac{144 Q_{cbdt}}{V_{np}}}{Area_{throat} blockage_{throat}}$$ (times 1/2 for double discharge volute)

<u>solidity</u>

$$\sigma_{volute} = \sqrt{1 + 2\sqrt{\frac{Area_{throat}}{\pi D^2_{rms-throat}}}}$$

losses: diffusion, scroll skin friction, scroll momentum

10) 1, 2 -Discharge exit diffuser

<u>exit</u>

$$C_{m2} = \frac{144 Q_{cbft} Area_{exit}}{448.765}$$ (times 1/2 for double discharge diffuser)

diffuser loss:

$$\psi_{diffuser} = \frac{0.175[\phi_{throat} - \phi_{exit}]}{2}$$

APPENDIX D

This section contains full outputs of two case studies of pump models.

Pump Type	Fluid Type	Stages	Property
1. A scaled up Mark 49-F water tester	Water	1	Constant
2. The Mark 49-F high pressure 3-stage turbopump with high velocity ratio crossover elements	LH2	3	Variable

Each case has the following order of outputs.

1. Model configuration
2. Overall performance output
3. Geometry
4. Operating conditions
5. Velocity triangles and fluid angle output
6. Element losses
7. Element performaces

<Pump Model Configuration>

Pump Name : Mark49-Water Tester

Element Number	Element Type	Inlet Node	Discharge Node
1	Inducer	1	2
2	Impeller	2	3
3	Leakage/w FS FWR	3	2
4	Vaneless Diffuser	3	4
5	Vaned Diffuser	4	5
6	Turning Channel	5	6
7	DownComer	6	7

<Overall Pump Performance>

Operating Speed = 6322 rpm

Vol. Flow Rate (GPM)	Mass Flow Rate (lb/s)	Flow Coef	Head Coef	Power Coef	Eff	Total Head (ft)	Sp Speed (rpm)	Exit Pres (psi)	Exit Temp (R)
380.00	52.793	0.0451	0.39126	0.85037	0.46010	1179.21	625.33	510.56	521.13
408.20	56.711	0.0478	0.40150	0.83752	0.47938	1209.22	635.68	523.55	521.17
466.50	64.811	0.0535	0.41324	0.81361	0.50791	1243.66	665.02	538.46	521.21
524.82	72.913	0.0592	0.41488	0.79213	0.52374	1248.44	703.28	540.53	521.22
583.13	81.014	0.0649	0.41115	0.77251	0.53222	1237.51	746.36	535.80	521.21
641.44	89.115	0.0706	0.39586	0.75434	0.52478	1192.71	805.35	516.40	521.15
699.76	97.218	0.0763	0.37578	0.73733	0.50964	1133.83	874.66	490.91	521.07
758.07	105.319	0.0820	0.35142	0.72128	0.48722	1062.44	957.30	460.00	520.98
816.38	113.420	0.0877	0.32317	0.70603	0.45774	979.65	1057.87	424.15	520.88

<Element Geometry>

Element #: 1 Inducer

	(Inlet)		(Discharge)
Node Number	1		2
Tip Diameter(in)	5.562		5.562
Hub Diameter(in)	3.851		4.635
Rms Diameter(in)	4.784		5.120
Area(in^2)	12.657		7.416
Solidity	3.192		2.947
Passage Width(in)	0.856		0.463
Blockage	0.950		0.900
Surface Roughness(in)		0.05700	
Number of Blades	4		4
Blade Angle(Deg)	12.000		26.000
Normal Thickness(in)	0.040		0.040
Blade Length(in)		11.800	
Bypass Flow%	0.000		0.000

Element #: 2 Impeller

	(Inlet)		(Discharge)
Node Number	2		3
Tip Diameter(in)	6.000		11.124
Hub Diameter(in)	4.680		11.124
Rms Diameter(in)	5.381		11.124
Area(in^2)	11.072		12.336
Solidity	2.206		2.117
Passage Width(in)	0.660		0.353
Blockage	0.950		0.900
Surface Roughness(in)		0.05700	
Number of Blades	4		8
Blade Angle(Deg)	19.000		30.000
Normal Thickness(in)	0.030		0.090
Blade Length(in)		9.250	
Bypass Flow%	0.000		0.000

Element #: 3 Leakage

	(Inlet)		(Discharge)
Front Shroud Clearance(in)		0.000	
Rear Shroud Clearance(in)		8.000	
Front Tip Leakage(in)		0.000	
Rear Tip Leakage(in)		0.000	
Front Wear Ring Clearance(in)		0.001	
Rear Wear Ring Clearance(in)		0.000	
Front Wear Ring Diameter(in)		0.500	
Rear Wear Ring Diameter(in)		0.000	
Front Leakage Coefficient		0.8000	

Rear Leakage Coefficient	0.0020
Rear Static Head Loss ( )	0.000
Leakage Type	FS FWR

Element #: 4 Vaneless Diffuser

	(Inlet)		(Discharge)
Node Number	3		4
Tip Diameter(in)	11.124		11.980
Hub Diameter(in)	11.124		11.980
Rms Diameter(in)	11.124		11.980
Area(in^2)	12.336		10.726
Solidity	0.000		0.000
Passage Width(in)	0.353		0.285
Blockage	0.900		0.950
Surface Roughness(in)		0.00860	
Bypass Flow%	0.000		0.000

Element #: 5 Vaned Diffuser

	(Inlet)		(Discharge)
Node Number	4		5
Tip Diameter(in)	11.980		15.656
Hub Diameter(in)	11.980		15.656
Rms Diameter(in)	11.980		15.656
Area(in^2)	10.726		23.166
Solidity	1.165		1.300
Passage Width(in)	0.285		0.471
Blockage	0.950		0.890
Surface Roughness(in)		0.00860	
Number of Blades	17		17
Blade Angle(Deg)	7.650		38.108
Normal Thickness(in)	0.040		0.807
Blade Length(in)		2.580	
Bypass Flow%	0.000		0.000

Element #: 6 Turning Channel

	(Inlet)		(Discharge)
Node Number	5		6
Blockage	0.900		0.900
Surface Roughness(in)		0.00860	
Hydraulic Diameter(in)	0.471		0.471
Passage Length(in)		4.859	
Number of Channel		17	
Bypass Flow%	0.000		0.000

Element #: 7 DownComer

(Inlet) (Discharge)

Node Number	6		7
Blockage	0.900		0.900
Surface Roughness(in)		0.00860	
Hydraulic Diameter(in)	0.471		0.471
Passage Length(in)		5.562	
Number of Channel		17	
Bypass Flow%	0.000		0.000

<Operating Condition>

Fluid Type : Water

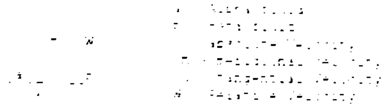
Operating Speed = 6322 rpm

Flow Rate (GPM)	Mass Flow Rate(lbm/s)	Flow Coef	NPSH Avail.(ft)
380.00	52.7935	0.0451	1.30
408.20	56.7113	0.0478	4.09
466.50	64.8109	0.0535	9.43
524.82	72.9133	0.0592	14.21
583.13	81.0144	0.0649	18.43
641.44	89.1154	0.0706	22.10
699.76	97.2178	0.0763	25.20
758.07	105.3188	0.0820	27.75
816.38	113.4198	0.0877	29.73

Inlet Temperature(R)	519.67
Inlet Pressure(psi)	14
Inlet Tangential Velocity(ft/s)	0
Inlet Density(lbm/ft^3)	62.347
Inlet Viscosity(ft^2/s)	1.204E-05
Inlet Specific Heat(Btu/lbm-R)	1.008
Max. Impeller Head Coef.	.45
Max. Impeller Disch. Flow Coef.	.05
Impeller Clearance Torque Coef.	.01

<Velocity Triangle Output>

Operating Speed = 6322 rpm



Element # 1 :Inducer

(Inlet) Node # 1 Urms1 = 132.0613 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
380.00	.034936	10.729	0.000	10.729	90.000	4.645	51.603	7.36
408.20	.037528	11.525	0.000	11.525	90.000	4.988	55.432	7.01
466.50	.042888	13.171	0.000	13.171	90.000	5.696	63.349	6.30
524.82	.048250	14.818	0.000	14.818	90.000	6.402	71.269	5.60
583.13	.053611	16.464	0.000	16.464	90.000	7.106	79.187	4.89
641.44	.058972	18.110	0.000	18.110	90.000	7.809	87.105	4.19
699.76	.064333	19.757	0.000	19.757	90.000	8.509	95.025	3.49
758.07	.069694	21.403	0.000	21.403	90.000	9.206	102.943	2.79
816.38	.075055	23.049	0.000	23.049	90.000	9.900	110.862	2.10

(Discharge) Node # 2 Urms2 = 141.3347 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
380.00	.061034	18.743	98.997	100.756	10.721	23.880	42.757	2.12
408.20	.065563	20.134	95.855	97.947	11.863	23.880	45.930	2.12
466.50	.074927	23.010	89.360	92.275	14.440	23.880	52.490	2.12
524.82	.084294	25.887	82.862	86.811	17.349	23.880	59.052	2.12
583.13	.093659	28.763	76.365	81.602	20.639	23.880	65.613	2.12
641.44	.103025	31.639	69.869	76.698	24.363	23.880	72.174	2.12
699.76	.112392	34.515	63.371	72.161	28.575	23.880	78.736	2.12
758.07	.121757	37.392	56.874	68.065	33.323	23.880	85.297	2.12
816.38	.131123	40.268	50.378	64.493	38.636	23.880	91.858	2.12

Element # 2 :Impeller

(Inlet) Node # 3 Urms1 = 148.543 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
380.00	.046476	14.273	94.193	95.268	8.616	14.714	43.840	4.29
408.20	.049319	15.146	91.203	92.453	9.429	14.796	46.521	4.20
466.50	.055193	16.950	85.023	86.696	11.274	14.941	52.063	4.06
524.82	.061068	18.754	78.841	81.041	13.380	15.059	57.604	3.94
583.13	.066940	20.557	72.659	75.512	15.798	15.158	63.143	3.84
641.44	.072813	22.361	66.478	70.138	18.591	15.242	68.683	3.76
699.76	.078688	24.165	60.296	64.958	21.840	15.314	74.224	3.69
758.07	.084563	25.969	54.114	60.023	25.636	15.377	79.766	3.62
816.38	.090439	27.774	47.933	55.398	30.089	15.432	85.309	3.57

(Discharge) Node # 4 Urms2 = 307.1001 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
380.00	.045077	13.843	229.999	230.415	3.444	10.179	27.686	19.82
408.20	.047834	14.690	228.067	228.540	3.685	10.529	29.380	19.47
466.50	.053531	16.440	224.140	224.742	4.195	11.209	32.879	18.79

524.82	.059229	18.189	220.295	221.045	4.720	11.835	36.378	18.17
583.13	.064925	19.938	216.528	217.444	5.261	12.415	39.877	17.89
641.44	.070621	21.688	212.832	213.935	5.818	12.956	43.375	17.24
699.76	.076318	23.437	209.203	210.512	6.392	13.464	46.875	16.54
758.07	.082017	25.187	205.638	207.175	6.983	13.941	50.375	16.16
816.38	.087716	26.938	202.132	203.919	7.591	14.393	53.875	15.61

Element # 3 :Leakage

Element # 4 :Vaneless Diffuser

(Inlet) Node # 7 Urms1 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
380.00	.035762	10.982	229.999	230.261	2.734	2.734	10.982	-2.73
408.20	.038416	11.797	228.067	228.372	2.961	2.961	11.797	-2.96
466.50	.043902	13.482	224.140	224.545	3.442	3.442	13.482	-3.44
524.82	.049391	15.168	220.295	220.817	3.939	3.939	15.168	-3.94
583.13	.054878	16.853	216.528	217.183	4.451	4.451	16.853	-4.45
641.44	.060366	18.538	212.832	213.638	4.978	4.978	18.538	-4.98
699.76	.065854	20.224	209.203	210.179	5.522	5.522	20.224	-5.52
758.07	.071342	21.909	205.638	206.802	6.081	6.081	21.909	-6.08
816.38	.076829	23.594	202.132	203.505	6.658	6.658	23.594	-6.66

(Discharge) Node # 8 Urms2 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
380.00	.038965	11.966	213.565	213.900	3.207	3.207	11.966	-3.21
408.20	.041856	12.854	211.771	212.161	3.473	3.473	12.854	-3.47
466.50	.047834	14.690	208.125	208.643	4.037	4.037	14.690	-4.04
524.82	.053814	16.526	204.555	205.221	4.619	4.619	16.526	-4.62
583.13	.059793	18.363	201.056	201.893	5.218	5.218	18.363	-5.22
641.44	.065773	20.199	197.625	198.655	5.836	5.836	20.199	-5.84
699.76	.071753	22.035	194.255	195.501	6.472	6.472	22.035	-6.47
758.07	.077732	23.871	190.945	192.431	7.126	7.126	23.871	-7.13
816.38	.083711	25.708	187.689	189.442	7.799	7.799	25.708	-7.80

Element # 5 :Vaned Diffuser

(Inlet) Node # 9 Urms1 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
380.00	.045459	13.961	213.565	214.021	3.740	3.740	104.871	3.91
408.20	.048833	14.997	211.771	212.302	4.051	4.051	112.654	3.60
466.50	.055807	17.138	208.125	208.829	4.708	4.708	128.743	2.94
524.82	.062784	19.281	204.555	205.461	5.385	5.385	144.838	2.27
583.13	.069760	21.423	201.056	202.195	6.082	6.082	160.930	1.57
641.44	.076735	23.565	197.625	199.025	6.800	6.800	177.022	0.85
699.76	.083712	25.708	194.255	195.949	7.539	7.539	193.117	0.11
758.07	.090688	27.850	190.945	192.965	8.298	8.298	209.210	-0.65
816.38	.097664	29.992	187.689	190.071	9.079	9.079	225.302	-1.43

(Discharge) Node # 10 Urms2 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
380.00	.039128	12.016	21.048	24.236	29.722	29.722	19.471	8.39
408.20	.042032	12.908	22.610	26.035	29.722	29.722	20.915	8.39
466.50	.048035	14.751	25.839	29.753	29.722	29.722	23.903	8.39
524.82	.054040	16.596	29.069	33.473	29.722	29.722	26.891	8.39
583.13	.060044	18.439	32.299	37.192	29.722	29.722	29.879	8.39

641.44	.066049	20.283	35.529	40.911	29.722	29.722	32.866	9.39
699.76	.072053	22.127	38.759	44.631	29.722	29.722	35.854	9.39
758.07	.078057	23.971	41.989	48.350	29.722	29.722	38.842	9.39
816.38	.084061	25.815	45.218	52.068	29.722	29.722	41.830	9.39

Element # 6 :Turning Channel

(Inlet) Node # 11 Urms1 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
380.00	.148944	37.050	21.048	42.611	60.399	60.399	37.050	-60.40
408.20	.159998	39.800	22.610	45.773	60.399	60.399	39.800	-60.40
466.50	.182849	45.484	25.839	52.311	60.399	60.399	45.484	-60.40
524.82	.205708	51.170	29.069	58.851	60.399	60.399	51.170	-60.40
583.13	.228563	56.855	32.299	65.389	60.399	60.399	56.855	-60.40
641.44	.251418	62.541	35.529	71.928	60.399	60.399	62.541	-60.40
699.76	.274277	68.227	38.759	78.467	60.399	60.399	68.227	-60.40
758.07	.297132	73.912	41.989	85.006	60.399	60.399	73.912	-60.40
816.38	.319987	79.597	45.218	91.545	60.399	60.399	79.597	-60.40

(Discharge) Node # 12 Urms2 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
380.00	.148944	37.050	0.000	37.050	90.000	0.000	37.050	0.00
408.20	.159998	39.800	0.000	39.800	90.000	0.000	39.800	0.00
466.50	.182849	45.484	0.000	45.484	90.000	0.000	45.484	0.00
524.82	.205708	51.170	0.000	51.170	90.000	0.000	51.170	0.00
583.13	.228563	56.855	0.000	56.855	90.000	0.000	56.855	0.00
641.44	.251418	62.541	0.000	62.541	90.000	0.000	62.541	0.00
699.76	.274277	68.227	0.000	68.227	90.000	0.000	68.227	0.00
758.07	.297132	73.912	0.000	73.912	90.000	0.000	73.912	0.00
816.38	.319987	79.597	0.000	79.597	90.000	0.000	79.597	0.00

Element # 7 :DownComer

(Inlet) Node # 13 Urms1 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
380.00	.148944	37.050	0.000	37.050	0.000	0.000	37.050	0.00
408.20	.159998	39.800	0.000	39.800	0.000	0.000	39.800	0.00
466.50	.182849	45.484	0.000	45.484	0.000	0.000	45.484	0.00
524.82	.205708	51.170	0.000	51.170	0.000	0.000	51.170	0.00
583.13	.228563	56.855	0.000	56.855	0.000	0.000	56.855	0.00
641.44	.251418	62.541	0.000	62.541	0.000	0.000	62.541	0.00
699.76	.274277	68.227	0.000	68.227	0.000	0.000	68.227	0.00
758.07	.297132	73.912	0.000	73.912	0.000	0.000	73.912	0.00
816.38	.319987	79.597	0.000	79.597	0.000	0.000	79.597	0.00

(Discharge) Node # 14 Urms2 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
380.00	.148944	37.050	0.000	37.050	90.000	0.000	37.050	0.00
408.20	.159998	39.800	0.000	39.800	90.000	0.000	39.800	0.00
466.50	.182849	45.484	0.000	45.484	90.000	0.000	45.484	0.00
524.82	.205708	51.170	0.000	51.170	90.000	0.000	51.170	0.00
583.13	.228563	56.855	0.000	56.855	90.000	0.000	56.855	0.00
641.44	.251418	62.541	0.000	62.541	90.000	0.000	62.541	0.00
699.76	.274277	68.227	0.000	68.227	90.000	0.000	68.227	0.00
758.07	.297132	73.912	0.000	73.912	90.000	0.000	73.912	0.00
816.38	.319987	79.597	0.000	79.597	90.000	0.000	79.597	0.00

<Element Losses>

Operating Speed = 6322 rpm

Element # 1 Inducer

<Inducer Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss	Euler Head Coef	Actual Head Coef
380.00	0.01059	0.01797	0.00273	0.03128	0.14836	0.11708
408.20	0.00964	0.02073	0.00252	0.03289	0.14365	0.11076
466.50	0.00781	0.02707	0.00212	0.03701	0.13392	0.09691
524.82	0.00618	0.03426	0.00176	0.04220	0.12418	0.08198
583.13	0.00474	0.04230	0.00143	0.04847	0.11444	0.06597
641.44	0.00349	0.05118	0.00113	0.05580	0.10471	0.04890
699.76	0.00243	0.06090	0.00087	0.06421	0.09497	0.03076
758.07	0.00156	0.07147	0.00065	0.07368	0.08523	0.01155
816.38	0.00089	0.08289	0.00046	0.08423	0.07550	-0.00874

