PUMP-FLO® METHOD OF SOLUTION

PUMP-FLO is a pump selection and analysis program. It can select both centrifugal and air operated double diaphragm (AODD) pumps. Centrifugal is a broad classification of pumps which use kinetic energy to move the fluid. They use the centrifugal force of a rotating impeller to impart kinetic energy to the fluid (as opposed to jet pumps and eductors). AODD pumps are positive displacement pumps which use compressed air to move a diaphragm back and forth, pumping the fluid on the other side of the diaphragm.

For centrifugal pumps, the *Hydraulic Institute Standards* (Reference 1) is the basis for the PUMP-FLO program. The Hydraulic Institute is composed of organizations and individuals who manufacture and sell pumps in the open market. When there is a discrepancy between the PUMP-FLO program and the current revision of the *Hydraulic Institute Standards*, the Standards take precedence.

PUMP-FLO selects pumps from a pump catalog and evaluates their operation in an application. Within the range of the manufacturer’s recommendations, the program allows you to adjust the pump parameters and see the effect it has on the pump operation.

In general, the majority of this method of solution document applies to centrifugal pump selection. Please see the *Air Operated Double Diaphragm Pumps* section at the end of this document for a specific discussion of these pumps.

Definitions

The definitions that follow are found in Reference 1 and are used in this section for the discussion of PUMP-FLO’s solution method.

Head The quantity used to express a form (or combination of forms) of the energy content of the liquid, per unit weight of the liquid, referred to any arbitrary datum. All head quantities are in terms of foot-pounds of energy per pound of liquid, or feet of liquid.

Flow The unit of flow rate in the United States is expressed in units of gallons per minute (gpm). The standard fluid for all pump curves is water at 60 °F.

NPSH The net positive suction head is the total suction head in feet of liquid (absolute) determined at the suction nozzle and the referred datum less the vapor pressure of the liquid in feet (absolute). NPSHa is the net positive suction head available in the pumping system. NPSHr is the net positive suction head required by the pump.

Pump Input The horsepower delivered to the pump shaft (designated as brake horsepower).

Pump Efficiency The ratio of the energy delivered by the pump to the energy supplied to the pump shaft (the ratio of the liquid horsepower to the brake horsepower).

Pump Head Curve

Pump vendors perform pump tests to determine the operating characteristics of the pumps they manufacture. The pumps are tested as outlined in Reference 1. All pump data used by the PUMP-FLO program is supplied by the pump manufacturers who are solely responsible for the content.

Catalog Search Criteria

PUMP-FLO compiles a list of pumps that meet the criteria specified by the user. This criteria includes the manufacturer’s catalog, the types and speeds, and the design point (head and flow rate). The catalog search can be further limited by specifying that the design point must be to the left of a pump’s best efficiency point (BEP). Users can also specify a head tolerance, which is expressed as a percentage of the design point head. Specifying a tolerance places pumps on the selection list that do not meet the design point, or are outside of the selection window. This allows the consideration of pumps that are “near misses.”

Advanced Search Criteria

Advanced criteria can be used to further refine the catalog search. Pumps that do not meet one or more of the specified criteria are listed in red on the selection list. A detailed warnings list is also provided for each pump. The available criteria is listed below:

Preferred Operating Region

The preferred operating region has a lower and upper limit and is expressed as a percentage of the best efficiency point (BEP) flow rate. If the design point is outside of the preferred operating region, a warning flag is issued.

Secondary Operating Point

The secondary operating point is a flow rate and head specified by the user. If the secondary operating point is outside of the selection window, a warning flag is issued.

Pump Limits

Max temperature: The maximum operating temperature is compared to the maximum temperature specified in the catalog by the manufacturer. If the maximum temperature value exceeds the catalog value, a warning flag is issued.

Max suction pressure: The maximum pressure at the pump suction is added to the shutoff dP and then this sum is compared to the maximum pressure specified in the catalog by the manufacturer. If the maximum suction pressure plus the shutoff dP is greater than the catalog maximum pressure, a warning flag is issued.

Max sphere size: The largest particle size in the fluid is compared to the maximum sphere size specified in the catalog by the manufacturer. If the maximum sphere size exceeds the catalog value, a warning flag is issued.

