JET PUMP GEOMETRY SELECTION

Eddie E. Smart
Guiberson Division, Dresser Industries, Inc.

ABSTRACT

This paper presents a method of directly calculating an optimum jet pump geometry for a set of specified conditions. It reviews jet pump theory to the extent necessary for explaining the sizing technique. The method uses a design performance curve which is a composite of the family of performance curves for the pump. An exact nozzle area is calculated and an area ratio selected, based on the design curve. This data is then used to select an off the shelf geometry from a manufacturer. The calculation sequence is presented along with an example set of calculations which follow that sequence.

INTRODUCTION

Jet pumping is a form of hydraulic pumping which has become increasingly popular due to its flexibility and durability. In hydraulic pumping, fluid is pumped downhole as a power fluid to operate a downhole pump. This method allows energy transfer to the pump through a pressurized fluid which has advantages in deep and deviated wells. The positive displacement pumps, both hydraulic and rod pump, have reduced life when solids are present in the produced fluid. This is also true of the electric submersible pump. Since the jet pump has no moving parts, it is able to produce longer in corrosive and sand laden fluids.

The increasing interest in jet pumping means more user interest in jet pump calculations. References 1 and 2 presented a method of calculating the horsepower requirements of a specified jet pump, or the use of the performance of a specific size jet pump to calculate the well inflow performance. In both cases, the pump geometry is specified before the performance calculations are made. These references introduced a trial and error method of selecting a non-cavitating jet pump geometry but did not address the problem of a direct calculation of an optimum geometry (nozzle and mixing tube diameters).

JET PUMP THEORY

In order to understand the method of directly calculating a jet pump geometry, it will help to examine how a jet pump works. Power fluid is pumped, at a given rate, to the downhole jet pump where it reaches a nozzle with a total pressure designated as PN (Figure 1). This high pressure fluid is then directed through the nozzle which converts the fluid stream to a high velocity and low static pressure. The low pressure (PS) allows the well fluids to flow into the wellbore and pump at the desired production rate (QN). The high momentum power fluid is then mixed with the low momentum production in a constant area mixing tube (throat).

When the combined fluids reach the end of the mixing tube, they are at a low pressure and a high velocity. The fluid then exits the pump through a diffuser section which converts the fluid to a high static pressure, low velocity state. This high discharge pressure (PD) must be sufficient to lift the combined fluid rate (QD) to the surface.

There are two relationships that must be satisfied when modeling a jet pump. The first relationship applies only to the nozzle. It defines the rate at which a fluid can be pumped through a given size nozzle with a given pressure drop across the nozzle. This relationship is described by Equation 1.

$$QN = 832\ AN \sqrt{\frac{PN - PS}{GN}} \tag{1}$$

The second relationship is described by non-dimensional performance curves which relate the three pressures (PN, PS, PD) and two flow rates (QN, QS) seen in Figure 1. These curves are presented in Figure 2 and defined by Equation 2.

$$N = \frac{2R + (1 - 2R)\left[\frac{M \times R}{(1-R)}\right]^2 - (1 + KTD)\ R^2\ (1 + M)^2}{(1 + KN) - \text{Numerator}} \tag{2}$$

Where

$$R = \frac{AN}{AT} \tag{3}$$

$$M = \frac{QS \times GS}{QN \times GN} \tag{4}$$

$$N = \frac{PD - PS}{PN - PD} \tag{5}$$

FACTORS IN GEOMETRY SELECTION

As can be seen from Equations 1 and 2, there are two areas in the jet pump which determine its performance. In Equation 1, the area of the nozzle (AN) strongly influences the rate of power fluid which is needed. In Equation 2, the value of R is changed to modify the shape of the performance curves, as can be seen in Figure 2. Equation 3 defines this area ratio as the nozzle area divided by the mixing tube area (throat area). Therefore, the nozzle and mixing tube areas are the parameters changed in a jet pump in order to match the pump to the characteristics of the well it is to produce.

If the value of R (Area Ratio) in Equation 2 is held constant, a curve of pressure ratio (N) vs flow ratio (M) can be drawn. The value of R can be changed and another curve drawn. This is illustrated in Figure 2. From this plot it can be seen that for R = 0.6, the value of N (pressure ratio) is largest for all values of M (flow ratio) below 1.8. At this point the curves for R = 0.6 and R = 0.5 cross and the latter curve gives the largest value of N. Likewise, the curve representing an area ratio of 0.5 has the largest value of N until a value of M = 0.33 is reached. At this point, the curve for R = 0.4 crosses the curve for R = 0.5. This pattern continues as the value of R is decreased.