Flow Rate (GPM)	Euler Head(ft)	St. Head Rise(ft)	Pres. Rise (psi)	Temp Rise deg (R)	Efficiency	Reynold's Number
380.00	434.88	343.18	148.59	0.44	0.78916	2.312E+05
408.20	421.07	324.67	140.57	0.41	0.77106	2.483E+05
466.50	392.54	284.06	122.99	0.36	0.72365	2.838E+05
524.82	364.00	240.29	104.04	0.31	0.66015	3.193E+05
583.13	335.46	193.39	83.73	0.25	0.57649	3.548E+05
641.44	306.92	143.34	62.06	0.18	0.46704	3.902E+05
699.76	278.38	90.16	39.04	0.11	0.32389	4.257E+05
758.07	249.84	33.86	14.66	0.04	0.13552	4.612E+05
816.38	221.30	-25.61	-11.09	-0.03	-0.11572	4.967E+05

Flow Rate (GPM)	Friction Loss	Suction Specific Speed
380.00	0.09055	9088.5
408.20	0.09053	9419.7
466.50	0.09052	10069.9
524.82	0.09052	10680.8
583.13	0.09052	11258.5
641.44	0.09052	11808.0
699.76	0.09051	12333.1
758.07	0.09050	12836.7
816.38	0.09050	13321.2

Element # 2 Impeller

<Impeller Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss	Recirc. Loss	Clearance Loss
380.00	0.00026	0.00871	0.00080	0.00977	0.00019	0.10124
408.20	0.00028	0.00981	0.00058	0.01068	0.00002	0.09486
466.50	0.00032	0.01229	0.00030	0.01292	0.00000	0.08375
524.82	0.00037	0.01504	0.00015	0.01556	0.00000	0.07479
583.13	0.00042	0.01807	0.00007	0.01856	0.00000	0.06744
641.44	0.00047	0.02138	0.00003	0.02188	0.00000	0.06130
699.76	0.00052	0.02496	0.00001	0.02550	0.00000	0.05611
758.07	0.00057	0.02883	0.00000	0.02941	0.00000	0.05167

816.38	0.00063	0.03298	0.00000	0.03361	0.00000	0.14793

Flow Rate (GPM)	Theo/Inf Head Coef	Euler Head Coef	Ratio Euler/Infin	Head Rise (ft)	Actual Coef	Efficiency
380.00	0.77357	0.60058	0.77638	1731.81	0.59081	0.76274
408.20	0.77350	0.59900	0.77440	1724.52	0.58832	0.76060
466.50	0.77337	0.59595	0.77059	1709.01	0.58303	0.75388
524.82	0.77324	0.59316	0.76712	1693.10	0.57760	0.74633
583.13	0.77311	0.59063	0.76397	1676.89	0.57207	0.73897
641.44	0.77298	0.58833	0.76113	1660.44	0.56646	0.73233
699.76	0.77284	0.58625	0.75857	1643.73	0.56076	0.72559
758.07	0.77271	0.58438	0.75627	1626.77	0.55497	0.71921
816.38	0.77257	0.58270	0.75423	1609.53	0.54909	0.71073

Flow Rate (GPM)	Friction Loss	Suction Spec Speed	Pres. Rise (psi)	Temp. Rise (R)	Reynold's Number
380.00	0.09159	1444.7	749.81	2.21	1.715E+05
408.20	0.09158	1555.2	746.66	2.2	1.820E+05
466.50	0.09158	1820.2	739.94	2.18	2.037E+05
524.82	0.09157	2158.6	733.05	2.16	2.254E+05
583.13	0.09155	2621.5	726.04	2.14	2.471E+05
641.44	0.09155	3318.1	718.91	2.12	2.687E+05
699.76	0.09155	4541.8	711.68	2.1	2.904E+05
758.07	0.09154	7500.6	704.34	2.07	3.121E+05
816.38	0.09154	43249.6	696.87	2.05	3.338E+05

Element # 3 Leakage

<Leakage Output>

Total Leakage (ft^3/s)	QLeakF1 (ft^3/s)	QLeakF2 (ft^3/s)	QLeakR1 (ft^3/s)	QLeakR2 (ft^3/s)
0.171689	0.00000	0.171689	0.00000	0.00000
0.171151	0.00000	0.171151	0.00000	0.00000
0.169967	0.00000	0.169967	0.00000	0.00000
0.168737	0.00000	0.168737	0.00000	0.00000
0.167493	0.00000	0.167493	0.00000	0.00000
0.166254	0.00000	0.166254	0.00000	0.00000
0.165034	0.00000	0.165034	0.00000	0.00000
0.163843	0.00000	0.163843	0.00000	0.00000
0.162683	0.00000	0.162683	0.00000	0.00000

Total (lb-ft/s)	HPBRF (lb-ft/s)	HPDFF (lb-ft/s)	HPDFR (lb-ft/s)	HPBRR (lb-ft/s)	Leakage Power Loss
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000

Element # 4 Vaneless Diffuser

<Vaneless Diffuser Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss Coef	Friction Loss	Reynold's Number
380.00	0.00000	0.18068	0.00000	0.18068	0.04383	8.761E+05

408.20	0.00000	0.16411	0.00000	0.16411	0.04382	8.690E+05
466.50	0.00000	0.13653	0.00000	0.13653	0.04383	8.548E+05
524.82	0.00000	0.11543	0.00000	0.11543	0.04384	8.404E+05
583.13	0.00000	0.09887	0.00000	0.09887	0.04384	8.267E+05
641.44	0.00000	0.08558	0.00000	0.08558	0.04384	8.133E+05
699.76	0.00000	0.07471	0.00000	0.07471	0.04383	8.002E+05
758.07	0.00000	0.06571	0.00000	0.06571	0.04383	7.875E+05
816.38	0.00000	0.05817	0.00000	0.05817	0.04383	7.751E+05

Flow Rate (GPM)	Pre. Rise (psi)	Temp. Rise (R)	Head Rise (ft)
380.00	-229.31	-.68	-529.62
408.20	-208.27	-.61	-481.04
466.50	-173.27	-.51	-400.19
524.82	-146.5	-.43	-338.37
583.13	-125.48	-.37	-289.82
641.44	-108.61	-.32	-250.86
699.76	-94.81	-.28	-218.98
758.07	-83.4	-.25	-192.63
816.38	-73.83	-.22	-170.52

Element # 5 Vaned Diffuser

<Vaned Diffuser Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss Coef	Friction Loss	Reynold's Number
380.00	0.01911	0.01043	0.09366	0.12321	0.05104	5.642E+05
408.20	0.01594	0.01203	0.09081	0.11878	0.05104	5.596E+05
466.50	0.01031	0.01571	0.08495	0.11098	0.05104	5.505E+05
524.82	0.00592	0.01989	0.07918	0.10499	0.05104	5.416E+05
583.13	0.00000	0.02456	0.07351	0.09806	0.05104	5.330E+05
641.44	0.00000	0.02971	0.06796	0.09767	0.05104	5.246E+05
699.76	0.00000	0.03536	0.06254	0.09790	0.05105	5.165E+05
758.07	0.00000	0.04150	0.05728	0.09878	0.05105	5.087E+05
816.38	0.00000	0.04814	0.05218	0.10032	0.05105	5.010E+05

Flow Rate (GPM)	Pre. Rise (psi)	Temp. Rise (R)	Head Rise (ft)
380.00	-156.36	-.46	-361.15
408.20	-150.75	-.44	-348.18
466.50	-140.85	-.41	-325.31
524.82	-133.24	-.39	-307.74
583.13	-124.46	-.37	-287.45
641.44	-123.96	-.36	-286.30
699.76	-124.25	-.37	-286.98
758.07	-125.37	-.37	-289.55
816.38	-127.32	-.37	-294.06

Element # 6 Turning Channel

<Turning Channel Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss Coef	Friction Loss	Reynold's Number
380.00	0.00000	0.00891	0.00000	0.00891	0.04730	1.298E+05
408.20	0.00000	0.01028	0.00000	0.01028	0.04727	1.395E+05
466.50	0.00000	0.01342	0.00000	0.01342	0.04724	1.594E+05
524.82	0.00000	0.01699	0.00000	0.01699	0.04721	1.793E+05
583.13	0.00000	0.02097	0.00000	0.02097	0.04718	1.993E+05
641.44	0.00000	0.02536	0.00000	0.02536	0.04716	2.192E+05

699.76	0.00000	0.03018	0.00000	0.03018	0.04715	2.39[illegible]E+05
758.07	0.00000	0.03542	0.00000	0.03542	0.04714	2.590E+05
816.38	0.00000	0.04107	0.00000	0.04107	0.04713	2.790E+05

Flow Rate (GPM)	Pre. Rise (psi)	Temp. Rise (R)	Head Rise (ft)
380.00	-11.31	-.03	-26.12
408.20	-13.05	-.04	-30.14
466.50	-17.04	-.05	-39.35
524.82	-21.56	-.06	-49.79
583.13	-26.61	-.08	-61.46
641.44	-32.19	-.09	-74.35
699.76	-38.3	-.11	-88.47
758.07	-44.95	-.13	-103.82
816.38	-52.13	-.15	-120.40

Element # 7 DownComer

<DownComer Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss Coef	Friction Loss	Reynold's Number
380.00	0.00000	0.00383	0.00000	0.00383	0.04732	1.208E+05
408.20	0.00000	0.00442	0.00000	0.00442	0.04730	1.297E+05
466.50	0.00000	0.00577	0.00000	0.00577	0.04726	1.483E+05
524.82	0.00000	0.00729	0.00000	0.00729	0.04722	1.668E+05
583.13	0.00000	0.00900	0.00000	0.00900	0.04721	1.853E+05
641.44	0.00000	0.01088	0.00000	0.01088	0.04719	2.039E+05
699.76	0.00000	0.01295	0.00000	0.01295	0.04717	2.224E+05
758.07	0.00000	0.01519	0.00000	0.01519	0.04715	2.410E+05
816.38	0.00000	0.01761	0.00000	0.01761	0.04714	2.595E+05

Flow Rate (GPM)	Pre. Rise (psi)	Temp. Rise (R)	Head Rise (ft)
380.00	-4.86	-.01	-11.23
408.20	-5.61	-.02	-12.95
466.50	-7.32	-.02	-16.90
524.82	-9.25	-.03	-21.38
583.13	-11.42	-.03	-26.38
641.44	-13.81	-.04	-31.90
699.76	-16.43	-.05	-37.96
758.07	-19.28	-.06	-44.53
816.38	-22.35	-.07	-51.63

<Element Performance>

Operating Speed= 6322 rpm

Element # 1 Inducer

(Inlet) Node # : 1

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
380.00	52.793	519.67	13.23	0.77	14.00	62.35	30.55	1.79	32.34
408.20	56.711	519.67	13.11	0.89	14.00	62.35	30.27	2.06	32.34
466.50	64.811	519.67	12.83	1.17	14.00	62.35	29.64	2.70	32.34
524.82	72.913	519.67	12.52	1.48	14.00	62.35	28.92	3.41	32.34
583.13	81.014	519.67	12.18	1.82	14.00	62.35	28.12	4.21	32.34
641.44	89.115	519.67	11.79	2.21	14.00	62.35	27.24	5.10	32.34
699.76	97.218	519.67	11.37	2.63	14.00	62.35	26.27	6.07	32.34
758.07	105.319	519.67	10.92	3.08	14.00	62.35	25.22	7.12	32.34
816.38	113.420	519.67	10.43	3.57	14.00	62.35	24.08	8.26	32.34

(Discharge) Node # : 2

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
380.00	52.793	520.11	94.28	68.31	162.59	62.35	217.76	157.76	375.52
408.20	56.711	520.08	90.02	64.55	154.57	62.35	207.92	149.09	357.01
466.50	64.811	520.03	79.70	57.29	136.99	62.35	184.07	132.32	316.40
524.82	72.913	519.98	67.33	50.71	118.04	62.35	155.51	117.12	272.63
583.13	81.014	519.92	52.93	44.80	97.73	62.35	122.24	103.48	225.72
641.44	89.115	519.85	36.48	39.58	76.06	62.35	84.26	91.42	175.68
699.76	97.218	519.78	18.00	35.04	53.04	62.35	41.58	80.92	122.50
758.07	105.319	519.71	-2.51	31.17	28.66	62.35	-5.80	72.00	66.19
816.38	113.420	519.64	-25.07	27.99	2.91	62.35	-57.91	64.64	6.73

Element # 2 Impeller

(Inlet) Node # : 2

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
457.05	63.498	520.11	101.52	61.07	162.59	62.35	234.47	141.05	375.52
485.01	67.382	520.08	97.06	57.51	154.57	62.35	224.17	132.83	357.01
542.78	75.408	520.03	86.42	50.57	136.99	62.35	199.59	116.81	316.40
600.54	83.434	519.98	73.85	44.19	118.04	62.35	170.56	102.06	272.63
658.29	91.457	519.92	59.36	38.37	97.73	62.35	137.11	88.61	225.72
716.05	99.481	519.85	42.96	33.10	76.06	62.35	99.23	76.45	175.68
773.82	107.507	519.78	24.65	28.39	53.04	62.35	56.93	65.57	122.50
831.60	115.534	519.71	4.42	24.24	28.66	62.35	10.21	55.99	66.19
889.39	123.563	519.64	-17.74	20.65	2.91	62.35	-40.97	47.69	6.73

(Discharge) Node # : 3

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
457.05	63.498	522.32	555.18	357.22	912.40	62.35	1282.26	825.07	2107.33
485.01	67.382	522.28	549.80	351.43	901.23	62.35	1269.84	811.69	2081.53
542.78	75.408	522.21	537.08	339.85	876.93	62.35	1240.47	784.94	2025.41
600.54	83.434	522.13	522.33	328.76	851.09	62.35	1206.40	759.32	1965.72
658.29	91.457	522.05	505.63	318.14	823.77	62.35	1167.83	734.78	1902.62
716.05	99.481	521.97	487.02	307.95	794.97	62.35	1124.86	711.26	1836.11
773.82	107.507	521.88	466.54	298.18	764.71	62.35	1077.54	688.68	1766.23
831.60	115.534	521.79	444.20	288.80	732.99	62.35	1025.94	667.02	1692.96
889.39	123.563	521.69	419.99	279.79	699.78	62.35	970.03	646.22	1616.26

Element # 3 Leakage

Inlet Node # : 3 Disch Node # : 2

Element # 4 Vaneless Diffuser

(Inlet) Node # : 3

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
380.00	52.793	522.32	555.65	356.75	912.40	62.35	1283.37	823.96	2107.33
408.20	56.711	522.28	550.31	350.92	901.23	62.35	1271.03	810.50	2081.53
466.50	64.811	522.21	537.68	339.25	876.93	62.35	1241.85	783.56	2025.41
524.82	72.913	522.13	523.01	328.08	851.09	62.35	1207.97	757.76	1965.72
583.13	81.014	522.05	506.40	317.37	823.77	62.35	1169.60	733.02	1902.62
641.44	89.115	521.97	487.88	307.10	794.97	62.35	1126.83	709.29	1836.11
699.76	97.218	521.88	467.48	297.23	764.71	62.35	1079.72	686.50	1766.23
758.07	105.319	521.79	445.24	287.76	732.99	62.35	1028.34	664.62	1692.96
816.38	113.420	521.69	421.13	278.65	699.78	62.35	972.66	643.60	1616.26

(Discharge) Node # : 4

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
380.00	52.793	521.64	375.24	307.85	683.09	62.35	866.68	711.03	1577.71
408.20	56.711	521.67	390.09	302.87	692.96	62.35	900.98	699.51	1600.49
466.50	64.811	521.70	410.76	292.90	703.66	62.35	948.71	676.51	1625.22
524.82	72.913	521.70	421.21	283.38	704.59	62.35	972.85	654.50	1627.35
583.13	81.014	521.68	424.03	274.26	698.28	62.35	979.35	633.44	1612.80
641.44	89.115	521.65	420.83	265.53	686.36	62.35	971.97	613.28	1585.25
699.76	97.218	521.60	412.73	257.17	669.90	62.35	953.27	593.97	1547.24
758.07	105.319	521.54	400.44	249.15	649.59	62.35	924.88	575.46	1500.34
816.38	113.420	521.47	384.48	241.47	625.95	62.35	888.01	557.72	1445.74

Element # 5 Vaned Diffuser

(Inlet) Node # : 4

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
380.00	52.793	521.64	374.90	308.20	683.09	62.35	865.88	711.83	1577.71
408.20	56.711	521.67	389.69	303.27	692.96	62.35	900.05	700.44	1600.49
466.50	64.811	521.70	410.24	293.43	703.66	62.35	947.50	677.72	1625.22
524.82	72.913	521.70	420.55	284.04	704.59	62.35	971.32	656.03	1627.35
583.13	81.014	521.68	423.21	275.08	698.28	62.35	977.46	635.34	1612.80
641.44	89.115	521.65	419.84	266.52	686.36	62.35	969.68	615.57	1585.25
699.76	97.218	521.60	411.55	258.35	669.90	62.35	950.55	596.69	1547.24
758.07	105.319	521.54	399.06	250.54	649.59	62.35	921.68	578.66	1500.34
816.38	113.420	521.47	382.87	243.08	625.95	62.35	884.31	561.43	1445.74

(Discharge) Node # : 5

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
380.00	52.793	521.18	522.78	3.95	526.73	62.35	1207.44	9.13	1216.56
408.20	56.711	521.23	537.65	4.56	542.21	62.35	1241.78	10.53	1252.31
466.50	64.811	521.29	556.86	5.96	562.82	62.35	1286.15	13.76	1299.91
524.82	72.913	521.31	563.81	7.54	571.35	62.35	1302.20	17.41	1319.61
583.13	81.014	521.32	564.52	9.31	573.83	62.35	1303.85	21.50	1325.35
641.44	89.115	521.28	551.14	11.26	562.40	62.35	1272.95	26.01	1298.96
699.76	97.218	521.24	532.25	13.40	545.65	62.35	1229.31	30.95	1260.26
758.07	105.319	521.17	508.50	15.73	524.23	62.35	1174.46	36.33	1210.78
816.38	113.420	521.10	480.39	18.24	498.63	62.35	1109.54	42.13	1151.67