Max power: The maximum power for the pump assembly or magnetic drive is compared to the power limit specified in the catalog by the manufacturer. If the maximum power exceeds the catalog value, a warning flag is issued.

Max suction specific speed (Nss): The maximum suction specific speed is compared to the suction specific speed specified in the catalog by the manufacturer. If the catalog value exceeds the maximum suction specific speed, a warning flag is issued.

Curve Limits

Minimum trim: The design curve diameter, expressed as a percentage of the pump's maximum impeller diameter. If the selected design curve diameter is greater than this value, a warning flag is issued.

Min head rise: The minimum head rise from the design point to shutoff, expressed as a percentage from the design point head to the shutoff head. If a pump's head rise from design point to shutoff is less than this value, a warning flag is issued.

Pump Sizing

Each pump in the catalog can have up to ten impeller diameters or speed curves. Each curve can have up to twenty data points describing the pump operation. The data points for the curve consist of the flow rate and head, and optionally the pump's efficiency (or power) and NPSHr.

When the design point of the pump falls between a set of known curves, the program interpolates between them to arrive at a calculated curve. Often manufacturers allow impeller diameters to be adjusted only in fixed increments of their choosing. For example, a manufacturer can force the program to limit the impeller diameter increments to 0.125 inch. Or, they may not allow any trimming of the impellers.

The Affinity Laws

In hydraulically similar pumps, the head and capacity of a pump vary with the rotational speed of the impeller in such a way that the pump head curves retain their characteristic features. The variation of head, capacity, and brake horsepower follow a set of ratios that are known as the Affinity Laws. These laws are expressed in equations 1a, 1b and 1c

$$(Q_1/Q_0) = (N_1/N_0)(D_1/D_0)$$

equation 1a

$$(H_1/H_0) = (N_1/N_0)^2(D1/D_0)^2$$

equation 1b

$$(P_1/P_0) = (N_1/N_0)^3(D_1/D_0)^3$$

equation 1c

Q = Capacity, US gpm
N = Impeller speed, rpm
D = Impeller diameter
H = Pump head, ft
P = Pump power, hp
Subscripts
$_0$ = Pump test speed or diameter
$_1$ = New pump speed or diameter

Multi-stage Pumps

Pumps which have multiple impeller stages are designated as multi-stage pumps. For these pump types, the single stage base impeller curves and the impeller trim increment are specified in the manufacturer’s catalog along with the range of allowed impeller combinations.

During the pump selection process, PUMP-FLO determines the number of full diameter impeller stages necessary to achieve the design point. Once the number of stages has been determined, the program calculates the impeller diameter needed to go through the design point.

Adjustable Speed Pumps

Some pump manufacturers have pumps available in an Adjustable speed class. These pumps can be stored in a catalog under two different formats. Pumps that use the first format have one speed curve specified along with a maximum speed and a minimum speed. When adjustable speed pumps with this format are selected, PUMP-FLO uses the affinity laws to calculate the speed needed to pass through the specified design point. Pumps that use the second format have up to ten speed curves stored per pump. When the design point of the pump falls between a set of known speed curves, the program interpolates between them to arrive at a calculated curve.

Multiple Pump Configurations

PUMP-FLO can analyze multiple pumps for both parallel and series configurations. To plot the performance curve for multiple pumps in series, PUMP-FLO multiplies the head values of the single pump curve by the number of pumps in series. The flow values for series configurations are the same as those for a single pump.

To plot the performance curve for multiple pumps in parallel, PUMP-FLO multiplies the flow rate values for a single pump by the number of pumps in parallel. The head values for parallel configurations are the same as those for a single pump.

Net Positive Suction Head

The Net Positive Suction Head (NPSH) is the value of the minimum suction head required to prevent cavitation in a pump. Cavitation is the rapid formation and collapse of vapor pockets in regions of very low pressure.

In a centrifugal pump, cavitation causes a decrease in a pump's efficiency and is capable of causing physical damage to the pump and impeller. Since cavitation has such a detrimental affect on a pump, it must be avoided at all costs. Cavitation can be avoided by keeping the NPSH available (NPSHa) greater than the NPSH required (NPSHr).