Equation 5 is the definition of pressure ratio, N. This equation can be solved for PN, as in Equation 6 below.

$$PN = (PD - PS) / N + PD \tag{6}$$

The term PN is a combination of the surface operating pressure, the hydrostatic pressure of the power fluid and any pressure loss in the power fluid tubing. It can be seen from Equation 6 that the larger the value of N, for fixed values of PD and PS, the smaller the resulting value of PN. This would result in a lower value of surface operating pressure and a lower horsepower requirement.

Referring to Figure 2, this means for a given value of M the curve which will result in the lowest operating pressure is the curve that gives the highest value of N at that value of M. This would suggest the use of a Design Performance Curve which is a composite of the individual curves on Figure 2. This curve would be the line segments that represent maximum values of N. Stated another way, the Design Performance Curve is the upper envelope of the family of curves in Figure 2. Associated with each line segment is its value of area ratio. Figure 3 is the Design Performance Curve which is derived from Figure 2.

The Design Performance Curve can be used as if it were the performance curve of a single pump for calculating values of pressure ratio (N)and flow ratio (M) that are consistent with the wellbore description and well inflow performance. To calculate an optimum pump geometry, the desired surface pressure must be specified. As a general rule, higher overall efficiency is attained with higher surface operating pressure. This is due to a lower required power fluid rate and the resulting lower pressure loss in the tubulars.

When values of N and M are obtained, there will be an area ratio (R) from the Design Performance Curve which corresponds to those values. Since this solution is for a specified production rate and producing bottom hole pressure, the value of M along with production rate can be used to obtain a power fluid rate. This procedure will also yield the downhole power fluid pressure (PN). With this information, Equation 1 can be used to find the exact nozzle area required to pass the calculated power fluid rate at the calculated pressure drop across the nozzle.

The objective in selecting an optimum jet pump geometry is two fold. The first consideration will be for a pump that will lift a given well at the lowest horsepower. The second consideration is the selection of a geometry that will not cavitate. Cavitation will occur when the static pressure of the produced fluid inside the mixing tube drops below the vapor pressure of the produced fluid. When cavitation does occur, choked flow and mixing tube damage may result. It is often necessary to select a pump geometry which does not require the least horsepower in order to avoid cavitation damage.

Cavitation limits for the pump are predicted by theory, and lab testing is used to establish the constants in the theoretical equations. The cavitation limit used in References 1 and 2 is based on production rate. It is convenient for these calculations to use a limit based on the flow ratio. When the flow ratio is greater than the flow ratio at cavitation, as described by Equation 7, cavitation damage is possible. (Ref. 4)

Cavitation Limit Equation

$$ML = \frac{1 - R}{R} \sqrt{\frac{PS}{1.3\,(PN-PS)}} \qquad (7)$$

CALCULATION SEQUENCE

1. Specify the desired surface operating pressure, PT.

2. As a starting value, set the flow ratio to 1. This is used only for initial pressure loss calculations.

3. Compute the pressure gradient of the produced oil from its API gravity.

$$GO = \frac{0.433 \times 141.5}{131.5 + {}^{o}API} \qquad (8)$$

4. Compute the pressure gradient of the produced fluid from the oil and water gradients.

$$GS = WC \times GW + (1 - WC) \times GO \qquad (9)$$

5. Estimate the formation volume factor.

$$BT = [1 + 2.8\ (GOR/PS)^{1.2}](1-WC) + WC \qquad (10)$$

6. Compute the power fluid rate based on the desired production rate and the flow ratio (M).

$$QN = \frac{GS \times QS \times BT}{GN \times M} \qquad (11)$$

7. Using the equation below compute the pressure loss in the power fluid tubing string.

The friction pressure loss in annular or circular (tubing) sections can be determined from the following equation (Ref. 3).

$$PF = \left[\frac{.00000202 \times L}{(D1-D2)(D1^2-D2^2)^2(D1/(D1-D2))^{0.1}}\left(\frac{D1^2-D2^2}{D1-D2}\right)^{.21}\right]\left[\left(\frac{\mu}{G}\right)^{.21} G\right] Q^{1.79} \qquad (12)$$

	Annular Flow	Tubing Flow
D1	Casing I.D.	Tubing I.D.
D2	Tubing O.D.	0

The expression within the first set of brackets is a constant for a given tubing string or annular flow passage. The expression in the second set of brackets is a constant for the power fluid losses, but not for the production return conduit since it will contain a variable mix of power fluid and production.