Element # 6 Turning Channel

(Inlet) Node # : 5

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
380.00	52.793	521.18	514.51	12.22	526.73	62.35	1188.35	28.22	[illegible]
408.20	56.711	521.23	528.11	14.10	542.21	62.35	1219.75	32.56	[illegible]
466.50	64.811	521.29	544.40	18.41	562.82	62.35	1257.38	42.53	[illegible]
524.82	72.913	521.31	548.04	23.30	571.35	62.35	1265.79	53.82	[illegible]
583.13	81.014	521.32	545.06	28.77	573.83	62.35	1258.90	66.45	1325.35
641.44	89.115	521.28	527.59	34.81	562.40	62.35	1218.56	80.40	1298.96
699.76	97.218	521.24	504.22	41.43	545.65	62.35	1164.58	95.59	[illegible]
758.07	105.319	521.17	475.61	48.62	524.23	62.35	1098.49	112.30	1210.78
816.38	113.420	521.10	442.25	56.39	498.63	62.35	1021.44	130.24	[illegible]

(Discharge) Node # : 6

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
380.00	52.793	521.15	506.18	9.24	515.42	62.35	1169.11	21.33	1190.44
408.20	56.711	521.19	518.50	10.66	529.16	62.35	1197.56	24.62	1222.17
466.50	64.811	521.24	531.86	13.92	545.78	62.35	1228.41	32.15	1260.56
524.82	72.913	521.25	532.17	17.62	549.79	62.35	1229.13	40.69	1269.82
583.13	81.014	521.24	525.47	21.75	547.22	62.35	1213.66	50.23	1263.89
641.44	89.115	521.19	503.90	26.32	530.21	62.35	1163.83	60.78	1224.61
699.76	97.218	521.12	476.02	31.32	507.34	62.35	1099.45	72.34	1171.79
758.07	105.319	521.04	442.52	36.76	479.28	62.35	1022.07	84.90	1106.96
816.38	113.420	520.94	403.88	42.63	446.51	62.35	932.81	98.46	1031.28

Element # 7 DownComer

(Inlet) Node # : 6

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
380.00	52.793	521.15	506.18	9.24	515.42	62.35	1169.11	21.33	1190.44
408.20	56.711	521.19	518.50	10.66	529.16	62.35	1197.56	24.62	1222.17
466.50	64.811	521.24	531.86	13.92	545.78	62.35	1228.41	32.15	1260.56
524.82	72.913	521.25	532.17	17.62	549.79	62.35	1229.13	40.69	1269.82
583.13	81.014	521.24	525.47	21.75	547.22	62.35	1213.66	50.23	1263.89
641.44	89.115	521.19	503.90	26.32	530.21	62.35	1163.83	60.78	1224.61
699.76	97.218	521.12	476.02	31.32	507.34	62.35	1099.45	72.34	1171.79
758.07	105.319	521.04	442.52	36.76	479.28	62.35	1022.07	84.90	1106.96
816.38	113.420	520.94	403.88	42.63	446.51	62.35	932.81	98.46	1031.28

(Discharge) Node # : 7

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
380.00	52.793	521.13	501.32	9.24	510.56	62.35	1157.88	21.33	1179.21
408.20	56.711	521.17	512.89	10.66	523.55	62.35	1184.61	24.62	1209.22
466.50	64.811	521.21	524.54	13.92	538.46	62.35	1211.51	32.15	1243.66
524.82	72.913	521.22	522.92	17.62	540.53	62.35	1207.75	40.69	1248.44
583.13	81.014	521.21	514.05	21.75	535.80	62.35	1187.28	50.23	1237.51
641.44	89.115	521.15	490.08	26.32	516.40	62.35	1131.92	60.78	1192.71
699.76	97.218	521.07	459.59	31.32	490.91	62.35	1061.49	72.34	1133.83
758.07	105.319	520.98	423.24	36.76	460.00	62.35	977.54	84.90	1062.44
816.38	113.420	520.88	381.52	42.63	424.15	62.35	881.19	98.46	979.65

<Pump Model Configuration>

Pump Name : Mark49 LH2 Turbopump

Element Number	Element Type	Inlet Node	Discharge Node
1	Inducer	1	2
2	Impeller	2	3
3	Vaneless Diffuser	3	4
4	Vaned Diffuser	4	5
5	Turning Channel	5	6
6	DownComer	6	7
7	Turning Channel	7	8
8	Impeller	8	9
9	Vaneless Diffuser	9	10
10	Vaned Diffuser	10	11
11	Turning Channel	11	12
12	DownComer	12	13
13	Turning Channel	13	14
14	Impeller	14	15
15	Vaneless Diffuser	15	16
16	Vaned Diffuser	16	17
17	1-Discharge Volute	17	18
18	Leakage/w FS FWR	3	2
19	Leakage/w FS FWR	9	8
20	Leakage/w FS FWR	15	14

<Overall Pump Performance>

Operating Speed = 110000 rpm

Vol. Flow Rate (GPM)	Mass Flow Rate (lb/s)	Flow Coef	Head Coef	Power Coef	Eff	Total Head (ft)	Sp Speed (rpm)	Exit Pres (psi)	Exit Temp (R)
217.68	2.176	0.0286	1.09044	2.44034	0.44684	112260.30	253.39	3638.68	80.85
284.84	2.847	0.0374	1.48206	2.31390	0.64050	145953.40	230.27	5076.40	79.73
392.00	3.919	0.0515	1.61476	2.20531	0.73222	158617.60	253.31	5607.34	82.60
436.00	4.358	0.0573	1.63740	2.16694	0.75563	161650.00	264.37	5705.59	82.87
501.85	5.017	0.0659	1.62246	2.11098	0.76858	160354.70	285.59	5648.44	82.68
614.71	6.145	0.0808	1.56551	2.01869	0.77551	155262.40	324.66	5421.82	84.09
764.88	7.646	0.1005	1.40052	1.90208	0.73631	139079.80	393.70	4746.62	81.80
850.25	8.499	0.1117	1.27452	1.83852	0.69323	127359.50	445.50	4276.72	80.29
968.80	9.684	0.1273	1.04557	1.74517	0.59912	105028.80	551.69	3399.31	77.31

<Element Geometry>

Element #: 1 Inducer

	(Inlet)		(Discharge)
Node Number	1		2
Tip Diameter(in)	1.952		1.952
Hub Diameter(in)	1.351		1.626
Rms Diameter(in)	1.679		1.796
Area(in^2)	1.557		0.910
Solidity	3.192		2.946
Passage Width(in)	0.300		0.162
Blockage	0.950		0.900
Surface Roughness(in)		0.00030	
Number of Blades	4		4
Blade Angle(Deg)	12.000		26.000
Normal Thickness(in)	0.014		0.014
Blade Length(in)		4.140	
Bypass Flow%	0.000		0.000

Element #: 2 Impeller

	(Inlet)		(Discharge)
Node Number	2		3
Tip Diameter(in)	1.952		3.900
Hub Diameter(in)	1.351		3.900
Rms Diameter(in)	1.679		3.900
Area(in^2)	1.557		1.519
Solidity	3.192		2.703
Passage Width(in)	0.300		0.124
Blockage	0.950		0.900
Surface Roughness(in)		0.00030	
Number of Blades	4		8
Blade Angle(Deg)	12.000		30.000
Normal Thickness(in)	0.014		0.032
Blade Length(in)		4.140	
Bypass Flow%	0.000		0.000

Element #: 3 Vaneless Diffuser

	(Inlet)		(Discharge)
Node Number	3		4
Tip Diameter(in)	3.900		4.204
Hub Diameter(in)	3.900		4.204
Rms Diameter(in)	3.900		4.204
Area(in^2)	1.519		1.321
Solidity	0.000		0.000
Passage Width(in)	0.124		0.100
Blockage	0.900		0.950
Surface Roughness(in)		0.00030	

Bypass Flow	0.000		0.000

Element #: 4 Vaned Diffuser

	(Inlet)		(Discharge)
Node Number	4		5
Tip Diameter(in)	4.204		5.493
Hub Diameter(in)	4.204		5.493
Rms Diameter(in)	4.204		5.493
Area(in^2)	1.321		2.847
Solidity	1.165		1.300
Passage Width(in)	0.100		0.165
Blockage	0.950		0.890
Surface Roughness(in)		0.00030	
Number of Blades	17		17
Blade Angle(Deg)	7.650		38.108
Normal Thickness(in)	0.014		0.312
Blade Length(in)		0.905	
Bypass Flow%	0.000		0.000

Element #: 5 Turning Channel

	(Inlet)		(Discharge)
Node Number	5		6
Blockage	1.000		1.000
Surface Roughness(in)		0.00030	
Hydraulic Diameter(in)	0.471		0.471
Passage Length(in)		4.859	
Number of Channel		17	
Bypass Flow%	0.000		0.000

Element #: 6 DownComer

	(Inlet)		(Discharge)
Node Number	6		7
Blockage	1.000		1.000
Surface Roughness(in)		0.00030	
Hydraulic Diameter(in)	0.471		0.770
Passage Length(in)		3.200	
Number of Channel		17	
Bypass Flow%	0.000		0.000

Element #: 7 Turning Channel

	(Inlet)		(Discharge)
Node Number	7		8
Blockage	1.000		1.000
Surface Roughness(in)		0.00030	
Hydraulic Diameter(in)	0.770		0.601

Passage Length(in)		4.559	
Number of Channel		17	
Bypass Flow	0.000		0.000

Element #: 8 Impeller

	(Inlet)		(Discharge)
Node Number	8		9
Tip Diameter(in)	1.952		3.900
Hub Diameter(in)	1.351		3.900
Rms Diameter(in)	1.679		3.900
Area(in^2)	1.557		1.519
Solidity	3.192		2.703
Passage Width(in)	0.300		0.124
Blockage	0.950		0.900
Surface Roughness(in)		0.00030	
Number of Blades	4		8
Blade Angle(Deg)	12.000		30.000
Normal Thickness(in)	0.014		0.032
Blade Length(in)		4.140	
Bypass Flow%	0.000		0.000

Element #: 9 Vaneless Diffuser

	(Inlet)		(Discharge)
Node Number	9		10
Tip Diameter(in)	3.900		4.204
Hub Diameter(in)	3.900		4.204
Rms Diameter(in)	3.900		4.204
Area(in^2)	1.519		1.321
Solidity	0.000		0.000
Passage Width(in)	0.124		0.100
Blockage	0.900		0.950
Surface Roughness(in)		0.00030	
Bypass Flow%	0.000		0.000

Element #: 10 Vaned Diffuser

	(Inlet)		(Discharge)
Node Number	10		11
Tip Diameter(in)	4.204		5.493
Hub Diameter(in)	4.204		5.493
Rms Diameter(in)	4.204		5.493
Area(in^2)	1.321		2.847
Solidity	1.165		1.300
Passage Width(in)	0.100		0.165
Blockage	0.950		0.900
Surface Roughness(in)		0.00030	
Number of Blades	17		17
Blade Angle(Deg)	7.650		38.108
Normal Thickness(in)	0.014		0.312

Blade Length(in)		1.915	
Bypass Flow	0.000		0.000

Element #: 11 Turning Channel

	(Inlet)		(Discharge)
Node Number	11		12
Blockage	1.000		1.000
Surface Roughness(in)		0.00030	
Hydraulic Diameter(in)	0.471		0.471
Passage Length(in)		4.859	
Number of Channel		17	
Bypass Flow%	0.000		0.000

Element #: 12 DownComer

	(Inlet)		(Discharge)
Node Number	12		13
Blockage	1.000		1.000
Surface Roughness(in)		0.00030	
Hydraulic Diameter(in)	0.471		0.770
Passage Length(in)		3.200	
Number of Channel		17	
Bypass Flow%	0.000		0.000

Element #: 13 Turning Channel

	(Inlet)		(Discharge)
Node Number	13		14
Blockage	1.000		1.000
Surface Roughness(in)		0.00030	
Hydraulic Diameter(in)	0.770		0.601
Passage Length(in)		4.859	
Number of Channel		17	
Bypass Flow%	0.000		0.000

Element #: 14 Impeller

	(Inlet)		(Discharge)
Node Number	14		15
Tip Diameter(in)	1.952		3.900
Hub Diameter(in)	1.351		3.900
Rms Diameter(in)	1.679		3.900
Area(in^2)	1.557		1.519
Solidity	3.192		2.703
Passage Width(in)	0.300		0.124
Blockage	0.950		0.900
Surface Roughness(in)		0.00030	

Number of Blades	4		8
Blade Angle(Deg)	12.000		30.000
Normal Thickness(in)	0.014		0.032
Blade Length(in)		4.140	
Bypass Flow%	0.000		0.000

Element #: 15 Vaneless Diffuser

	(Inlet)		(Discharge)
Node Number	15		16
Tip Diameter(in)	3.900		4.204
Hub Diameter(in)	3.900		4.204
Rms Diameter(in)	3.900		4.204
Area(in^2)	1.519		1.321
Solidity	0.000		0.000
Passage Width(in)	0.124		0.100
Blockage	0.900		0.950
Surface Roughness(in)		0.00030	
Bypass Flow%	0.000		0.000

Element #: 16 Vaned Diffuser

	(Inlet)		(Discharge)
Node Number	16		17
Tip Diameter(in)	4.204		5.493
Hub Diameter(in)	4.204		5.493
Rms Diameter(in)	4.204		5.493
Area(in^2)	1.321		2.847
Solidity	1.165		1.300
Passage Width(in)	0.100		0.165
Blockage	0.950		0.900
Surface Roughness(in)		0.00030	
Number of Blades	17		17
Blade Angle(Deg)	7.650		38.108
Normal Thickness(in)	0.014		0.312
Blade Length(in)		0.905	
Bypass Flow%	0.000		0.000

Element #: 17 1-Discharge Volute

	(Inlet)		(Discharge)
Node Number	17		18
Blockage	0.950		0.900
Surface Roughness(in)		0.00030	
Throat Diameter(in)		5.540	
Throat Area(in^2)		15.010	
Bypass Flow%	0.000		0.000

Element #: 18 Leakage

	(Inlet)	(Discharge)
Front Shroud Clearance(in)	0.000	
Rear Shroud Clearance(in)	2.800	
Front Tip Leakage(in)	0.000	
Rear Tip Leakage(in)	0.000	
Front Wear Ring Clearance(in)	0.000	
Rear Wear Ring Clearance(in)	0.000	
Front Wear Ring Diameter(in)	6001.000	
Rear Wear Ring Diameter(in)	0.000	
Front Leakage Coefficient	0.1000	
Rear Leakage Coefficient	0.0000	
Rear Static Head Loss (%)	0.000	
Leakage Type	FS FWR	

Element #: 19 Leakage

	(Inlet)	(Discharge)
Front Shroud Clearance(in)	0.000	
Rear Shroud Clearance(in)	2.800	
Front Tip Leakage(in)	0.000	
Rear Tip Leakage(in)	0.000	
Front Wear Ring Clearance(in)	0.000	
Rear Wear Ring Clearance(in)	0.000	
Front Wear Ring Diameter(in)	6001.000	
Rear Wear Ring Diameter(in)	0.000	
Front Leakage Coefficient	0.1000	
Rear Leakage Coefficient	0.0000	
Rear Static Head Loss (%)	0.000	
Leakage Type	FS FWR	

Element #: 20 Leakage

	(Inlet)	(Discharge)
Front Shroud Clearance(in)	0.000	
Rear Shroud Clearance(in)	2.800	
Front Tip Leakage(in)	0.000	
Rear Tip Leakage(in)	0.000	
Front Wear Ring Clearance(in)	0.000	
Rear Wear Ring Clearance(in)	0.000	
Front Wear Ring Diameter(in)	6001.000	
Rear Wear Ring Diameter(in)	0.000	
Front Leakage Coefficient	0.1000	
Rear Leakage Coefficient	0.0000	
Rear Static Head Loss (%)	0.000	
Leakage Type	FS FWR	

Mark49 LH2 Turbopump

<Operating Condition>

Fluid Type : Hydrogen

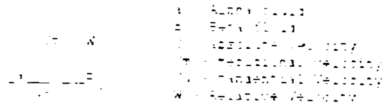
Operating Speed = 110000 rpm

Flow Rate (GPM)	Mass Flow Rate(lbm/s)	Flow Coef	NPSH Avail.(ft)
217.68	2.1760	0.0286	4898.64
284.84	2.8474	0.0374	5260.44
392.00	3.9186	0.0515	5736.14
436.00	4.3584	0.0573	5895.30
501.85	5.0167	0.0659	6094.17
614.71	6.1448	0.0808	6325.34
764.88	7.6460	0.1005	6419.97
850.25	8.4994	0.1117	6419.97
968.80	9.6844	0.1273	6151.60

Inlet Temperature(R)	40
Inlet Pressure(psi)	200
Inlet Tangential Velocity(ft/s)	0
Inlet Density(lbm/ft^3)	4.486
Inlet Viscosity(ft^2/s)	1.81E-06
Inlet Specific Heat(Btu/lbm-R)	17.635
Max. Impeller Head Coef.	.45
Max. Impeller Disch. Flow Coef.	.05
Impeller Clearance Torque Coef.	.01

<Velocity Triangle Output>

Operating Speed = 110000 rpm



Element # 1 :Inducer

(Inlet) Node # 1 Urms1 = 806.3222 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.026673	49.968	0.000	49.968	90.000	3.546	240.334	8.45
284.84	.034902	65.385	0.000	65.385	90.000	4.636	314.483	7.36
392.00	.048033	89.983	0.000	89.983	90.000	6.368	432.795	5.63
436.00	.053424	100.083	0.000	100.083	90.000	7.076	481.375	4.92
501.85	.061493	115.199	0.000	115.199	90.000	8.131	554.078	3.87
614.71	.075322	141.106	0.000	141.106	90.000	9.926	678.683	2.07
764.88	.093723	175.578	0.000	175.578	90.000	12.284	844.481	-0.28
850.25	.104184	195.174	0.000	195.174	90.000	13.607	938.736	-1.61
968.80	.118710	222.387	0.000	222.387	90.000	15.419	1069.623	-3.42

(Discharge) Node # 2 Urms2 = 862.9045 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.046680	87.449	665.374	671.096	7.487	23.879	199.485	2.12
284.84	.061082	114.429	604.431	615.167	10.720	23.879	261.032	2.12
392.00	.084062	157.478	507.190	531.075	17.249	23.879	359.235	2.12
436.00	.093497	175.154	467.263	499.013	20.549	23.879	399.557	2.12
501.85	.107618	201.608	407.508	454.653	26.323	23.879	459.903	2.12
614.71	.131821	246.948	305.095	392.513	38.987	23.879	563.330	2.12
764.88	.164024	307.275	168.826	350.600	61.214	23.879	700.948	2.12
850.25	.182331	341.571	91.358	353.578	75.026	23.879	779.183	2.12
968.80	.207753	389.196	-16.219	-389.534	-87.614	23.879	887.824	2.12