The NPSH available can be entered directly or calculated using the NPSHa Calculator.

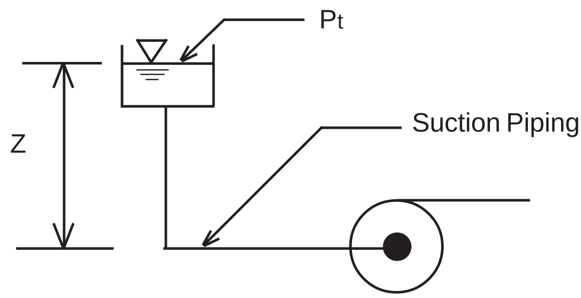

Figure 1

The formula used to calculate the NPSHa is as follows (refer to Figure 1 above):

$$NPSHa = ((P_t - P_{vp})/\rho) + Z - HL$$

equation 2

P_t = absolute pressure on the free surface of the liquid in the tank connected to the pump suction
P_{vp} = pumping fluid vapor pressure in absolute pressure units at the operating temperature
ρ = fluid density
Z = static suction head (this value is negative if a suction lift condition exists)
HL = head loss due to friction in the pipeline between the tank and the pump suction.

The units of NPSH are in feet of fluid absolute.

An NPSH margin ratio can also be specified. This factor is applied to the pump's NPSHr value. PUMP-FLO checks that the NPSHa is greater than the pump's NPSHr multiplied by the margin ratio. If it is not, a warning flag is issued.

The NPSHr for a pump is determined by the pump manufacturer and is listed in their catalog. The NPSHr values are arrived at through actual tests as outlined in Reference 1.

If the fluid is a hydrocarbon, or high temperature water, then the required NPSH of the pump may be reduced as outlined in Reference 1. Using the *NPSH Reductions for Pumps Handling Hydrocarbon Liquids and High Temperature Water* chart found in Reference 1, it is possible to reduce the NPSHr values specified by the vendor without causing cavitation.

The PUMP-FLO program does not perform the NPSH reduction calculations. If based on your experience you can reduce the NPSH requirements of the pump, the reduction value should be subtracted from the value presented by PUMP-FLO. Always check with your pump supplier when adjusting the NPSH requirements.

Total Head Calculator

Total Head Calculator feature in PUMP-FLO can be used to calculate the total head for simple systems like the ones shown below:

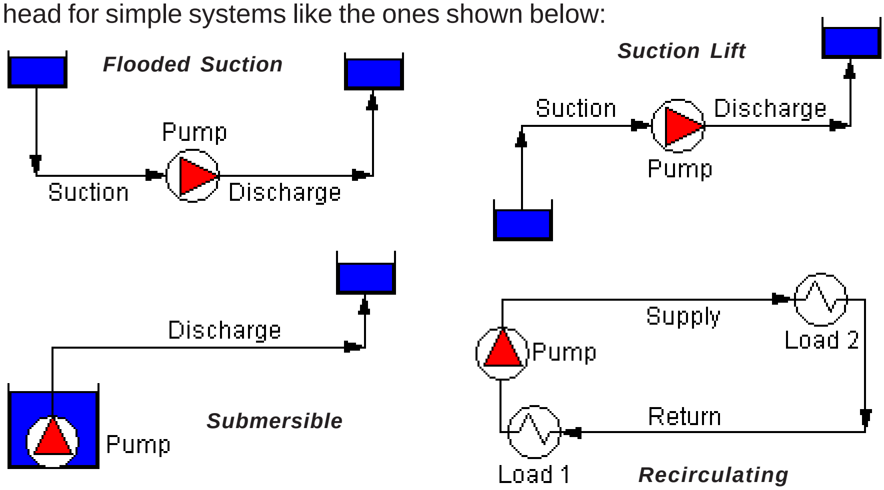

Figure 2

The formulas used to calculate the total head are listed below.