Power Fluid Pressure Loss = PFN
Return Fluid Pressure Loss = PFD

8. Calculate the power fluid pressure at the nozzle. PN is the sum of the operating pressure plus the hydrostatic pressure in the tubing minus friction losses in the tubing.

$$PN = PT + GN \times D - PFN \qquad (13)$$

9. Calculate the flow rate of the return fluid. QD is the sum of the production rate and the power fluid rate.

$$QD = QN + QS \qquad (14)$$

10. Calculate the gradient of the return fluid. GD is a weighted average of the power fluid gradient and the production gradient.

$$GD = \frac{GS \times QS + GN \times QN}{QD} \qquad (15)$$

11. Calculate the water fraction for the return fluid. WCD can be computed based on the gradients of the oil, water, and return fluid.

$$WCD = \frac{GD - GO}{GW - GO} \qquad (16)$$

12. Determine the return flow gas liquid ratio.

$$GLR = \frac{QS\ (1-WC)\ GOR}{QD} \tag{17}$$

13. Determine the viscosity of the return fluid. μ_D is a weighted average of the water and oil viscosities.

$$\mu_D = WCD \times \mu_W + (1-WCD) \times \mu_O \tag{18}$$

14. Determine the pump discharge pressure. PD is the sum of the hydrostatic pressure in the return conduit, the friction loss, and the wellhead back pressure <u>IF</u> the return GLR is less the 10. Determine PFD using Equation 12.

$$PD = PWH + GDxD + PFD \tag{19}$$

For a higher return GLR, a flowing gradient correlation should be used to determine PD.

15. Calculate a new value of pressure ratio. N is determined from its definition in Equation 5.

$$N = \frac{PD - PS}{PN - PD}$$

16. Based on the value of N, use Figure 3 or Table 1 to determine the optimum area ratio (R).

17. Using the Performance Design Curve in Figure 3, find a new value of M corresponding to the value of N from STEP 15. Rather than the curve, Equation 7a in the appendix can be used to calculate M, using the value of R found in Table 1.

IF CAVITATION WAS DETERMINED IN STEP 20, use the performance curve in Figure 2 to find a new value of M rather than the curve in Figure 3. Use the value of R determined in STEP 16. Rather than using Figure 2, Equation 7a in the appendix can be used to calculate M.

18. Compare the new value of M to the previous value of M. If the change in M is less than 1%, consider the solution to be converged and go to STEP 19. Otherwise, go to STEP 6 using the new value of M.

19. Compute the flow ratio at the cavitation limit. ML is determined from Equation 7.

$$ML = \frac{1 - R}{R} \sqrt{\frac{PS}{1.3\ (PN-PS)}}$$

20. If $M < ML$, cavitation is not a problem. Proceed to STEP 24. If $M > ML$, this solution will result in cavitation and adjustments are necessary. Go to STEP 21.

21. Set $M = ML$ and use the selected value of area ratio, R in Equation 2 to compute a new value of pressure ratio, N. The performance curves in Figure 2 can also be used to find the value of N corresponding to ML. The value or R should be held constant in the calculations for avoiding cavitation.

22. Compute a reduced triplex pressure for avoiding cavitation.

$$PT = \frac{PD - PS}{N} + PD - GNxD + PFN \qquad (20)$$

23. Repeat calculations to avoid cavitation. Go to STEP 5.

24. Compute the nozzle area required for the calculated power fluid rate. Use Equation 1.

$$AN = \frac{QN}{832\sqrt{(PN-PS)/GN}}$$

The area ratio found in STEP 16 along with the nozzle area found in STEP 24 define the optimum jet pump geometry for the designated surface operating pressure. This nozzle area is an ideal nozzle size required to pass the calculated power fluid rate. Since this exact nozzle size is usually not commercially available, the next step is to select the closest nozzle size which is available. A mixing tube is then selected that will combine with the selected nozzle to give the optimum area ratio.

EXAMPLE CALCULATIONS

The above procedure is used with the following well data as an example.