Element # 2 :Impeller

(Inlet) Node # 3 Urms1 = 806.3222 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.026673	49.968	712.066	713.817	4.014	27.929	240.334	-15.93
284.84	.034902	65.385	646.846	650.142	5.772	22.293	314.483	-10.29
392.00	.048033	89.983	542.781	550.190	9.413	18.852	432.795	-6.85
436.00	.053424	100.083	500.052	509.970	11.318	18.096	481.375	-6.10
501.85	.061493	115.199	436.104	451.063	14.797	17.284	554.078	-5.28
614.71	.075322	141.106	326.505	355.691	23.373	16.388	678.683	-4.39
764.88	.093723	175.578	180.673	251.933	44.181	15.676	844.481	-3.68
850.25	.104184	195.174	97.769	218.293	63.392	15.400	938.736	-3.40
968.80	.118710	222.387	17.357	223.063	-85.537	15.742	1069.623	-3.74

(Discharge) Node # 4 Urms2 = 1873.363 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.028596	53.571	1477.628	1478.598	2.076	7.709	107.142	22.29
284.84	.037419	70.099	1437.747	1439.455	2.791	9.142	140.199	20.86
392.00	.051496	96.471	1377.114	1380.489	4.007	11.001	192.943	19.00

436.00	.057277	[illegible]	1353.156	1357.403	4.534	11.655	[illegible]	18.33
501.85	.065927	[illegible]	1318.208	1323.981	5.353	12.542	[illegible]	17.46
614.71	.080754	151.281	1260.582	1269.627	6.843	13.868	302.561	16.13
764.88	.100481	188.238	1187.760	1202.583	9.005	15.353	376.475	14.65
850.25	.111696	209.247	1148.069	1166.982	10.329	16.093	418.494	13.31
968.80	.127270	238.422	1094.758	1120.420	12.286	17.026	476.845	12.37

Element # 3 :Vaneless Diffuser

(Inlet) Node # 5 Urms1 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.027269	51.084	1477.628	1478.510	1.980	1.980	51.084	-1.98
284.84	.035682	66.845	1437.747	1439.300	2.662	2.662	66.845	-2.66
392.00	.049105	91.992	1377.114	1380.183	3.822	3.822	91.992	-3.82
436.00	.054617	102.318	1353.156	1357.019	4.324	4.324	102.318	-4.32
501.85	.062866	117.771	1318.208	1323.458	5.105	5.105	117.771	-5.11
614.71	.077004	144.256	1260.582	1268.809	6.528	6.528	144.256	-6.53
764.88	.095816	179.497	1187.760	1201.246	8.594	8.594	179.497	-8.59
850.25	.106510	199.531	1148.069	1165.279	9.859	9.859	199.531	-9.86
968.80	.121360	227.352	1094.758	1118.116	11.732	11.732	227.352	-11.73

(Discharge) Node # 6 Urms2 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.029717	55.671	1370.777	1371.907	2.326	2.326	55.671	-2.33
284.84	.038885	72.846	1333.780	1335.768	3.126	3.126	72.846	-3.13
392.00	.053515	100.252	1277.532	1281.460	4.487	4.487	100.252	-4.49
436.00	.059521	111.505	1255.306	1260.249	5.076	5.076	111.505	-5.08
501.85	.068511	128.346	1222.885	1229.602	5.991	5.991	128.346	-5.99
614.71	.083918	157.209	1169.427	1179.947	7.657	7.657	157.209	-7.66
764.88	.104419	195.614	1101.870	1119.099	10.067	10.067	195.614	-10.07
850.25	.116073	217.447	1065.049	1087.021	11.539	11.539	217.447	-11.54
968.80	.132257	247.766	1015.594	1045.380	13.710	13.710	247.766	-13.71

Element # 4 :Vaned Diffuser

(Inlet) Node # 7 Urms1 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.034655	64.921	1370.777	1372.314	2.712	2.712	487.686	4.94
284.84	.045347	84.951	1333.780	1336.483	3.644	3.644	638.150	4.01
392.00	.062407	116.911	1277.532	1282.870	5.229	5.229	878.229	2.42
436.00	.069412	130.034	1255.306	1262.023	5.914	5.914	976.806	1.74
501.85	.079895	149.673	1222.885	1232.011	6.978	6.978	1124.335	0.67
614.71	.097863	183.333	1169.427	1183.710	8.910	8.910	1377.184	-1.26
764.88	.121770	228.120	1101.870	1125.237	11.697	11.697	1713.622	-4.05
850.25	.135361	253.581	1065.049	1094.821	13.392	13.392	1904.884	-5.74
968.80	.154235	288.937	1015.594	1055.896	15.881	15.881	2170.481	-8.23

(Discharge) Node # 8 Urms2 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.033408	62.584	109.629	126.235	29.721	29.721	101.410	8.39
284.84	.043715	81.893	143.452	165.182	29.721	29.721	132.697	8.39
392.00	.060161	112.703	197.420	227.325	29.721	29.721	182.619	8.39
436.00	.066913	125.353	219.580	252.841	29.721	29.721	203.117	8.39
501.85	.077019	144.285	252.744	291.028	29.721	29.721	233.794	8.39
614.71	.094340	176.733	309.582	356.477	29.721	29.721	286.372	8.39
764.88	.117387	219.908	385.212	443.562	29.721	29.721	356.331	8.39
850.25	.130489	244.453	428.206	493.069	29.721	29.721	396.102	8.39
968.80	.148683	278.537	487.911	561.818	29.721	29.721	451.330	8.39

Element # 5 :Turning Channel

(Inlet) Node # 9 Urms1 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle deg
217.68	.012588	23.582	109.629	112.136	12.140	12.140	23.582	-12.14
284.84	.016472	30.858	143.452	146.733	12.140	12.140	30.858	-12.14
392.00	.022669	42.467	197.420	201.936	12.140	12.140	42.467	-12.14
436.00	.025213	47.233	219.580	224.603	12.140	12.140	47.233	-12.14
501.85	.029021	54.367	252.744	258.525	12.140	12.140	54.367	-12.14
614.71	.035548	66.594	309.582	316.664	12.140	12.140	66.594	-12.14
764.88	.044232	82.862	385.212	394.023	12.140	12.140	82.862	-12.14
850.25	.049169	92.111	428.206	438.001	12.140	12.140	92.111	-12.14
968.80	.056024	104.954	487.911	499.071	12.140	12.140	104.954	-12.14

(Discharge) Node # 10 Urms2 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.012588	23.582	0.000	23.582	90.000	0.000	23.582	0.00
284.84	.016472	30.858	0.000	30.858	90.000	0.000	30.858	0.00
392.00	.022669	42.467	0.000	42.467	90.000	0.000	42.467	0.00
436.00	.025213	47.233	0.000	47.233	90.000	0.000	47.233	0.00
501.85	.029021	54.367	0.000	54.367	90.000	0.000	54.367	0.00
614.71	.035548	66.594	0.000	66.594	90.000	0.000	66.594	0.00
764.88	.044232	82.862	0.000	82.862	90.000	0.000	82.862	0.00
850.25	.049169	92.111	0.000	92.111	90.000	0.000	92.111	0.00
968.80	.056024	104.954	0.000	104.954	90.000	0.000	104.954	0.00

Element # 6 :DownComer

(Inlet) Node # 11 Urms1 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.012588	23.582	0.000	23.582	0.000	0.000	23.582	0.00
284.84	.016472	30.858	0.000	30.858	0.000	0.000	30.858	0.00
392.00	.022669	42.467	0.000	42.467	0.000	0.000	42.467	0.00
436.00	.025213	47.233	0.000	47.233	0.000	0.000	47.233	0.00
501.85	.029021	54.367	0.000	54.367	0.000	0.000	54.367	0.00
614.71	.035548	66.594	0.000	66.594	0.000	0.000	66.594	0.00
764.88	.044232	82.862	0.000	82.862	0.000	0.000	82.862	0.00
850.25	.049169	92.111	0.000	92.111	0.000	0.000	92.111	0.00
968.80	.056024	104.954	0.000	104.954	0.000	0.000	104.954	0.00

(Discharge) **Node #** 12 **Urms2 =** 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.012588	23.582	0.000	23.582	90.000	0.000	23.582	0.00
284.84	.016472	30.858	0.000	30.858	90.000	0.000	30.858	0.00
392.00	.022669	42.467	0.000	42.467	90.000	0.000	42.467	0.00
436.00	.025213	47.233	0.000	47.233	90.000	0.000	47.233	0.00
501.85	.029021	54.367	0.000	54.367	90.000	0.000	54.367	0.00
614.71	.035548	66.594	0.000	66.594	90.000	0.000	66.594	0.00
764.88	.044232	82.862	0.000	82.862	90.000	0.000	82.862	0.00
850.25	.049169	92.111	0.000	92.111	90.000	0.000	92.111	0.00
968.80	.056024	104.954	0.000	104.954	90.000	0.000	104.954	0.00

Element # 7 :Turning Channel

(Inlet) Node # 13 Urms1 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)

217.68	.004710	8.824	0.000	8.824	0.000	0.000	8.824	0.00
284.84	.006163	11.546	0.000	11.546	0.000	0.000	11.546	0.00
392.00	.008482	15.889	0.000	15.889	0.000	0.000	15.889	0.00
436.00	.009434	17.673	0.000	17.673	0.000	0.000	17.673	0.00
501.85	.010859	20.342	0.000	20.342	0.000	0.000	20.342	0.00
614.71	.013301	24.917	0.000	24.917	0.000	0.000	24.917	0.00
764.88	.016550	31.004	0.000	31.004	0.000	0.000	31.004	0.00
850.25	.018397	34.464	0.000	34.464	0.000	0.000	34.464	0.00
968.80	.020962	39.270	0.000	39.270	0.000	0.000	39.270	0.00

(Discharge) Node # 14 Urms2 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.007731	14.484	0.000	14.484	90.000	0.000	14.484	0.00
284.84	.010117	18.952	0.000	18.952	90.000	0.000	18.952	0.00
392.00	.013923	26.082	0.000	26.082	90.000	0.000	26.082	0.00
436.00	.015485	29.010	0.000	29.010	90.000	0.000	29.010	0.00
501.85	.017824	33.391	0.000	33.391	90.000	0.000	33.391	0.00
614.71	.021833	40.900	0.000	40.900	90.000	0.000	40.900	0.00
764.88	.027166	50.892	0.000	50.892	90.000	0.000	50.892	0.00
850.25	.030198	56.572	0.000	56.572	90.000	0.000	56.572	0.00
968.80	.034409	64.460	0.000	64.460	90.000	0.000	64.460	0.00

Element # 8 :Impeller

(Inlet) Node # 15 Urms1 = 806.3222 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.026673	49.968	0.000	49.968	90.000	3.546	240.334	8.45
284.84	.034902	65.385	0.000	65.385	90.000	4.636	314.483	7.36
392.00	.048033	89.983	0.000	89.983	90.000	6.368	432.795	5.63
436.00	.053424	100.083	0.000	100.083	90.000	7.076	481.375	4.92
501.85	.061493	115.199	0.000	115.199	90.000	8.131	554.078	3.87
614.71	.075322	141.106	0.000	141.106	90.000	9.926	678.683	2.07
764.88	.093723	175.578	0.000	175.578	90.000	12.284	844.481	-0.28
850.25	.104184	195.174	0.000	195.174	90.000	13.607	938.736	-1.61
968.80	.118710	222.387	0.000	222.387	90.000	15.419	1069.623	-3.42

(Discharge) Node # 16 Urms2 = 1873.363 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.028596	53.571	1477.628	1478.598	2.076	7.709	107.142	22.29
284.84	.037419	70.099	1437.747	1439.455	2.791	9.142	140.199	20.86
392.00	.051496	96.471	1377.114	1380.489	4.007	11.001	192.943	19.00
436.00	.057277	107.300	1353.156	1357.403	4.534	11.655	214.600	18.35
501.85	.065927	123.506	1318.208	1323.981	5.353	12.542	247.011	17.46
614.71	.080754	151.281	1260.582	1269.627	6.843	13.868	302.561	16.13
764.88	.100481	188.238	1187.760	1202.583	9.005	15.353	376.475	14.65
850.25	.111696	209.247	1148.069	1166.982	10.329	16.093	418.494	13.91
968.80	.127270	238.422	1094.758	1120.420	12.286	17.026	476.845	12.97

Element # 9 :Vaneless Diffuser

(Inlet) Node # 17 Urms1 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.027269	51.084	1477.628	1478.510	1.980	1.980	51.084	-1.98
284.84	.035682	66.845	1437.747	1439.300	2.662	2.662	66.845	-2.66
392.00	.049105	91.992	1377.114	1380.183	3.822	3.822	91.992	-3.82
436.00	.054617	102.318	1353.156	1357.019	4.324	4.324	102.318	-4.32
501.85	.062866	117.771	1318.208	1323.458	5.105	5.105	117.771	-5.11
614.71	.077004	144.256	1260.582	1268.809	6.528	6.528	144.256	-6.53

764.88	.095816	179.497	1187.760	1201.246	8.594	8.594	179.497	-8.59
850.25	.106510	199.531	1148.069	1165.279	9.859	9.859	199.531	-9.86
968.80	.121360	227.352	1094.758	1113.116	11.732	11.732	227.352	-11.73

(Discharge) Node # 18 Urms2 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.029717	55.671	1370.777	1371.907	2.326	2.326	55.671	-2.33
284.84	.038885	72.846	1333.780	1335.768	3.126	3.126	72.846	-3.13
392.00	.053515	100.252	1277.532	1281.460	4.487	4.487	100.252	-4.49
436.00	.059521	111.505	1255.306	1260.249	5.076	5.076	111.505	-5.08
501.85	.068511	128.346	1222.885	1229.602	5.991	5.991	128.346	-5.99
614.71	.083918	157.209	1169.427	1179.947	7.657	7.657	157.209	-7.66
764.88	.104419	195.614	1101.870	1119.099	10.067	10.067	195.614	-10.07
850.25	.116073	217.447	1065.049	1087.021	11.539	11.539	217.447	-11.54
968.80	.132257	247.766	1015.594	1045.380	13.710	13.710	247.766	-13.71

Element # 10 :Vaned Diffuser

(Inlet) Node # 19 Urms1 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.034655	64.921	1370.777	1372.314	2.712	2.712	487.686	4.94
284.84	.045347	84.951	1333.780	1336.483	3.644	3.644	638.150	4.01
392.00	.062407	116.911	1277.532	1282.870	5.229	5.229	878.229	2.42
436.00	.069412	130.034	1255.306	1262.023	5.914	5.914	976.806	1.74
501.85	.079895	149.673	1222.885	1232.011	6.978	6.978	1124.335	0.67
614.71	.097863	183.333	1169.427	1183.710	8.910	8.910	1377.184	-1.26
764.88	.121770	228.120	1101.870	1125.237	11.697	11.697	1713.622	-4.05
850.25	.135361	253.581	1065.049	1094.821	13.392	13.392	1904.884	-5.74
968.80	.154235	288.937	1015.594	1055.896	15.881	15.881	2170.481	-8.23

(Discharge) Node # 20 Urms2 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.032576	61.028	106.901	123.095	29.721	29.721	98.887	8.39
284.84	.042627	79.856	139.883	161.073	29.721	29.721	129.396	8.39
392.00	.058664	109.899	192.509	221.670	29.721	29.721	178.076	8.39
436.00	.065249	122.234	214.117	246.551	29.721	29.721	198.064	8.39
501.85	.075103	140.696	246.456	283.788	29.721	29.721	227.978	8.39
614.71	.091993	172.337	301.881	347.609	29.721	29.721	279.248	8.39
764.88	.114467	214.437	375.629	432.528	29.721	29.721	347.466	8.39
850.25	.127242	238.371	417.553	480.803	29.721	29.721	386.248	8.39
968.80	.144984	271.607	475.773	547.841	29.721	29.721	440.102	8.39

Element # 11 :Turning Channel

(Inlet) Node # 21 Urms1 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.012588	23.582	106.901	109.472	12.440	12.440	23.582	-12.44
284.84	.016472	30.858	139.883	143.247	12.440	12.440	30.858	-12.44
392.00	.022669	42.467	192.509	197.137	12.440	12.440	42.467	-12.44
436.00	.025213	47.233	214.117	219.265	12.440	12.440	47.233	-12.44
501.85	.029021	54.367	246.456	252.381	12.440	12.440	54.367	-12.44
614.71	.035548	66.594	301.881	309.139	12.440	12.440	66.594	-12.44
764.88	.044232	82.862	375.629	384.660	12.440	12.440	82.862	-12.44
850.25	.049169	92.111	417.553	427.592	12.440	12.440	92.111	-12.44
968.80	.056024	104.954	475.773	487.211	12.440	12.440	104.954	-12.44

(Discharge) Node # 22 Urms2 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.012588	23.582	0.000	23.582	90.000	0.000	23.582	0.00
284.84	.016472	30.858	0.000	30.858	90.000	0.000	30.858	0.00
392.00	.022669	42.467	0.000	42.467	90.000	0.000	42.467	0.00
436.00	.025213	47.233	0.000	47.233	90.000	0.000	47.233	0.00
501.85	.029021	54.367	0.000	54.367	90.000	0.000	54.367	0.00
614.71	.035548	66.594	0.000	66.594	90.000	0.000	66.594	0.00
764.88	.044232	82.862	0.000	82.862	90.000	0.000	82.862	0.00
850.25	.049169	92.111	0.000	92.111	90.000	0.000	92.111	0.00
968.80	.056024	104.954	0.000	104.954	90.000	0.000	104.954	0.00

Element # 12 :DownComer

(Inlet) Node # 23 Urms1 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.012588	23.582	0.000	23.582	0.000	0.000	23.582	0.00
284.84	.016472	30.858	0.000	30.858	0.000	0.000	30.858	0.00
392.00	.022669	42.467	0.000	42.467	0.000	0.000	42.467	0.00
436.00	.025213	47.233	0.000	47.233	0.000	0.000	47.233	0.00
501.85	.029021	54.367	0.000	54.367	0.000	0.000	54.367	0.00
614.71	.035548	66.594	0.000	66.594	0.000	0.000	66.594	0.00
764.88	.044232	82.862	0.000	82.862	0.000	0.000	82.862	0.00
850.25	.049169	92.111	0.000	92.111	0.000	0.000	92.111	0.00
968.80	.056024	104.954	0.000	104.954	0.000	0.000	104.954	0.00

(Discharge) Node # 24 Urms2 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.012588	23.582	0.000	23.582	90.000	0.000	23.582	0.00
284.84	.016472	30.858	0.000	30.858	90.000	0.000	30.858	0.00
392.00	.022669	42.467	0.000	42.467	90.000	0.000	42.467	0.00
436.00	.025213	47.233	0.000	47.233	90.000	0.000	47.233	0.00
501.85	.029021	54.367	0.000	54.367	90.000	0.000	54.367	0.00
614.71	.035548	66.594	0.000	66.594	90.000	0.000	66.594	0.00
764.88	.044232	82.862	0.000	82.862	90.000	0.000	82.862	0.00
850.25	.049169	92.111	0.000	92.111	90.000	0.000	92.111	0.00
968.80	.056024	104.954	0.000	104.954	90.000	0.000	104.954	0.00