Flooded Suction and Suction Lift

$$\text{Total head} = ((P_d - P_s)/\rho) + (Z_d - Z_s) + HL_s + HL_d$$

equation 3a

P_d = discharge tank surface pressure
P_s = suction tank surface pressure
Z_d = static discharge head
Z_s = static suction head (this value is negative if a suction lift condition exists)
HL_s = head loss in the suction piping, including valve/fitting losses
HL_d = head loss in the discharge piping, including valve/fitting losses
ρ = fluid density

Submersible

$$\text{Total head} = ((P_d - P_s)/\rho) + (Z_d - Z_s) + HL_d$$

equation 3b

P_d = discharge tank surface pressure
P_s = suction tank surface pressure
Z_d = static discharge head
Z_s = suction tank liquid level
HL_d = head loss in the discharge piping, including valve/fitting losses
ρ = fluid density

Submersible

$$\text{Total head} = HL_r + HL_s + Load_1 + Load_2$$

equation 3c

HL_r = head loss in the return piping, including valve/fitting losses
HL_s = head loss in the supply piping, including valve/fitting losses
$Load_1$ = return side load
$Load_2$ = supply side load

A list of typical valves/fittings is provided for both the suction and discharge piping. The table below lists the valve/fitting coefficients (obtained from Reference 4):

Valve/Fitting	**L/D coefficient or K value**
Entrance	K = 0.78
Exit	K = 1
90° Elbow	L/D = 30
Ball valve	L/D = 3
Butterfly valve	2" (50 mm) to 8" (400 mm), L/D = 45 10" (250 mm) to 14" (350 mm), L/D = 35 16" (400 mm) to 24" (600 mm), L/D = 25
Gate valve	L/D = 8
Globe valve	L/D = 340
Plug valve	L/D = 18
Lift check valve	L/D = 600
Stop check valve	L/D = 400
Swing check valve	L/D = 100

NOTE: The Total Head Calculator uses the Darcy-Weisbach method to calculate the piping head loss. This method takes into account fluid viscosity and pipe roughness, providing valid results for incompressible Newtonian fluids flowing in any round fully charged pipe. If you are pumping a non-Newtonian fluid, *you should not use* the Total Head Calculator to determine the required head for your pumping application.

Temperature Variations

Variations in the temperature of the fluid being pumped cause changes in the fluid density. Any reduction in the fluid density results in a reduction of the liquid horsepower, along with a proportional reduction to the input power. As a result, there is little or no change in the pump's efficiency.

Viscosity Variations with Hot Water

The viscosity of a fluid has the greatest impact on the pump curves. Variations in fluid viscosity also have an influence on the pump's efficiency. The changes in efficiency are due to:

- Internal leakage losses within the pump
- Disc friction losses
- Hydraulic skin friction losses

When pumping hot water in circulating pumps, Reference 1 allows vendors to adjust the performance data of their pump using an empirical formula. The PUMP-FLO program, however, does not perform the efficiency variation corrections for circulating hot water.

Viscosity Variations with Viscous Fluids

The viscosity of oils and other viscous fluids (as compared to water) has a more pronounced impact on the operating conditions of the pump. Pumps that are tested with water but are used to transport viscous fluids must have their head, flow, and efficiency values corrected to approximate their performance with the viscous fluid.

The methodology outlined in Reference 6 is used by PUMP-FLO to correct the pump performance curves for viscous conditions. The correction equations are based on a pump performance Reynolds number adjusted for specific speed (parameter B), which has been statistically curve-fitted to a body of test data. The parameter B is calculated as follows:

$$B = 26.6 * [(\nu^{1/2}) * (H_{BEP-W}^{0.0625})]/[(Q_{BEP-W}^{0.375}) * (N^{0.25})]$$

equation 4

ν = kinematic viscosity of the pump liquid, centistokes (cSt)
Q_{BEP-W} = the water flow rate at the best efficiency point, US gpm
H_{BEP-W} = the water head per stage at the best efficiency flow rate, ft
N = pump speed, rpm

The test data includes conventional single-stage and multi-stage pumps, and covers the following ranges:

$1 \text{ cSt} < \nu < 3000 \text{ cSt}$

13 US gpm < Q (@ BEP) < 1140 US gpm

20 ft < H per stage (@ BEP) < 430 ft

B < 40

NOTE: PUMP-FLO uses 4.3 cSt for the lower limit of the viscosity range (this corresponds to the value listed in Reference 1 and was used in previous versions of the program).

The correction equations are not exact for any particular pump, but are rather a generalized method based on empirical data. This method may be applied to pump performance outside the ranges listed above, however the uncertainty of the performance prediction is increased. In such situations, PUMP-FLO still corrects the pump performance data, then issues a warning to indicate that there is increased uncertainty in the performance prediction.

For a complete listing of the correction equations, please see Reference 6.

Curve Corrections & Losses

In some cases, it may be necessary to apply hydraulic correction factors to a pump's performance data. For example, with vertical turbine pumps, the performance can vary depending on the material used for the impeller. Solids in suspension also affect the operation of a pump, depending on the both the percentage and nature of the solids. Reference 1 does not offer a recommendation for the modification of the pump data in these cases. However, through the use of hydraulic correction factors, PUMP-FLO allows for the modification of the pump data for specific pumping applications.

To adjust the pump data, the program multiplies the appropriate water pump data (head, flow rate, NPSHr and efficiency) by the corresponding correction factors specified by the user. Users also have the option of specifying additional power losses to account for mechanical seal losses.

The correction factors and losses are values that a user should have obtained from his or her own experience or preferably from the pump manufacturer. In the case of slurries, pump vendors should be consulted regarding the impact of solids in suspension on the operation of specific pumps.

NOTE: Speed adjustments on a pump are done prior to applying the hydraulic curve corrections. If viscous conditions exist (viscosity of 4.3 centistokes or greater), hydraulic curve corrections are first applied to the pump performance data, then the viscosity corrections. Power losses are applied after both the curve corrections and viscosity corrections are performed.

Motor Sizing

Motor size tables used by PUMP-FLO can contain up to four different standards. Each standard can have a maximum of four enclosure types. For each standard and enclosure type, the table contains speed, frame, and motor efficiency data.

When specifying the standard and enclosure type to use, the user also specifies the sizing criteria. There are three different criteria available: the power required at the design point flow rate, the maximum power required on the design curve, and the maximum power required for the maximum impeller diameter. The user can also specify an uncertainty factor. PUMP-FLO multiplies the pump's horsepower by the uncertainty factor and uses this value when selecting the motor size.

Based on the sizing criteria specified by the user, PUMP-FLO automatically sizes the motor for each pump that is put on the selection list. The smallest motor that meets the sizing criteria is selected. When performing operating cost analyses, the program uses the efficiency data stored in the motor size table.

Energy Cost

The energy cost is the cost of the power required to run a pump for one year. PUMP-FLO can calculate the annual energy cost for pumps running under both fixed and variable speed conditions. This cost information provides another parameter for consideration when comparing the advantages of using one pump over another. It also provides useful information for determining if the cost savings associated with operating a variable speed pump justifies the cost of the variable speed drive.

PUMP-FLO uses information from the operating load profile and the manufacturer's pump curve to calculate the energy cost. If the cost is being calculated for a variable speed drive pump, the resistance curve information is used as well. The pump and motor efficiencies are also factored into the calculation.

For a fixed speed pump, the sequence outlined below is followed for each load specified in the operating load profile.

The brake horsepower is calculated:

$$bhp = Q*TH*\rho/(247{,}000 * eff_p)$$

equation 5

bhp = brake horsepower
Q = flow rate, US gpm
TH = total head, ft
ρ = fluid density, lb/ft^3
eff_p = pump efficiency

The electrical horsepower is calculated:

$$ehp = bhp / eff_m$$

equation 6

ehp = motor electrical horsepower
eff_m = motor efficiency

The cost for the load is calculated:

$$Cost/Load = ehp * (0.7457\ kW/hp) * T * COST$$

equation 7

T = duration of load, hrs/yr
COST = power cost, per kWh

Once this process is completed, the total annual energy cost is determined by summing up the costs calculated for each specified load in the profile.

Calculating the energy cost for a variable speed pump requires two more steps for each load specified in the operating load profile. First, the speed of the pump is determined at which the pump curve intersects the selected resistance curve at the required flow rate. Next, the operating condition of the pump is determined for the required speed using the affinity laws. The procedure then follows that for the fixed speed drive as outlined above.