Element # 13 :Turning Channel

(Inlet) Node # 25 Urms1 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.004710	8.824	0.000	8.824	0.000	0.000	8.824	0.00
284.84	.006163	11.546	0.000	11.546	0.000	0.000	11.546	0.00
392.00	.008482	15.889	0.000	15.889	0.000	0.000	15.889	0.00
436.00	.009434	17.673	0.000	17.673	0.000	0.000	17.673	0.00
501.85	.010859	20.342	0.000	20.342	0.000	0.000	20.342	0.00
614.71	.013301	24.917	0.000	24.917	0.000	0.000	24.917	0.00
764.88	.016550	31.004	0.000	31.004	0.000	0.000	31.004	0.00
850.25	.018397	34.464	0.000	34.464	0.000	0.000	34.464	0.00
968.80	.020962	39.270	0.000	39.270	0.000	0.000	39.270	0.00

(Discharge) Node # 26 Urms2 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.007731	14.484	0.000	14.484	90.000	0.000	14.484	0.00
284.84	.010117	18.952	0.000	18.952	90.000	0.000	18.952	0.00
392.00	.013923	26.082	0.000	26.082	90.000	0.000	26.082	0.00

436.00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.000	[illegible]	[illegible]
501.85	.017624	33.391	0.000	33.391	90.000	0.000	33.391	[illegible]
614.71	.021833	40.900	0.000	40.900	90.000	0.000	40.900	[illegible]
764.88	.027166	50.892	0.000	50.892	90.000	0.000	50.892	[illegible]
850.25	.030198	56.572	0.000	56.572	90.000	0.000	56.572	0.00
968.80	.034409	64.460	0.000	64.460	90.000	0.000	64.460	0.00

Element # 14 :Impeller

(Inlet) Node # 27 Urms1 = 806.3222 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.026673	49.968	0.000	49.968	90.000	3.546	240.334	8.45
284.84	.034902	65.385	0.000	65.385	90.000	4.636	314.483	7.36
392.00	.048033	89.983	0.000	89.983	90.000	6.368	432.795	5.63
436.00	.053424	100.083	0.000	100.083	90.000	7.076	481.375	4.92
501.85	.061493	115.199	0.000	115.199	90.000	8.131	554.078	3.87
614.71	.075322	141.106	0.000	141.106	90.000	9.926	678.683	2.07
764.88	.093723	175.578	0.000	175.578	90.000	12.284	844.481	-0.28
850.25	.104184	195.174	0.000	195.174	90.000	13.607	938.736	-1.61
968.80	.118710	222.387	0.000	222.387	90.000	15.419	1069.623	-3.42

(Discharge) Node # 28 Urms2 = 1873.363 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.028596	53.571	1477.628	1478.598	2.076	7.709	107.142	22.29
284.84	.037419	70.099	1437.747	1439.455	2.791	9.142	140.199	20.86
392.00	.051496	96.471	1377.114	1380.489	4.007	11.001	192.943	19.00
436.00	.057277	107.300	1353.156	1357.403	4.534	11.655	214.600	18.35
501.85	.065927	123.506	1318.208	1323.981	5.353	12.542	247.011	17.46
614.71	.080754	151.281	1260.582	1269.627	6.843	13.868	302.561	16.13
764.88	.100481	188.238	1187.760	1202.583	9.005	15.353	376.475	14.65
850.25	.111696	209.247	1148.069	1166.982	10.329	16.093	418.494	13.91
968.80	.127270	238.422	1094.758	1120.420	12.286	17.026	476.845	12.97

Element # 15 :Vaneless Diffuser

(Inlet) Node # 29 Urms1 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.027269	51.084	1477.628	1478.510	1.980	1.980	51.084	-1.98
284.84	.035682	66.845	1437.747	1439.300	2.662	2.662	66.845	-2.66
392.00	.049105	91.992	1377.114	1380.183	3.822	3.822	91.992	-3.82
436.00	.054617	102.318	1353.156	1357.019	4.324	4.324	102.318	-4.32
501.85	.062866	117.771	1318.208	1323.458	5.105	5.105	117.771	-5.11
614.71	.077004	144.256	1260.582	1268.809	6.528	6.528	144.256	-6.53
764.88	.095816	179.497	1187.760	1201.246	8.594	8.594	179.497	-8.59
850.25	.106510	199.531	1148.069	1165.279	9.859	9.859	199.531	-9.86
968.80	.121360	227.352	1094.758	1118.116	11.732	11.732	227.352	-11.73

(Discharge) Node # 30 Urms2 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.029717	55.671	1370.777	1371.907	2.326	2.326	55.671	-2.33
284.84	.038885	72.846	1333.780	1335.768	3.126	3.126	72.846	-3.13
392.00	.053515	100.252	1277.532	1281.460	4.487	4.487	100.252	-4.49
436.00	.059521	111.505	1255.306	1260.249	5.076	5.076	111.505	-5.08
501.85	.068511	128.346	1222.885	1229.602	5.991	5.991	128.346	-5.99
614.71	.083918	157.209	1169.427	1179.947	7.657	7.657	157.209	-7.66
764.88	.104419	195.614	1101.870	1119.099	10.067	10.067	195.614	-10.07
850.25	.116073	217.447	1065.049	1087.021	11.539	11.539	217.447	-11.54
968.80	.132257	247.766	1015.594	1045.380	13.710	13.710	247.766	-13.71

Element # 16 :Vaned Diffuser

(Inlet) Node # 31 Urms1 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.034655	64.921	1370.777	1372.314	2.712	2.712	487.686	4.94
284.84	.045347	84.951	1333.780	1336.483	3.644	3.644	638.150	4.01
392.00	.062407	116.911	1277.532	1282.870	5.229	5.229	878.229	2.42
436.00	.069412	130.034	1255.306	1262.023	5.914	5.914	976.806	1.74
501.85	.079895	149.673	1222.885	1232.011	6.978	6.978	1124.335	0.67
614.71	.097863	183.333	1169.427	1183.710	8.910	8.910	1377.184	-1.26
764.88	.121770	228.120	1101.870	1125.237	11.697	11.697	1713.622	-4.05
850.25	.135361	253.581	1065.049	1094.821	13.392	13.392	1904.884	-5.74
968.80	.154235	288.937	1015.594	1055.896	15.881	15.881	2170.481	-8.23

(Discharge) Node # 32 Urms2 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.032576	61.028	106.901	123.095	29.721	29.721	98.887	8.39
284.84	.042627	79.856	139.883	161.073	29.721	29.721	129.396	8.39
392.00	.058664	109.899	192.509	221.670	29.721	29.721	178.076	8.39
436.00	.065249	122.234	214.117	246.551	29.721	29.721	198.064	8.39
501.85	.075103	140.696	246.456	283.788	29.721	29.721	227.978	8.39
614.71	.091993	172.337	301.881	347.609	29.721	29.721	279.248	8.39
764.88	.114467	214.437	375.629	432.528	29.721	29.721	347.466	8.39
850.25	.127242	238.371	417.553	480.803	29.721	29.721	386.248	8.39
968.80	.144984	271.607	475.773	547.841	29.721	29.721	440.102	8.39

Element # 17 :1-Discharge Volute

(Inlet) Node # 33 Urms1 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.013784	25.822	106.901	123.095	29.721	29.721	25.822	-29.72
284.84	.018037	33.789	139.883	161.073	29.721	29.721	33.789	-29.72
392.00	.024822	46.501	192.509	221.670	29.721	29.721	46.501	-29.72
436.00	.027608	51.721	214.117	246.551	29.721	29.721	51.721	-29.72
501.85	.031778	59.532	246.456	283.788	29.721	29.721	59.532	-29.72
614.71	.038925	72.920	301.881	347.609	29.721	29.721	72.920	-29.72
764.88	.048434	90.734	375.629	432.528	29.721	29.721	90.734	-29.72
850.25	.053840	100.861	417.553	480.803	29.721	29.721	100.861	-29.72
968.80	.061346	114.924	475.773	547.841	29.721	29.721	114.924	-29.72

(Discharge) Node # 34 Urms2 = 0 (ft/s)

Flow Rate (GPM)	Flow Coef	Cm (ft/s)	Cu (ft/s)	C (ft/s)	Alpha/f (deg)	Beta/f (deg)	W (ft/s)	Dev Angle (deg)
217.68	.002760	5.171	0.000	5.171	90.000	90.000	5.171	-90.00
284.84	.003612	6.766	0.000	6.766	90.000	90.000	6.766	-90.00
392.00	.004970	9.311	0.000	9.311	90.000	90.000	9.311	-90.00
436.00	.005528	10.356	0.000	10.356	90.000	90.000	10.356	-90.00
501.85	.006363	11.920	0.000	11.920	90.000	90.000	11.920	-90.00
614.71	.007794	14.601	0.000	14.601	90.000	90.000	14.601	-90.00
764.88	.009698	18.168	0.000	18.168	90.000	90.000	18.168	-90.00
850.25	.010781	20.196	0.000	20.196	90.000	90.000	20.196	-90.00
968.80	.012284	23.012	0.000	23.012	90.000	90.000	23.012	-90.00

Element # 18 :Leakage

Element # 19 :Leakage

Element # 20 :Leakage

Mark49 LH2 Turbopump

<Element Losses>

Operating Speed = 110000 rpm

Element # 1 Inducer

<Inducer Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss	Euler Head Coef	Actual Head Coef
217.68	0.01395	0.00240	0.00344	0.01979	0.16360	0.14381
284.84	0.01063	0.00410	0.00273	0.01746	0.14862	0.13115
392.00	0.00627	0.00776	0.00177	0.01580	0.12471	0.10891
436.00	0.00481	0.00960	0.00144	0.01585	0.11489	0.09904
501.85	0.00299	0.01271	0.00101	0.01670	0.10020	0.08349
614.71	0.00087	0.01906	0.00045	0.02037	0.07502	0.05464
764.88	0.00000	0.02950	0.00005	0.02955	0.04151	0.01196
850.25	0.00000	0.03645	0.00000	0.03645	0.02246	-0.01399
968.80	0.00246	0.04731	0.00000	0.04977	-0.00399	-0.05376

Flow Rate (GPM)	Euler Head(ft)	St. Head Rise(ft)	Pres. Rise (psi)	Temp Rise deg (R)	Efficiency	Reynold's Number
217.68	17845.29	15686.87	488.69	1.14	0.87905	2.512E+06
284.84	16210.79	14305.87	445.67	1.04	0.88249	3.287E+06
392.00	13602.80	11879.53	370.08	0.87	0.87331	4.524E+06
436.00	12531.96	10803.45	336.56	0.79	0.86207	5.031E+06
501.85	10929.34	9107.41	283.72	0.66	0.83330	5.791E+06
614.71	8182.63	5960.52	185.69	0.43	0.72844	7.094E+06
764.88	4527.89	1304.10	40.63	0.10	0.28802	8.826E+06
850.25	2450.21	-1525.51	-47.52	-0.11	-0.62260	9.812E+06
968.80	-434.98	-5863.78	-182.67	-0.43	13.48057	1.118E+07

Flow Rate (GPM)	Friction Loss	Suction Specific Speed
217.68	0.02068	2262.8
284.84	0.02066	2588.5
392.00	0.02063	3036.6
436.00	0.02063	3202.5
501.85	0.02062	3435.8
614.71	0.02061	3802.6
764.88	0.02061	4241.7
850.25	0.02060	4472.1
968.80	0.02060	4773.8

Element # 2 Impeller

<Impeller Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss	Recirc. Loss	Clearance Loss
217.68	0.00085	0.00188	0.32850	0.33122	0.02469	0.00000
284.84	0.00094	0.00322	0.06052	0.06468	0.00383	0.00000
392.00	0.00109	0.00610	0.00866	0.01585	0.00000	0.00000
436.00	0.00116	0.00755	0.00436	0.01306	0.00000	0.00000
501.85	0.00126	0.01000	0.00163	0.01289	0.00000	0.00000
614.71	0.00145	0.01500	0.00029	0.01674	0.00000	0.00000
764.88	0.00172	0.02323	0.00001	0.02496	0.00000	0.00000
850.25	0.00188	0.02870	0.00000	0.03058	0.00000	0.00000

968.80	0.00283	0.03726	0.00000	0.04009	[illegible]	[illegible]

Flow Rate (GPM)	Theo/Inf Head Coef	Euler Head Coef	Ratio Euler/Infin	Head Rise (ft)	Actual Coef	Efficiency
217.68	0.78687	0.62516	0.79449	32061.56	0.29393	0.37355
284.84	0.78657	0.61885	0.78677	60448.49	0.55417	0.70454
392.00	0.78610	0.61040	0.77649	64852.33	0.59455	0.75633
436.00	0.78590	0.60742	0.77290	64832.00	0.59436	0.75628
501.85	0.78561	0.60346	0.76814	64418.85	0.59057	0.75174
614.71	0.78511	0.59788	0.76152	63390.23	0.58114	0.74020
764.88	0.78445	0.59252	0.75532	61908.50	0.56756	0.72351
850.25	0.78407	0.59038	0.75296	61061.77	0.55980	0.71396
968.80	0.78355	0.58039	0.74072	58935.56	0.54030	0.68956

Flow Rate (GPM)	Friction Loss	Suction Spec Speed	Pres. Rise (psi)	Temp. Rise (R)	Reynold's Number
217.68	0.02101	908.8	1019.11	15.8	1.040E+08
284.84	0.02101	1091.1	1921.42	29.78	1.392E+08
392.00	0.02101	1391.1	2033.67	31.93	1.994E+08
436.00	0.02101	1532.3	2027.84	31.91	2.257E+08
501.85	0.02101	1770.5	2005.19	31.7	2.672E+08
614.71	0.02101	2332.0	1984.23	33.4	3.448E+08
764.88	0.02101	3650.1	1899.23	32.59	4.634E+08
850.25	0.02101	5370.7	1851.21	32.12	5.398E+08
968.80	0.02101	29087.8	1770.26	30.97	6.608E+08

Element # 3 Vaneless Diffuser

<Vaneless Diffuser Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss Coef	Friction Loss	Reynold's Number
217.68	0.00000	0.13844	0.00000	0.13844	0.02172	4.354E+08
284.84	0.00000	0.09762	0.00000	0.09762	0.02172	2.686E+08
392.00	0.00000	0.06258	0.00000	0.06258	0.02172	2.527E+08
436.00	0.00000	0.05349	0.00000	0.05349	0.02172	2.537E+08
501.85	0.00000	0.04312	0.00000	0.04312	0.02172	2.576E+08
614.71	0.00000	0.03105	0.00000	0.03105	0.02172	2.632E+08
764.88	0.00000	0.02121	0.00000	0.02121	0.02172	2.818E+08
850.25	0.00000	0.01744	0.00000	0.01744	0.02172	2.940E+08
968.80	0.00000	0.01355	0.00000	0.01355	0.02172	3.168E+08

Flow Rate (GPM)	Pre. Rise (psi)	Temp. Rise (R)	Head Rise (ft)
217.68	-472.16	-3.62	-15101.15
284.84	-332.39	-1.16	-10648.69
392.00	-211.6	-.73	-6825.65
436.00	-180.31	-.63	-5834.26
501.85	-144.48	-.51	-4703.72
614.71	-101.92	-.37	-3386.76
764.88	-68.88	-.25	-2313.56
850.25	-55.86	-.21	-1902.17
968.80	-42.89	-.16	-1477.90

Element # 4 Vaned Diffuser

<Vaned Diffuser Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss Coef	Friction Loss	Reynold's Number
217.68	0.03366	0.00302	0.10037	0.13705	0.02438	3.474E+08

284.84	0.02102	0.00518	0.09056	0.11676	0.02438	1.991E+08
392.00	0.00708	0.00981	0.07538	0.09227	0.02438	1.755E+08
436.00	0.00000	0.01213	0.06937	0.08150	0.02438	1.736E+08
501.85	0.00000	0.01607	0.06068	0.07675	0.02438	1.731E+08
614.71	0.00000	0.02411	0.04681	0.07092	0.02438	1.712E+08
764.88	0.01521	0.03733	0.03079	0.08333	0.02438	1.828E+08
850.25	0.02894	0.04613	0.02313	0.09820	0.02438	1.899E+08
968.80	0.05512	0.05989	0.01438	0.12939	0.02438	2.040E+08

Flow Rate (GPM)	Pre. Rise (psi)	Temp. Rise (R)	Head Rise (ft)
217.68	-449.7	-5.06	-14949.60
284.84	-386.71	-1.4	-12735.94
392.00	-306.63	-1.08	-10064.27
436.00	-270.65	-.96	-8889.56
501.85	-254.	-.9	-8371.64
614.71	-230.62	-.84	-7735.66
764.88	-268.77	-.99	-9089.55
850.25	-312.68	-1.16	-10711.53
968.80	-407.53	-1.56	-14113.88

Element # 5 Turning Channel

<Turning Channel Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss Coef	Friction Loss	Reynold's Number
217.68	0.00000	0.00051	0.00000	0.00051	0.01765	7.965E+07
284.84	0.00000	0.00087	0.00000	0.00087	0.01765	5.930E+07
392.00	0.00000	0.00164	0.00000	0.00164	0.01765	7.194E+07
436.00	0.00000	0.00203	0.00000	0.00203	0.01765	7.884E+07
501.85	0.00000	0.00269	0.00000	0.00269	0.01764	9.186E+07
614.71	0.00000	0.00404	0.00000	0.00404	0.01764	1.157E+08
764.88	0.00000	0.00625	0.00000	0.00625	0.01764	1.632E+08
850.25	0.00000	0.00772	0.00000	0.00772	0.01764	1.982E+08
968.80	0.00000	0.01002	0.00000	0.01002	0.01764	2.645E+08

Flow Rate (GPM)	Pre. Rise (psi)	Temp. Rise (R)	Head Rise (ft)
217.68	-1.65	-.02	-55.21
284.84	-2.8	-.01	-94.54
392.00	-5.36	-.02	-179.04
436.00	-6.58	-.02	-221.48
501.85	-8.79	-.03	-293.44
614.71	-12.97	-.05	-440.24
764.88	-19.57	-.07	-681.60
850.25	-23.99	-.09	-842.23
968.80	-30.05	-.13	-1093.45