Life Cycle Cost

The life cycle cost (LCC) for a pump is the total “lifetime” cost to purchase, install, operate, maintain, and dispose of the pump. The LCC is calculated as follows:

$$LCC = C_i + C_{in} + df * \Sigma[C_e + C_m + C_o + C_s + C_{annual\ other}]$$

$$+ [C_d + C_{d\ other}]/[1 + (i - p)]^n$$

equation 8

C_i = initial cost
C_{in} = installation and commissioning cost
df = discount factor, a total sum factor over the n years for the present value
C_e = annual energy cost
C_m = annual maintenance and repair cost
C_o = annual operating cost
C_s = annual downtime cost
$C_{annual\ other}$ = annual miscellaneous costs
C_d = disposal and decommissioning cost
$C_{d\ other}$ = miscellaneous costs associated with decommissioning the equipment
i = interest rate
p = inflation rate
n = number of years

NOTE: The annual energy cost used in calculating the life cycle cost is the last type of energy cost calculated (fixed speed or variable speed).

For more information, refer to Reference 7.

Air Operated Double Diaphragm Pumps

AODD pumps are positive displacement pumps which use compressed air to move a diaphragm back and forth, pumping the fluid on the other side of the diaphragm. Figure 3 below shows a cutaway diagram of an AODD pump.

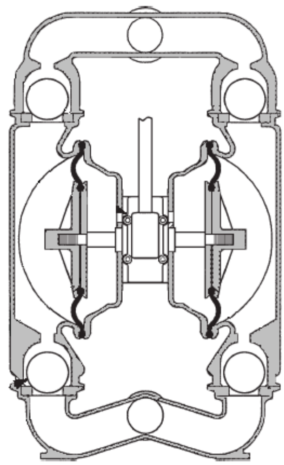

Figure 3

Performance Curves

A typical AODD pump performance curve is shown below in Figure 4.

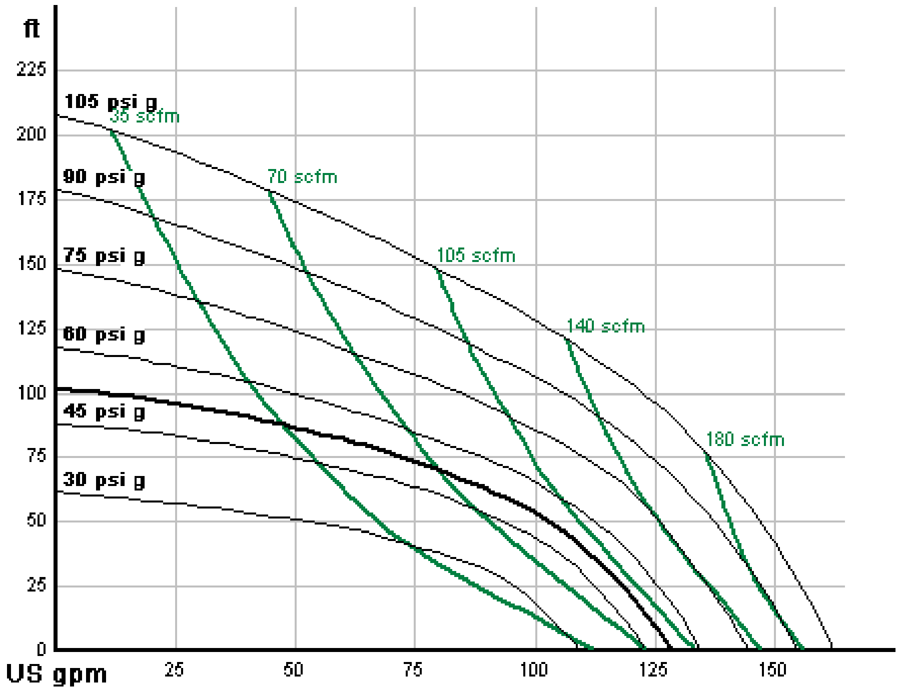

Figure 4

The pump performance (head vs. flow) is plotted for a series of air supply pressures. Air consumption curves are overlaid on the head curves in either an iso or line format. These curves indicate the air supply volume needed to provide the required flow rate at a given discharge head.