Element # 6 DownComer

<DownComer Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss Coef	Friction Loss	Reynold's Number
217.68	0.00000	0.00001	0.00000	0.00001	0.01765	2.770E+07
284.84	0.00000	0.00002	0.00000	0.00002	0.01766	2.064E+07
392.00	0.00000	0.00003	0.00000	0.00003	0.01765	2.507E+07
436.00	0.00000	0.00004	0.00000	0.00004	0.01765	2.749E+07
501.85	0.00000	0.00005	0.00000	0.00005	0.01766	3.207E+07
614.71	0.00000	0.00007	0.00000	0.00007	0.01765	4.050E+07

764.88	0.00000	0.00011	0.00000	0.00011	0.01765	5.729E+07
850.25	0.00000	0.00014	0.00000	0.00014	0.01765	6.376E+07
968.80	0.00000	0.00018	0.00000	0.00018	0.01764	9.341E+07

Flow Rate (GPM)	Pre. Rise (psi)	Temp. Rise (R)	Head Rise (ft)
217.68	-.03	.	-0.98
284.84	-.05	.	-1.67
392.00	-.09	.	-3.16
436.00	-.12	.	-3.91
501.85	-.16	.	-5.19
614.71	-.23	.	-7.79
764.88	-.35	.	-12.05
850.25	-.42	.	-14.89
968.80	-.53	.	-19.33

Element # 7 Turning Channel

<Turning Channel Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss Coef	Friction Loss	Reynold's Number
217.68	0.00000	0.00001	0.00000	0.00001	0.01583	2.238E+07
284.84	0.00000	0.00002	0.00000	0.00002	0.01583	1.667E+07
392.00	0.00000	0.00005	0.00000	0.00005	0.01583	2.026E+07
436.00	0.00000	0.00006	0.00000	0.00006	0.01583	2.221E+07
501.85	0.00000	0.00008	0.00000	0.00008	0.01582	2.591E+07
614.71	0.00000	0.00012	0.00000	0.00012	0.01581	3.272E+07
764.88	0.00000	0.00018	0.00000	0.00018	0.01582	4.629E+07
850.25	0.00000	0.00022	0.00000	0.00022	0.01581	5.637E+07
968.80	0.00000	0.00029	0.00000	0.00029	0.01581	7.548E+07

Flow Rate (GPM)	Pre. Rise (psi)	Temp. Rise (R)	Head Rise (ft)
217.68	-.05	.	-1.59
284.84	-.08	.	-2.72
392.00	-.15	.	-5.16
436.00	-.19	.	-6.38
501.85	-.25	.	-8.45
614.71	-.37	.	-12.69
764.88	-.56	.	-19.64
850.25	-.69	.	-24.27
968.80	-.86	.	-31.50

Element # 8 Impeller

<Impeller Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss	Recirc. Loss	Clearance Loss
217.68	0.01395	0.00188	0.00209	0.01792	0.02469	0.00000
284.84	0.01063	0.00322	0.00152	0.01537	0.00383	0.00000
392.00	0.00627	0.00610	0.00086	0.01323	0.00000	0.00000
436.00	0.00481	0.00755	0.00067	0.01302	0.00000	0.00000
501.85	0.00299	0.01000	0.00044	0.01343	0.00000	0.00000
614.71	0.00087	0.01500	0.00019	0.01606	0.00000	0.00000
764.88	0.00000	0.02323	0.00004	0.02327	0.00000	0.00000
850.25	0.00000	0.02870	0.00001	0.02871	0.00000	0.00000
968.80	0.00246	0.03726	0.00000	0.03972	0.00000	0.00000

Flow Rate	Theo/Inf	Euler	Ratio	Head Rise	Actual	Efficiency

(GPM)	Head Coef	Head Coef	Euler/Infin	(ft)	Coef	
217.68	0.95047	0.78876	0.82986	84081.44	0.77084	0.81100
284.84	0.93519	0.76747	0.82066	82037.73	0.75210	0.80422
392.00	0.91081	0.73510	0.80709	78740.46	0.72187	0.79256
436.00	0.90079	0.72231	0.80186	77368.10	0.70929	0.78740
501.85	0.88581	0.70366	0.79437	75289.41	0.69023	0.77921
614.71	0.86013	0.67290	0.78232	71646.73	0.65684	0.76365
764.88	0.82596	0.63403	0.76762	66620.38	0.61076	0.73945
850.25	0.80654	0.61284	0.75984	63715.57	0.58413	0.72424
968.80	0.77956	0.58438	0.74963	59410.59	0.54466	0.69967

Flow Rate (GPM)	Friction Loss	Suction Spec Speed	Pres. Rise (psi)	Temp. Rise (R)	Reynold's Number
217.68	0.02101	787.7	2514.85	32.75	9.882E+07
284.84	0.02101	470.1	2424.78	9.35	7.362E+07
392.00	0.02101	508.8	2356.53	8.66	8.944E+07
436.00	0.02101	532.5	2321.42	8.5	9.808E+07
501.85	0.02101	575.5	2253.54	8.28	1.144E+08
614.71	0.02101	642.2	2108.32	7.78	1.445E+08
764.88	0.02101	772.4	1908.37	7.27	2.045E+08
850.25	0.02101	873.0	1809.41	7.08	2.490E+08
968.80	0.02101	1057.5	1619.7	6.86	3.334E+08

Element # 9 Vaneless Diffuser

<Vaneless Diffuser Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss Coef	Friction Loss	Reynold's Number
217.68	0.00000	0.13845	0.00000	0.13845	0.02172	1.871E+08
284.84	0.00000	0.09764	0.00000	0.09764	0.02172	1.088E+08
392.00	0.00000	0.06258	0.00000	0.06258	0.02172	9.549E+07
436.00	0.00000	0.05349	0.00000	0.05349	0.02172	9.433E+07
501.85	0.00000	0.04313	0.00000	0.04313	0.02172	9.668E+07
614.71	0.00000	0.03105	0.00000	0.03105	0.02172	1.033E+08
764.88	0.00000	0.02121	0.00000	0.02121	0.02172	1.237E+08
850.25	0.00000	0.01744	0.00000	0.01744	0.02172	1.387E+08
968.80	0.00000	0.01355	0.00000	0.01355	0.02172	1.731E+08

Flow Rate (GPM)	Pre. Rise (psi)	Temp. Rise (R)	Head Rise (ft)
217.68	-470.95	-1.9	-15102.20
284.84	-357.37	-1.16	-10649.95
392.00	-229.35	-.78	-6826.60
436.00	-195.95	-.67	-5835.09
501.85	-157.23	-.54	-4704.37
614.71	-111.37	-.42	-3387.19
764.88	-74.9	-.27	-2313.79
850.25	-60.82	-.21	-1902.34
968.80	-46.08	-.16	-1477.98

Element # 10 Vaned Diffuser

<Vaned Diffuser Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss Coef	Friction Loss	Reynold's Number
217.68	0.03366	0.00295	0.10110	0.13772	0.02427	1.517E+08
284.84	0.02102	0.00506	0.09148	0.11756	0.02427	8.305E+07
392.00	0.00708	0.00958	0.07654	0.09321	0.02428	6.817E+07
436.00	0.00000	0.01186	0.07061	0.08247	0.02428	6.618E+07

501.85	0.00000	0.01571	0.06202	0.07773	0.02428	6.651E+07
614.71	0.00000	0.02357	0.04825	0.07182	0.02428	6.945E+07
764.88	0.01521	0.03648	0.03223	0.08392	0.02427	8.188E+07
850.25	0.02894	0.04508	0.02449	0.09852	0.02427	9.129E+07
968.80	0.05512	0.05853	0.01557	0.12921	0.02427	1.136E+08

Flow Rate (GPM)	Pre. Rise (psi)	Temp. Rise (R)	Head Rise (ft)
217.68	-456.21	-1.78	-15021.76
284.84	-426.3	-1.36	-12823.15
392.00	-337.87	-1.17	-10167.13
436.00	-299.28	-1.03	-8995.63
501.85	-281.38	-.97	-8478.83
614.71	-258.04	-.9	-7833.98
764.88	-293.91	-1.06	-9154.24
850.25	-342.21	-1.19	-10746.10
968.80	-437.9	-1.53	-14094.31

Element # 11 Turning Channel

<Turning Channel Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss Coef	Friction Loss	Reynold's Number
217.68	0.00000	0.00049	0.00000	0.00049	0.01766	3.364E+07
284.84	0.00000	0.00083	0.00000	0.00083	0.01766	2.436E+07
392.00	0.00000	0.00158	0.00000	0.00158	0.01765	2.736E+07
436.00	0.00000	0.00195	0.00000	0.00195	0.01765	2.942E+07
501.85	0.00000	0.00259	0.00000	0.00259	0.01766	3.453E+07
614.71	0.00000	0.00388	0.00000	0.00388	0.01765	4.540E+07
764.88	0.00000	0.00601	0.00000	0.00601	0.01765	7.141E+07
850.25	0.00000	0.00742	0.00000	0.00742	0.01764	9.332E+07
968.80	0.00000	0.00963	0.00000	0.00963	0.01764	1.443E+08

Flow Rate (GPM)	Pre. Rise (psi)	Temp. Rise (R)	Head Rise (ft)
217.68	-1.56	-.01	-53.07
284.84	-2.94	-.01	-90.87
392.00	-5.67	-.02	-172.09
436.00	-7.03	-.02	-212.88
501.85	-9.3	-.03	-282.07
614.71	-13.75	-.05	-423.18
764.88	-20.81	-.07	-655.15
850.25	-25.4	-.09	-809.52
968.80	-31.83	-.11	-1050.97

Element # 12 DownComer

<DownComer Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss Coef	Friction Loss	Reynold's Number
217.68	0.00000	0.00001	0.00000	0.00001	0.01767	1.193E+07
284.84	0.00000	0.00002	0.00000	0.00002	0.01769	8.650E+06
392.00	0.00000	0.00003	0.00000	0.00003	0.01768	9.727E+06
436.00	0.00000	0.00004	0.00000	0.00004	0.01768	1.047E+07
501.85	0.00000	0.00005	0.00000	0.00005	0.01767	1.230E+07
614.71	0.00000	0.00007	0.00000	0.00007	0.01767	1.621E+07
764.88	0.00000	0.00011	0.00000	0.00011	0.01765	2.559E+07
850.25	0.00000	0.00014	0.00000	0.00014	0.01766	3.353E+07
968.80	0.00000	0.00018	0.00000	0.00018	0.01765	5.202E+07

Flow Rate (GPM)	Pre. Rise (psi)	Temp. Rise (R)	Head Rise (ft)
217.68	-.03	.	-0.98
284.84	-.05	.	-1.67
392.00	-.1	.	-3.17
436.00	-.13	.	-3.92
501.85	-.17	.	-5.20
614.71	-.25	.	-7.80
764.88	-.38	.	-12.05
850.25	-.47	.	-14.90
968.80	-.58	.	-19.34

Element # 13 Turning Channel

<Turning Channel Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss Coef	Friction Loss	Reynold's Number
217.68	0.00000	0.00001	0.00000	0.00001	0.01587	9.642E+06
284.84	0.00000	0.00002	0.00000	0.00002	0.01589	6.988E+06
392.00	0.00000	0.00005	0.00000	0.00005	0.01588	7.859E+06
436.00	0.00000	0.00006	0.00000	0.00006	0.01587	8.457E+06
501.85	0.00000	0.00008	0.00000	0.00008	0.01587	9.938E+06
614.71	0.00000	0.00012	0.00000	0.00012	0.01585	1.310E+07
764.88	0.00000	0.00018	0.00000	0.00018	0.01583	2.068E+07
850.25	0.00000	0.00022	0.00000	0.00022	0.01582	2.709E+07
968.80	0.00000	0.00029	0.00000	0.00029	0.01581	4.204E+07

Flow Rate (GPM)	Pre. Rise (psi)	Temp. Rise (R)	Head Rise (ft)
217.68	-.05	.	-1.59
284.84	-.09	.	-2.73
392.00	-.17	.	-5.16
436.00	-.21	.	-6.38
501.85	-.28	.	-8.46
614.71	-.41	.	-12.69
764.88	-.62	.	-19.64
850.25	-.76	.	-24.27
968.80	-.95	.	-31.50

Element # 14 Impeller

<Impeller Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss	Recirc. Loss	Clearance Loss
217.68	0.01395	0.00188	0.00209	0.01792	0.02469	0.00000
284.84	0.01063	0.00322	0.00152	0.01537	0.00383	0.00000
392.00	0.00627	0.00610	0.00086	0.01323	0.00000	0.00000
436.00	0.00481	0.00755	0.00067	0.01303	0.00000	0.00000
501.85	0.00299	0.01000	0.00044	0.01343	0.00000	0.00000
614.71	0.00087	0.01501	0.00019	0.01606	0.00000	0.00000
764.88	0.00000	0.02323	0.00004	0.02327	0.00000	0.00000
850.25	0.00000	0.02870	0.00001	0.02871	0.00000	0.00000
968.80	0.00246	0.03726	0.00000	0.03972	0.00000	0.00000

Flow Rate (GPM)	Theo/Inf Head Coef	Euler Head Coef	Ratio Euler/Infin	Head Rise (ft)	Actual Coef	Efficiency
217.68	0.95047	0.78876	0.82986	84081.38	0.77083	0.81100
284.84	0.93519	0.76747	0.82066	82037.59	0.75210	0.80422
392.00	0.91081	0.73510	0.80709	78740.21	0.72187	0.79256
436.00	0.90079	0.72231	0.80186	77367.80	0.70929	0.78740

501.85	0.88581	0.70366	0.79437	75299.07	0.69123	0.77921
614.71	0.86013	0.67290	0.78232	71646.36	0.65683	0.76364
764.88	0.82596	0.63403	0.76762	66620.02	0.61075	0.73945
850.25	0.80654	0.61284	0.75984	63715.25	0.58412	0.72424
968.80	0.77956	0.58438	0.74963	59410.34	0.54466	0.69367

Flow Rate (GPM)	Friction Loss	Suction Spec Speed	Pres. Rise (psi)	Temp. Rise (R)	Reynold's Number
217.68	0.02102	339.8	2477.6	9.53	4.257E+07
284.84	0.02102	312.4	2654.74	8.78	3.085E+07
392.00	0.02102	343.5	2592.21	8.64	3.470E+07
436.00	0.02102	358.8	2554.97	8.48	3.734E+07
501.85	0.02102	387.3	2481.49	8.26	4.388E+07
614.71	0.02101	435.6	2326.88	8.31	5.784E+07
764.88	0.02101	525.3	2113.27	7.4	9.134E+07
850.25	0.02101	590.6	1995.66	6.89	1.197E+08
968.80	0.02101	721.5	1793.99	6.4	1.857E+08

Element # 15 Vaneless Diffuser

<Vaneless Diffuser Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss Coef	Friction Loss	Reynold's Number
217.68	0.00000	0.13847	0.00000	0.13847	0.02172	8.220E+07
284.84	0.00000	0.09767	0.00000	0.09767	0.02173	4.035E+07
392.00	0.00000	0.06261	0.00000	0.06261	0.02173	3.269E+07
436.00	0.00000	0.05352	0.00000	0.05352	0.02173	3.173E+07
501.85	0.00000	0.04315	0.00000	0.04315	0.02173	3.285E+07
614.71	0.00000	0.03106	0.00000	0.03106	0.02173	3.681E+07
764.88	0.00000	0.02122	0.00000	0.02122	0.02173	4.958E+07
850.25	0.00000	0.01744	0.00000	0.01744	0.02172	6.038E+07
968.80	0.00000	0.01355	0.00000	0.01355	0.02172	8.791E+07

Flow Rate (GPM)	Pre. Rise (psi)	Temp. Rise (R)	Head Rise (ft)
217.68	-504.84	-2.82	-15104.35
284.84	-378.71	-1.62	-10653.20
392.00	-244.32	-1.25	-6829.23
436.00	-209.02	-1.07	-5837.42
501.85	-167.84	-.86	-4706.19
614.71	-119.52	-.62	-3388.34
764.88	-79.91	-.36	-2314.34
850.25	-64.84	-.26	-1902.70
968.80	-48.77	-.18	-1478.16

Element # 16 Vaned Diffuser

<Vaned Diffuser Losses>

Flow Rate (GPM)	Incidence Loss	Skin Fric Loss	Diffusion Loss	Total Loss Coef	Friction Loss	Reynold's Number
217.68	0.03366	0.00296	0.10110	0.13772	0.02428	6.785E+07
284.84	0.02102	0.00506	0.09148	0.11756	0.02428	3.116E+07
392.00	0.00708	0.00959	0.07654	0.09321	0.02428	2.353E+07
436.00	0.00000	0.01186	0.07061	0.08247	0.02429	2.242E+07
501.85	0.00000	0.01571	0.06202	0.07774	0.02428	2.273E+07
614.71	0.00000	0.02357	0.04825	0.07183	0.02428	2.486E+07
764.88	0.01521	0.03649	0.03223	0.08393	0.02428	3.289E+07
850.25	0.02894	0.04509	0.02449	0.09853	0.02428	3.983E+07
968.80	0.05512	0.05854	0.01557	0.12922	0.02428	5.774E+07

Flow Rate (GPM)	Pre. Rise (psi)	Temp. Rise (R)	Head Rise (ft)
217.68	-491.94	-2.35	-15021.80
284.84	-451.74	-1.71	-12823.30
392.00	-362.42	-1.54	-10167.50
436.00	-321.38	-1.36	-8996.13
501.85	-302.13	-1.29	-8479.47
614.71	-275.09	-1.44	-7834.84
764.88	-315.03	-1.41	-9155.20
850.25	-365.11	-1.45	-10747.03
968.80	-467.23	-1.62	-14095.07

Element # 17 1-Discharge Volute

<1-Discharge Volute Losses>

Flow Rate (GPM)	Incidence Loss	S.Skin Fri Loss	Diffusion Loss	Momentum Loss	Total Loss	Friction's Loss
217.68	0.00000	0.00019	0.05896	0.00093	0.06008	1.118E-02
284.84	0.00000	0.00033	0.05896	0.00160	0.06088	1.119E-02
392.00	0.00000	0.00062	0.05896	0.00302	0.06260	1.119E-02
436.00	0.00000	0.00077	0.05896	0.00374	0.06347	1.119E-02
501.85	0.00000	0.00102	0.05896	0.00496	0.06493	1.118E-02
614.71	0.00000	0.00153	0.05896	0.00744	0.06792	1.117E-02
764.88	0.00000	0.00237	0.05896	0.01152	0.07284	1.117E-02
850.25	0.00000	0.00293	0.05896	0.01423	0.07611	1.117E-02
968.80	0.00000	0.00380	0.05896	0.01847	0.08123	1.116E-02

Flow Rate (GPM)	Pre. Rise (psi)	Temp. Rise (R)	Head Rise (ft)	Reynold's Number
217.68	-212.42	-.82	-6553.45	1.373E+08
284.84	-230.98	-.8	-6640.89	8.289E+07
392.00	-241.4	-.91	-6828.72	8.558E+07
436.00	-244.36	-1.06	-6923.06	9.021E+07
501.85	-249.49	-1.08	-7082.94	1.067E+08
614.71	-258.73	-1.13	-7409.11	1.467E+08
764.88	-271.17	-1.07	-7945.48	2.596E+08
850.25	-278.79	-1.02	-8302.34	3.688E+08
968.80	-286.77	-1.03	-8860.45	6.668E+08

Element # 18 Leakage

<Leakage Output>

Total Leakage (ft^3/s)	QLeakF1 (ft^3/s)	QLeakF2 (ft^3/s)	QLeakR1 (ft^3/s)	QLeakR2 (ft^3/s)
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000

Total (lb-ft/s)	HPBRF (lb-ft/s)	HPDFF (lb-ft/s)	HPDFR (lb-ft/s)	HPBRR (lb-ft/s)	Leakage Power Loss
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000

0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000

Element # 19 Leakage

<Leakage Output>

Total Leakage (ft^3/s)	QLeakF1 (ft^3/s)	QLeakF2 (ft^3/s)	QLeakR1 (ft^3/s)	QLeakR2 (ft^3/s)
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000

Total (lb-ft/s)	HPBRF (lb-ft/s)	HPDFF (lb-ft/s)	HPDFR (lb-ft/s)	HPBRR (lb-ft/s)	Leakage Power Loss
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000

Element # 20 Leakage

<Leakage Output>

Total Leakage (ft^3/s)	QLeakF1 (ft^3/s)	QLeakF2 (ft^3/s)	QLeakR1 (ft^3/s)	QLeakR2 (ft^3/s)
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000
0.000000	0.00000	0.000000	0.00000	0.00000

Total (lb-ft/s)	HPBRF (lb-ft/s)	HPDFF (lb-ft/s)	HPDFR (lb-ft/s)	HPBRR (lb-ft/s)	Leakage Power Loss
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000

0.000000	0.00000	0.000000	0.00000	0.00000	0.0000
0.000000	0.00000	0.000000	0.00000	0.00000	0.0000

Mark49 LH2 Turbopump

<Element Performance>

Operating Speed= 110000 rpm

Element # 1 Inducer

(Inlet) Node # : 1

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
217.68	2.176	40.00	198.79	1.21	200.00	4.49	6381.17	38.80	6419.97
284.84	2.847	40.00	197.93	2.07	200.00	4.49	6353.53	66.44	6419.97
392.00	3.919	40.00	196.08	3.92	200.00	4.49	6294.14	125.83	6419.97
436.00	4.358	40.00	195.15	4.85	200.00	4.49	6264.31	155.66	6419.97
501.85	5.017	40.00	193.58	6.42	200.00	4.49	6213.74	206.24	6419.97
614.71	6.145	40.00	190.36	9.64	200.00	4.49	6110.55	309.43	6419.97
764.88	7.646	40.00	185.08	14.92	200.00	4.49	5940.90	479.07	6419.97
850.25	8.499	40.00	181.56	18.44	200.00	4.49	5827.99	591.98	6419.97
968.80	9.684	40.00	176.06	23.94	200.00	4.49	5651.40	768.57	6419.97

(Discharge) Node # : 2

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
213.34	2.176	41.14	470.65	218.04	688.69	4.58	15107.87	6998.97	22106.85
279.17	2.847	41.04	462.46	183.21	645.67	4.58	14844.84	5881.00	20725.84
389.43	3.919	40.87	433.54	136.54	570.08	4.52	13916.44	4383.06	18299.50
434.25	4.358	40.79	416.00	120.55	536.56	4.50	13353.62	3869.80	17223.42
502.26	5.017	40.66	383.65	100.07	483.72	4.48	12315.03	3212.36	15527.38
611.78	6.145	40.43	311.10	74.59	385.69	4.51	9986.22	2394.26	12380.49
776.72	7.646	40.10	181.12	59.51	240.63	4.42	5813.83	1910.24	7724.07
873.69	8.499	39.89	91.95	60.52	152.48	4.37	2951.63	1942.83	4894.46
1004.78	9.684	39.57	-56.13	73.46	17.33	4.33	-1801.87	2358.07	556.20

Element # 2 Impeller

(Inlet) Node # : 2

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
213.34	2.176	41.14	436.99	251.70	688.69	4.58	13747.99	7918.42	21666.40
279.17	2.847	41.04	436.87	208.79	645.67	4.58	13744.20	6568.73	20312.92
389.43	3.919	40.87	422.56	147.52	570.08	4.52	13475.22	4704.24	18179.46
434.25	4.358	40.79	410.14	126.41	536.56	4.50	13112.67	4041.60	17154.27
502.26	5.017	40.66	385.30	98.42	483.72	4.48	12378.22	3161.84	15540.06
611.78	6.145	40.43	324.14	61.54	385.69	4.51	10355.42	1966.13	12321.55
776.72	7.646	40.10	210.37	30.26	240.63	4.42	6857.27	986.36	7843.63
873.69	8.499	39.89	130.03	22.45	152.48	4.37	4288.85	740.53	5029.38
1004.78	9.684	39.57	-5.90	23.23	17.33	4.33	-196.40	773.25	576.85

(Discharge) Node # : 3

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
216.89	2.176	56.95	627.85	1079.95	1707.80	4.50	19752.50	33975.46	53727.97
284.28	2.847	70.83	1543.56	1023.52	2567.09	4.49	48561.04	32200.38	80761.41
393.92	3.919	72.80	1675.03	928.72	2603.75	4.46	53415.50	29616.29	83031.80
439.50	4.358	72.70	1668.77	895.63	2564.40	4.45	53352.21	28634.05	81986.27
508.98	5.017	72.36	1640.96	847.95	2488.91	4.42	52717.57	27241.34	79958.91
636.34	6.145	73.84	1585.79	784.13	2369.92	4.33	50661.22	25050.56	75711.78
800.37	7.646	72.68	1450.37	689.48	2139.85	4.29	47277.36	22474.77	69752.13
902.01	8.499	72.01	1362.07	641.62	2003.69	4.23	44927.38	21163.77	66091.14
1040.04	9.684	70.55	1201.61	585.99	1787.59	4.18	40003.80	19508.62	59512.41

Element # 3 Vaneless Diffuser

(Inlet) Node # : 3

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
216.89	2.176	56.95	645.64	1062.16	1707.80	4.50	20649.92	33971.42	54621.34
284.28	2.847	70.83	1562.18	1004.90	2567.09	4.49	50046.70	32193.45	82240.15
393.92	3.919	72.80	1686.01	917.74	2603.75	4.46	54385.26	29603.18	83988.44
439.50	4.358	72.70	1679.97	884.43	2564.40	4.45	54359.31	28617.82	82977.13
508.98	5.017	72.36	1652.82	836.09	2488.91	4.42	53809.48	27219.84	81029.32
636.34	6.145	73.84	1617.01	752.90	2369.92	4.33	53732.05	25018.30	78750.35
800.37	7.646	72.68	1472.23	667.62	2139.85	4.29	49451.09	22424.83	71875.92
902.01	8.499	72.01	1384.03	619.66	2003.69	4.23	47131.83	21102.05	68233.88
1040.04	9.684	70.55	1223.80	563.79	1787.59	4.18	42172.37	19428.49	61600.86

(Discharge) Node # : 4

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
225.43	2.176	53.33	321.13	914.51	1235.65	4.33	10270.96	29249.23	39520.19
292.25	2.847	69.67	1369.16	865.53	2234.69	4.37	43862.91	27728.55	71591.47
400.83	3.919	72.07	1601.00	791.14	2392.15	4.39	51643.14	25519.65	77162.79
446.13	4.358	72.07	1621.30	762.79	2384.09	4.38	52461.03	24681.84	77142.88
515.29	5.017	71.85	1622.72	721.71	2344.43	4.37	52829.59	23496.02	76325.60
642.34	6.145	73.47	1616.86	651.13	2267.99	4.29	53726.96	21636.63	75363.59
805.85	7.646	72.43	1491.54	579.43	2070.97	4.26	50099.70	19462.66	69562.36
907.39	8.499	71.80	1408.61	539.23	1947.83	4.20	47968.84	18362.86	66331.70
1045.25	9.684	70.38	1251.88	492.83	1744.70	4.16	43140.01	16982.95	60122.96

Element # 4 Vaned Diffuser

(Inlet) Node # : 4

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
225.43	2.176	53.33	355.27	880.37	1235.65	4.33	11810.45	29266.57	41077.02
292.25	2.847	69.67	1391.86	842.83	2234.69	4.37	45840.04	27758.23	73598.27
400.83	3.919	72.07	1612.93	779.21	2392.15	4.39	52940.75	25575.87	78516.62
446.13	4.358	72.07	1630.52	753.57	2384.09	4.38	53555.18	24751.39	78306.57
515.29	5.017	71.85	1628.76	715.68	2344.43	4.37	53682.65	23588.16	77270.80
642.34	6.145	73.47	1618.82	649.17	2267.99	4.29	54299.20	21774.88	76074.08
805.85	7.646	72.43	1489.16	581.82	2070.97	4.26	50362.24	19676.71	70038.95
907.39	8.499	71.80	1404.08	543.75	1947.83	4.20	48099.71	18627.36	66727.07
1045.25	9.684	70.38	1244.42	500.29	1744.70	4.16	43097.64	17326.35	60423.98

(Discharge) Node # : 5

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
226.71	2.176	48.26	778.49	7.45	785.94	4.31	25879.78	247.64	26127.42
300.13	2.847	68.27	1835.11	12.87	1847.99	4.26	60438.31	424.02	60862.34
407.82	3.919	70.98	2061.05	24.47	2085.52	4.31	67649.26	803.09	68452.34
457.41	4.358	71.12	2083.19	30.25	2113.44	4.28	68423.52	993.48	69417.01
521.86	5.017	70.95	2050.50	39.94	2090.43	4.31	67582.92	1316.24	68899.16
649.86	6.145	72.63	1978.50	58.88	2037.37	4.24	66363.59	1974.83	68338.42
829.81	7.646	71.45	1711.80	90.41	1802.21	4.13	57891.84	3057.55	60949.40
929.73	8.499	70.64	1524.86	110.29	1635.15	4.10	52237.37	3778.17	56015.54
1098.07	9.684	68.82	1195.54	141.63	1337.17	3.96	41404.92	4905.19	46310.11

Element # 5 Turning Channel

(Inlet) Node # : 5

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
226.71	2.176	48.26	780.10	5.85	785.94	4.31	26079.53	195.42	26274.94

300.13	2.847	68.27	1838.09	9.89	1847.99	4.26	62168.98	334.60	62503.58
407.82	3.919	70.98	2066.54	18.98	2085.52	4.31	69013.30	633.71	69647.02
457.41	4.358	71.12	2090.16	23.28	2113.44	4.28	70388.88	783.96	71172.84
521.86	5.017	70.95	2059.31	31.12	2090.43	4.31	68739.22	1038.65	69777.87
649.86	6.145	72.63	1991.45	45.92	2037.37	4.24	67580.48	1558.34	69138.81
829.81	7.646	71.45	1732.92	69.28	1802.21	4.13	60348.79	2412.73	62761.52
929.73	8.499	70.64	1550.21	84.94	1635.15	4.10	54413.04	2981.36	57394.40
1098.07	9.684	68.82	1230.79	106.39	1337.17	3.96	44779.63	3870.70	48650.33

(Discharge) Node # : 6

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
226.73	2.176	48.24	784.03	0.26	784.29	4.31	26211.09	8.64	26219.73
300.22	2.847	68.26	1844.75	0.44	1845.19	4.26	62394.25	14.80	62409.04
408.03	3.919	70.96	2079.32	0.84	2080.16	4.31	69439.95	28.02	69467.98
452.67	4.358	71.09	2105.83	1.03	2106.86	4.32	70916.68	34.67	70951.35
522.30	5.017	70.92	2080.26	1.38	2081.64	4.31	69438.49	45.94	69484.43
650.73	6.145	72.59	2022.37	2.03	2024.40	4.24	68629.66	68.91	68698.57
831.74	7.646	71.37	1779.57	3.06	1782.63	4.13	61973.21	106.70	62079.92
932.59	8.499	70.55	1607.40	3.76	1611.16	4.09	56420.32	131.85	56552.17
1106.64	9.684	68.69	1302.42	4.71	1307.12	3.93	47385.69	171.18	47556.88

Element # 6 DownComer

(Inlet) Node # : 6

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
226.73	2.176	48.24	784.03	0.26	784.29	4.31	26213.23	8.64	26221.88
300.22	2.847	68.26	1844.75	0.44	1845.19	4.26	62412.89	14.80	62427.69
408.03	3.919	70.96	2079.32	0.84	2080.16	4.31	69476.07	28.02	69504.09
452.67	4.358	71.09	2105.82	1.04	2106.86	4.32	70180.69	34.67	70215.36
522.30	5.017	70.92	2080.27	1.38	2081.64	4.31	69497.65	45.94	69543.59
650.73	6.145	72.59	2022.37	2.03	2024.40	4.24	68721.66	68.91	68790.58
831.74	7.646	71.37	1779.58	3.06	1782.63	4.13	62117.56	106.70	62224.26
932.59	8.499	70.55	1607.41	3.74	1611.16	4.09	56594.32	131.85	56726.17
1106.64	9.684	68.69	1302.45	4.67	1307.12	3.93	47757.09	171.18	47928.28

(Discharge) Node # : 7

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
226.73	2.176	48.24	784.00	0.26	784.26	4.31	26212.26	8.64	26220.90
300.22	2.847	68.26	1844.70	0.44	1845.14	4.26	62411.22	14.80	62426.02
408.04	3.919	70.96	2079.23	0.84	2080.06	4.31	69472.91	28.02	69500.93
452.67	4.358	71.09	2105.71	1.04	2106.75	4.32	70176.77	34.67	70211.45
522.31	5.017	70.92	2080.11	1.38	2081.49	4.31	69492.46	45.94	69538.40
650.74	6.145	72.59	2022.14	2.03	2024.17	4.24	68713.88	68.91	68782.79
831.77	7.646	71.37	1779.23	3.06	1782.29	4.13	62105.51	106.70	62212.21
932.64	8.499	70.54	1606.99	3.74	1610.73	4.09	56579.43	131.85	56711.28
1106.79	9.684	68.69	1301.93	4.67	1306.59	3.93	47737.76	171.18	47908.95

Element # 7 Turning Channel

(Inlet) Node # : 7

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
226.73	2.176	48.24	784.23	0.04	784.26	4.31	26219.73	1.21	26220.94
300.22	2.847	68.26	1845.08	0.06	1845.14	4.26	62424.28	2.07	62426.35
408.04	3.919	70.96	2079.95	0.12	2080.06	4.31	69497.65	3.92	69501.57
452.67	4.358	71.09	2106.60	0.15	2106.75	4.32	70207.38	4.85	70212.23
522.31	5.017	70.92	2081.29	0.19	2081.49	4.31	69533.01	6.43	69539.44
650.74	6.145	72.59	2023.89	0.28	2024.17	4.24	68774.77	9.65	68784.42
831.77	7.646	71.37	1781.86	0.43	1782.29	4.13	62199.84	14.94	62214.77
932.64	8.499	70.54	1610.21	0.52	1610.73	4.09	56695.92	18.46	56714.38
1106.79	9.684	68.69	1305.94	0.65	1306.59	3.93	47891.44	23.96	47915.41

(Discharge) Node # : 8

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
226.73	2.176	48.24	784.12	0.10	784.22	4.31	26216.08	3.26	26219.34
300.22	2.847	68.26	1844.90	0.17	1845.06	4.26	62418.05	5.58	62423.63
408.04	3.919	70.96	2079.59	0.32	2079.91	4.31	69485.84	10.57	69496.41
452.68	4.358	71.09	2106.16	0.39	2106.56	4.32	70192.77	13.08	70205.84
522.32	5.017	70.92	2080.71	0.52	2081.23	4.31	69513.66	17.33	69530.99
650.77	6.145	72.58	2023.03	0.77	2023.80	4.24	68745.73	26.00	68771.73
831.83	7.646	71.37	1780.57	1.15	1781.73	4.12	62154.88	40.25	62195.13
932.72	8.499	70.54	1608.63	1.41	1610.04	4.09	56640.38	49.73	56690.11
1107.03	9.684	68.69	1303.97	1.76	1305.73	3.93	47819.33	64.57	47883.90

Element # 8 Impeller

(Inlet) Node # : 8

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
226.73	2.176	48.24	783.05	1.16	784.22	4.31	26180.61	38.80	26219.41
300.22	2.847	68.26	1843.10	1.96	1845.06	4.26	62357.73	66.44	62424.16
408.04	3.919	70.96	2076.14	3.77	2079.91	4.31	69371.63	125.83	69497.46
452.68	4.358	71.09	2101.89	4.67	2106.56	4.32	70051.47	155.66	70207.13
522.32	5.017	70.92	2075.06	6.17	2081.23	4.31	69326.45	206.23	69532.69
650.77	6.145	72.58	2014.69	9.11	2023.80	4.24	68464.97	309.43	68774.40
831.83	7.646	71.37	1768.00	13.72	1781.73	4.12	61720.24	479.07	62199.31
932.72	8.499	70.54	1593.23	16.81	1610.04	4.09	56103.18	591.98	56695.16
1107.03	9.684	68.69	1284.78	20.95	1305.73	3.93	47125.85	768.57	47894.42

(Discharge) Node # : 9

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
217.46	2.176	80.99	2282.87	1016.20	3299.07	4.49	76325.38	33975.46	110300.80
264.44	2.847	77.61	3318.10	951.74	4269.84	4.83	112261.50	32200.38	144461.90
363.48	3.919	79.62	3550.09	886.35	4436.44	4.84	118621.60	29616.30	148237.90
404.46	4.358	79.60	3568.81	859.16	4427.98	4.84	118941.20	28634.05	147575.20
467.78	5.017	79.20	3519.39	815.38	4334.77	4.81	117580.80	27241.34	144822.10
582.40	6.145	80.36	3394.96	737.15	4132.11	4.73	115370.60	25050.55	140421.10
736.05	7.646	78.64	3046.30	643.80	3690.09	4.66	106344.90	22474.77	128819.70
828.51	8.499	77.63	2818.44	601.01	3419.46	4.60	99246.97	21163.77	120410.70
968.10	9.684	75.55	2393.57	531.86	2925.43	4.49	87796.40	19508.62	107305.00