Fluid Compatibility

Each AODD catalog must have a corresponding Fluids Compatibility Table (FCT file). The FCT file contains a list of fluids and fluid properties, along with casing and diaphragm material compatibility ratings for the fluid.

For each fluid and material combination, the manufacturer can assign a code which indicates the fluid/material compatibility. PUMP-FLO appends this code to the front of the material name. If a code has not been specified for a particular fluid/material combination, a "?" is appended to the material name, indicating that the compatibility is unknown.

Viscosity Corrections

For high viscosity fluids, a flow capacity correction factor is applied to the pump performance.

A graph of available pump capacity (expressed as a percentage) vs. fluid viscosity (cP) is provided in Reference 5. Figure 5 below is a plot of data obtained from that graph.

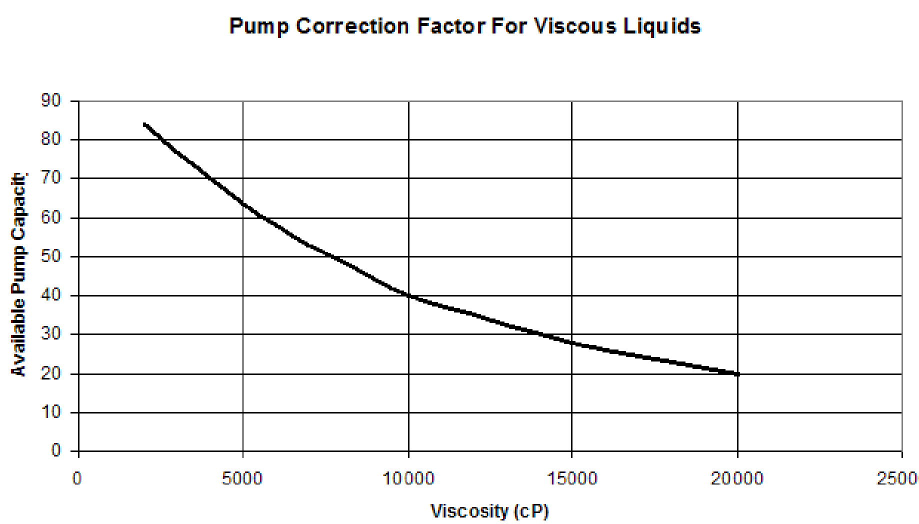

Figure 5

PUMP-FLO uses an equation that is derived from Figure 5 to calculate the capacity correction factor. The program automatically applies the correction factor to the pump data found in the pump catalog to determine the reduced capacity.

$$CQ = (A + B*\mu + C*\mu^2 + D*\mu^3)/100$$

equation 9

CQ = capacity correction factor
μ = viscosity, centipoise (cP)
A = 100.81
B = -0.00918886
C = 3.800408E-07
D = -6.13588E-12

The range of application for the capacity reduction formula is as follows:

$$93 \text{ cP} < \mu \leq 30000 \text{ cP}$$

References

1 Hydraulic Institute Standards for Centrifugal, Rotary & Reciprocating Pumps, 14th edition, Hydraulic Institute, 1983.

2 Pump Handbook, Igor J. Karassik, William C. Krutzsch, Warren H. Fraser, and Joseph P. Messina, editors; McGraw-Hill, Inc., 1976.

3 Science and Engineering Programs, edited by John Heilborn, McGraw-Hill, Inc., 1981.

4 Crane, Crane Technical Paper 410, “Flow of Fluids through Valves, Fittings, and Pipe” twenty fourth printing, Crane Company 1988.

5 Engineering Handbook AODD Pumps, Yamada America, Inc.

6 Effects of Liquid Viscosity on Rotodynamic (Centrifugal and Vertical) Pump Performance, ANSI/HI 9.6.7, 2004.

7 Pump Life Cycle Costs: A Guide to LCC Analysis for Pumping Systems, Europump and Hydraulic Institute, 2001.