Element # 9 Vaneless Diffuser

(Inlet) Node # : 9

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
217.46	2.176	80.99	2239.70	1059.37	3299.07	4.49	71821.38	33971.42	105792.80
264.44	2.847	77.61	3189.54	1080.30	4269.84	4.83	95050.03	32193.45	127243.50
363.48	3.919	79.62	3441.87	994.58	4436.44	4.84	102445.90	29603.18	132049.10
404.46	4.358	79.60	3466.93	961.05	4427.98	4.84	103237.50	28617.82	131855.30
467.78	5.017	79.20	3425.04	909.73	4334.77	4.81	102479.40	27219.84	129699.20
582.40	6.145	80.36	3309.49	822.63	4132.11	4.73	100650.30	25018.30	125668.60
736.05	7.646	78.64	2964.14	725.95	3690.09	4.66	91562.68	22424.83	113987.50
828.51	8.499	77.63	2744.82	674.64	3419.46	4.60	85854.93	21102.05	106957.00
968.10	9.684	75.55	2319.74	605.69	2925.43	4.49	74409.52	19428.49	93838.02

(Discharge) Node # : 10

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
223.29	2.176	79.09	1916.00	912.12	2828.12	4.37	61441.38	29249.23	90690.61
266.92	2.847	76.45	2981.99	930.47	3912.46	4.79	88864.98	27728.55	116593.50
367.48	3.919	78.84	3349.71	857.38	4207.09	4.79	99702.85	25519.66	125222.50
408.27	4.358	78.93	3403.15	828.87	4232.02	4.79	101338.40	24681.84	126020.20

471.10	5.017	78.66	3392.27	785.28	4177.54	4.78	101498.80	23496.02	124994.90
581.38	6.145	79.94	3309.31	711.44	4020.74	4.74	100644.70	21636.63	122281.40
742.17	7.646	78.37	2985.13	630.06	3615.19	4.62	92211.05	19462.66	111673.70
831.77	8.499	77.42	2771.57	587.07	3358.64	4.59	86691.77	18362.87	105054.60
971.42	9.684	75.39	2349.91	529.45	2879.36	4.47	75377.08	16982.95	92360.03

Element # 10 Vaned Diffuser

(Inlet) Node # : 10

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
223.29	2.176	79.09	1939.30	888.82	2828.12	4.37	63856.26	29266.57	93122.83
266.92	2.847	76.45	2989.66	922.80	3912.46	4.79	89930.01	27758.23	117688.20
367.48	3.919	78.84	3357.17	849.92	4207.09	4.79	101024.60	25575.87	126600.40
408.27	4.358	78.93	3408.57	823.46	4232.02	4.79	102454.60	24751.40	127206.00
471.10	5.017	78.66	3394.75	782.80	4177.54	4.78	102294.20	23588.16	125882.40
581.38	6.145	79.94	3303.50	717.24	4020.74	4.74	100291.30	21774.88	122066.20
742.17	7.646	78.37	2983.45	631.74	3615.19	4.62	92924.91	19676.72	112601.60
831.77	8.499	77.42	2765.45	593.19	3358.64	4.59	86840.87	18627.36	105468.20
971.42	9.684	75.39	2341.04	538.31	2879.36	4.47	75350.06	17326.35	92676.41

(Discharge) Node # : 11

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
230.10	2.176	77.32	2364.76	7.15	2371.91	4.24	77865.59	235.48	78101.07
274.16	2.847	75.10	3472.76	13.40	3486.17	4.66	104461.90	403.19	104865.10
370,83	3.919	77.67	3843.85	25.38	3869.23	4.74	115669.70	763.63	116433.30
411.15	4.358	77.90	3901.32	31.43	3932.74	4.76	117265.70	944.67	118210.30
474.11	5.017	77.68	3854.63	41.53	3896.16	4.75	116152.00	1251.57	117403.60
589.18	6.145	79.04	3700.84	61.85	3762.70	4.68	112354.40	1877.79	114232.20
750.09	7.646	77.31	3227.94	93.34	3321.28	4.57	100540.10	2907.32	103447.40
844.06	8.499	76.22	2902.03	114.40	3016.43	4.52	91129.60	3592.52	94722.13
996.56	9.684	73.86	2296.55	144.91	2441.46	4.36	73917.93	4664.17	78582.10

Element # 11 Turning Channel

(Inlet) Node # : 11

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
230.10	2.176	77.32	2366.42	5.49	2371.91	4.24	80295.72	186.23	80481.95
274.16	2.847	75.10	3475.84	10.32	3486.17	4.66	107391.60	318.88	107710.50
370.83	3.919	77.67	3849.34	19.89	3869.23	4.74	116891.30	603.95	117495.20
411.15	4.358	77.90	3908.06	24.68	3932.74	4.76	118298.00	747.14	119045.20
474.11	5.017	77.68	3863.52	32.64	3896.16	4.75	117162.90	989.88	118152.80
589.18	6.145	79.04	3714.43	48.27	3762.70	4.68	114279.90	1485.16	115765.00
750.09	7.646	77.31	3248.24	73.05	3321.28	4.57	102251.80	2299.41	104551.20
844.06	8.499	76.22	2927.26	89.17	3016.43	4.52	93280.51	2841.35	96121.86
996.56	9.684	73.86	2329.74	111.72	2441.46	4.36	76927.38	3688.92	80616.30

(Discharge) Node # : 12

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
230.13	2.176	77.31	2370.09	0.25	2370.35	4.24	80420.24	8.64	80428.88
274.21	2.847	75.09	3482.75	0.48	3483.22	4.66	107604.80	14.80	107619.60
370.94	3.919	77.66	3862.64	0.92	3863.56	4.74	117295.10	28.02	117323.10
411.29	4.358	77.87	3924.57	1.15	3925.71	4.76	118797.60	34.67	118832.30
474.33	5.017	77.65	3885.35	1.51	3886.86	4.75	117824.80	45.94	117870.70
589.62	6.145	78.99	3746.70	2.24	3748.94	4.68	115273.00	68.91	115341.90
751.12	7.646	77.24	3297.08	3.39	3300.47	4.57	103789.30	106.70	103896.00
845.59	8.499	76.14	2986.89	4.14	2991.03	4.51	95180.48	131.85	95312.34
999.34	9.684	73.75	2404.45	5.18	2409.63	4.35	79394.15	171.18	79565.33

Element # 12 DownComer

(Inlet) Node # : 12

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
230.13	2.176	77.31	2370.09	0.25	2370.35	4.24	80432.29	8.64	80440.93
274.21	2.847	75.09	3482.75	0.48	3483.22	4.66	107624.10	14.80	107638.90
370.94	3.919	77.66	3862.64	0.92	3863.56	4.74	117328.80	28.02	117356.90
411.29	4.358	77.87	3924.57	1.15	3925.71	4.76	118839.00	34.67	118873.60
474.33	5.017	77.65	3885.35	1.51	3886.86	4.75	117879.80	45.94	117925.80
589.62	6.145	78.99	3746.70	2.24	3748.94	4.68	115359.50	68.91	115428.40
751.12	7.646	77.24	3297.09	3.39	3300.47	4.57	103932.70	106.70	104039.40
845.59	8.499	76.14	2986.90	4.13	2991.03	4.51	95353.76	131.85	95485.61
999.34	9.684	73.75	2404.46	5.17	2409.63	4.35	79616.27	171.18	79787.45

(Discharge) Node # : 13

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
230.13	2.176	77.31	2370.06	0.25	2370.32	4.24	80431.31	8.64	80439.95
274.21	2.847	75.09	3482.69	0.48	3483.17	4.66	107622.40	14.80	107637.20
370.94	3.919	77.66	3862.53	0.92	3863.45	4.74	117325.70	28.02	117353.70
411.29	4.358	77.87	3924.44	1.15	3925.58	4.76	118835.00	34.67	118869.70
474.33	5.017	77.65	3885.18	1.51	3886.69	4.75	117874.60	45.94	117920.60
589.63	6.145	78.99	3746.45	2.24	3748.69	4.68	115351.70	68.91	115420.60
751.14	7.646	77.23	3296.70	3.39	3300.09	4.57	103920.60	106.70	104027.30
845.62	8.499	76.13	2986.43	4.13	2990.56	4.51	95338.86	131.85	95470.71
999.40	9.684	73.74	2403.88	5.17	2409.05	4.35	79596.94	171.18	79768.12

Element # 13 Turning Channel

(Inlet) Node # : 13

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
230.13	2.176	77.31	2370.28	0.04	2370.32	4.24	80438.96	1.21	80440.17
274.21	2.847	75.09	3483.10	0.07	3483.17	4.66	107635.50	2.07	107637.60
370.94	3.919	77.66	3863.32	0.13	3863.45	4.74	117350.40	3.92	117354.30
411.29	4.358	77.87	3925.42	0.16	3925.58	4.76	118865.60	4.85	118870.50
474.33	5.017	77.65	3886.48	0.21	3886.69	4.75	117915.20	6.43	117921.60
589.63	6.145	78.99	3748.38	0.31	3748.69	4.68	115412.60	9.65	115422.20
751.14	7.646	77.23	3299.62	0.47	3300.09	4.57	104015.00	14.94	104030.00
845.62	8.499	76.13	2989.98	0.58	2990.56	4.51	95455.45	18.46	95473.91
999.40	9.684	73.74	2408.32	0.72	2409.05	4.35	79748.26	23.97	79772.23

(Discharge) Node # : 14

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
230.14	2.176	77.31	2370.18	0.10	2370.27	4.24	80435.32	3.26	80438.58
274.21	2.847	75.09	3482.90	0.18	3483.08	4.66	107629.30	5.58	107634.80
370.95	3.919	77.65	3862.94	0.35	3863.28	4.74	117338.60	10.57	117349.20
411.30	4.358	77.87	3924.94	0.43	3925.37	4.76	118851.00	13.08	118864.10
474.34	5.017	77.65	3885.84	0.57	3886.41	4.75	117895.80	17.33	117913.10
589.64	6.145	78.99	3747.43	0.84	3748.28	4.68	115383.60	26.00	115409.60
751.17	7.646	77.23	3298.19	1.28	3299.47	4.57	103970.10	40.25	104010.30
845.67	8.499	76.13	2988.24	1.56	2989.80	4.51	95399.91	49.73	95449.64
999.48	9.684	73.74	2406.15	1.95	2408.10	4.35	79676.16	64.57	79740.73

Element # 14 Impeller

(Inlet) Node # : 14

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
230.14	2.176	77.31	2369.13	1.14	2370.27	4.24	80400.14	38.80	80438.95
274.21	2.847	75.09	3480.93	2.15	3483.08	4.66	107569.00	66.44	107635.40
370.95	3.919	77.65	3859.14	4.14	3863.28	4.74	117224.30	125.83	117350.20
411.30	4.358	77.87	3920.23	5.14	3925.37	4.76	118709.70	155.66	118865.30

474.34	5.017	77.65	3879.62	6.80	3886.41	4.79	117708.50	206.23	117914.80
589.64	6.145	78.99	3738.23	10.05	3748.28	4.68	115102.70	309.43	115412.20
751.17	7.646	77.23	3284.27	15.20	3299.47	4.57	103535.60	479.07	104014.60
845.67	8.499	76.13	2971.26	18.54	2989.80	4.51	94862.88	591.98	95454.86
999.48	9.684	73.74	2384.89	23.21	2408.10	4.35	78978.85	768.57	79747.42

(Discharge) Node # : 15

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
202.89	2.176	86.84	3846.73	1001.15	4847.87	4.81	130544.90	33975.46	164520.30
249.62	2.847	83.86	5095.81	1042.00	6137.82	5.12	157472.60	32200.38	189673.00
341.35	3.919	86.30	5480.49	975.00	6455.49	5.15	166474.10	29616.30	196090.40
379.32	4.358	86.35	5534.74	945.60	6480.34	5.16	167599.10	28634.05	196233.10
438.39	5.017	85.91	5470.04	897.86	6367.90	5.14	165962.50	27241.34	193203.80
542.88	6.145	87.30	5261.58	813.57	6075.16	5.08	162008.00	25050.56	187058.50
690.08	7.646	84.63	4699.81	712.93	5412.73	4.97	148159.90	22474.78	170634.70
777.28	8.499	83.02	4322.58	662.88	4985.46	4.91	138006.30	21163.77	159170.10
914.82	9.684	80.14	3612.99	589.09	4202.08	4.75	119649.20	19508.62	139157.80

Element # 15 Vaneless Diffuser

(Inlet) Node # : 15

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
202.89	2.176	86.84	3712.43	1135.44	4847.87	4.81	111072.80	33971.42	145044.20
249.62	2.847	83.86	4993.39	1144.43	6137.82	5.12	140466.50	32193.45	172660.00
341.35	3.919	86.30	5396.41	1059.08	6455.49	5.15	150839.80	29603.19	180443.00
379.32	4.358	86.35	5455.61	1024.74	6480.34	5.16	152358.80	28617.83	180976.70
438.39	5.017	85.91	5397.17	970.73	6367.90	5.14	151339.10	27219.84	178558.90
542.88	6.145	87.30	5192.65	882.51	6075.16	5.08	147206.90	25018.30	172225.20
690.08	7.646	84.63	4638.41	774.32	5412.73	4.97	134330.90	22424.83	156755.80
777.28	8.499	83.02	4266.36	719.10	4985.46	4.91	125196.80	21102.05	146298.80
914.82	9.684	80.14	3561.12	640.97	4202.08	4.75	107942.10	19428.49	127370.60

(Discharge) Node # : 16

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
207.07	2.176	84.02	3365.42	977.61	4343.03	4.72	100690.60	29249.23	129939.80
251.89	2.847	82.24	4773.40	985.71	5759.11	5.07	134278.20	27728.55	162006.80
342.59	3.919	85.05	5298.18	912.99	6211.17	5.13	148094.10	25519.66	173613.80
380.21	4.358	85.28	5387.52	883.80	6271.32	5.14	150457.40	24681.84	175139.20
438.78	5.017	85.05	5362.14	837.93	6200.07	5.13	150356.70	23496.02	173852.70
545.41	6.145	86.67	5192.42	763.22	5955.64	5.06	147200.20	21636.64	168836.90
692.49	7.646	84.28	4660.78	672.04	5332.82	4.95	134978.80	19462.66	154441.40
779.67	8.499	82.77	4294.87	625.76	4920.62	4.89	126033.20	18362.87	144396.10
910.47	9.684	79.96	3593.03	560.28	4153.32	4.77	108909.50	16982.95	125892.40

Element # 16 Vaned Diffuser

(Inlet) Node # : 16

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
207.07	2.176	84.02	3384.60	958.43	4343.03	4.72	103352.30	29266.56	132618.80
251.89	2.847	82.24	4781.25	977.86	5759.11	5.07	135723.80	27758.23	163482.10
342.59	3.919	85.05	5299.51	911.66	6211.17	5.13	148673.40	25575.88	174249.20
380.21	4.358	85.28	5387.10	884.22	6271.32	5.14	150798.40	24751.39	175549.80
438.78	5.017	85.05	5359.61	840.46	6200.07	5.13	150420.80	23588.16	174009.00
545.41	6.145	86.67	5191.10	764.54	5955.64	5.06	147848.20	21774.88	169623.00
692.49	7.646	84.28	4655.75	677.07	5332.82	4.95	135304.30	19676.72	154981.00
779.67	8.499	82.77	4287.80	632.83	4920.62	4.89	126212.30	18627.36	144839.70
910.47	9.684	79.96	3578.97	574.35	4153.32	4.77	107967.10	17326.35	125293.40

(Discharge) Node # : 17

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
209.22	2.176	81.67	3843.38	7.71	3851.10	4.67	117361.50	235.48	117597.00
255.13	2.847	80.54	5293.17	14.20	5307.38	5.01	150255.60	403.19	150658.80
345.44	3.919	83.50	5821.52	27.22	5848.74	5.09	163318.10	763.63	164081.70
384.82	4.358	83.92	5916.19	33.75	5949.94	5.08	165609.00	944.67	166553.70
443.84	5.017	83.76	5853.34	44.59	5897.94	5.07	164277.90	1251.56	165529.50
548.39	6.145	85.23	5614.62	65.93	5680.55	5.03	159910.40	1877.78	161788.20
698.18	7.646	82.87	4917.75	100.04	5017.79	4.91	142918.50	2907.31	145825.80
788.79	8.499	81.31	4433.47	122.05	4555.51	4.84	130500.10	3592.52	134092.70
932.50	9.684	78.34	3531.47	154.61	3686.08	4.66	106534.20	4664.17	111198.30

Element # 17 1-Discharge Volute

(Inlet) Node # : 17

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
209.22	2.176	81.67	3843.46	7.63	3851.10	4.67	118578.30	235.48	118813.80
255.13	2.847	80.54	5293.35	14.02	5307.38	5.01	152191.10	403.19	152594.30
345.44	3.919	83.50	5821.75	27.00	5848.74	5.09	164682.60	763.63	165446.30
384.82	4.358	83.92	5916.60	33.34	5949.94	5.08	167628.40	944.67	168573.10
443.84	5.017	83.76	5853.85	44.09	5897.94	5.07	166186.10	1251.56	167437.70
548.39	6.145	85.23	5614.97	65.57	5680.55	5.03	160793.80	1877.78	162671.60
698.18	7.646	82.87	4918.57	99.22	5017.79	4.91	144118.00	2907.31	147025.30
788.79	8.499	81.31	4434.88	120.64	4555.51	4.84	132069.30	3592.52	135661.80
932.50	9.684	78.34	3535.13	150.96	3686.08	4.66	109225.10	4664.17	113889.30

(Discharge) Node # : 18

Vol. Flow (GPM)	Mass Flow (lb/s)	Temp. (R)	S Press. (psi)	D Press. (psi)	Tot Pre (psi)	Density (lb/ft^3)	St. Head (ft)	Dyn Head (ft)	Tot Head (ft)
211.74	2.176	80.85	3638.67	0.01	3638.68	4.61	112259.90	0.41	112260.30
256.15	2.847	79.73	5076.37	0.02	5076.40	4.99	145952.70	0.72	145953.40
348.77	3.919	82.60	5607.29	0.05	5607.34	5.04	158616.20	1.34	158617.60
386.38	4.358	82.87	5705.53	0.06	5705.59	5.06	161648.30	1.67	161650.00
445.76	5.017	82.68	5648.37	0.08	5648.44	5.05	160352.50	2.20	160354.70
554.37	6.145	84.09	5421.70	0.12	5421.82	4.97	155259.10	3.31	155262.40
702.82	7.646	81.80	4746.45	0.18	4746.62	4.88	139074.70	5.13	139079.80
800.09	8.499	80.29	4276.51	0.21	4276.72	4.77	127353.10	6.34	127359.50
945.24	9.684	77.31	3399.04	0.27	3399.31	4.60	105020.60	8.23	105028.80

Element # 18 Leakage

Inlet Node # : 3 **Disch Node # :** 2

Element # 19 Leakage

Inlet Node # : 9 **Disch Node # :** 8

Element # 20 Leakage

Inlet Node # : 15 **Disch Node # :** 14