WELL DATA

Depth:	5000 ft.	Oil API Gravity:	30 °API
Tbg. Length:	6000 ft.	Water Gradient:	0.45 psi/ft
Tbg. O.D.:	2.375 in.	Oil Viscosity:	2.5 cp
Tbg. I.D.:	1.995 in.	GOR:	0 scf/bbl
Return I.D.:	4.892 in.	Water Fraction:	0.30
Wellhead Press:	100 psi	Production Rate:	500 BPD
Power Fluid:	Oil	Bottomhole Press:	1000 psi

1. Specify the desired surface operating pressure, PT.

$$PT = 3000 \text{ psi}$$

2. As a starting value, set the flow ratio to 1.

$$M = 1$$

3. Compute the pressure gradient of the produced oil from its API gravity.

$$GO = \frac{0.433 \times 141.5}{131.5 + {}^{\circ}API}$$

$$GO = \frac{0.433 \times 141.5}{131.5 + 30} = 0.38 \text{ psi/ft}$$

4. Compute the pressure gradient of the produced fluid from the oil and water gradients.

$GS = WC \times GW + (1 - WC) \times GO$

$GS = 0.30 \times 0.45 + (1 - 0.30) \times 0.38 = 0.40$

5. Estimate the formation volume factor.

$BT = [1 + 2.8\ (GOR/PS)^{1.2}](1-WC) + WC$

$BT = [1 + 2.8\ (0/1000)^{1.2}](1-0.30) + 0.30 = 1.0$

6. Compute the power fluid rate based on the desired production rate and the flow ratio (M).

$$QN = \frac{GS \times QS \times BT}{GN \times M}$$

$$QN = \frac{0.4 \times 500 \times 1}{0.38 \times 1} = 526 \text{ BPD}$$

7. Using Equation 12, compute the pressure loss in the power fluid tubing string.

For L=6000 ft, Q=536 BPD, D1=1.995, D2=0., μ=2.5 cp, G=.38

PFN = 19 psi

8. Calculate the power fluid pressure at the nozzle.

$PN = PT + GN \times D - PFN$

$PN = 3000 + 0.38 \times 5000 - 19 = 4881$ psi

9. Calculate the flow rate of the return fluid.

$QD = QN + QS$

$QD = 526 + 500 = 1026$ BPD

10. Calculate the gradient of the return fluid.

$$GD = \frac{GS \times QS + GN \times QN}{QD}$$

$$GD = \frac{0.4 \times 500 + 0.38 \times 526}{1026} = 0.39 \text{ psi/ft}$$

11. Calculate the water fraction for the return fluid.

$$WCD = \frac{GD - GO}{GW - GO}$$

$$WCD = \frac{0.39 - 0.38}{0.45 - 0.38} = 0.14$$

12. Determine the return flow gas liquid ratio.

$$GLR = \frac{QS\ (1-WC)\ GOR}{QD}$$

$$GLR = \frac{500(1-0.3)\ 0}{1026} = 0 \text{ scf/bbl}$$

13. Determine the viscosity of the return fluid.

$$\mu_D = WCD \times \mu_w + (1-WCD) \times \mu_o$$

$$\mu_D = 0.14x.55 + (1-0.14)x2.5 = 2.2$$

14. Determine the pump discharge pressure.

PFD is calculated using Equation 12.
L=6000 ft., Q=1026 BPD, D1=4.892, D2=2.375, μ=2.2cp, G=0.39

PFD = 3 psi

PD = PWH + GDxD + PFD

PD = 100 + 0.39x5000 + 3 = 2053 psi

15. Calculate a new value of pressure ratio.

$$N = \frac{PD - PS}{PN - PD}$$

$$N = \frac{2053 - 1000}{4881 - 2053} = 0.372$$

16. Based on the value of N, use Figure 3 or Table 1 to determine the optimum area ratio (R).

From Table 1, R = 0.25

17. Using the Performance Design Curve in Figure 3, find a new value of M corresponding to the value of N from STEP 15. Rather than the curve, Equation 7a in the appendix can be used to calculate M, using the value of R found in Table 1.

From the appendix C1=.5, C2=.0556, C3=0.75, C4=1.03

From Equation 7a M=0.873

18. Compare the new value of M to the previous value of M. If the change in M is less than 1%, consider the solution to be converged.

M=0.873, Previous M = 1.

No convergence. Go to STEP 6 using the new value of M.

SECOND ITERATION

6. Compute the power fluid rate based on the desired production rate and the flow ratio (M).

$$QN = \frac{GS \times QS \times BT}{GN \times M}$$

$$QN = \frac{0.4 \times 500 \times 1}{0.38 \times 0.873} = 603 \text{ BPD}$$

7. Using the Equation 12 compute the pressure loss in the power fluid tubing string.

For L=6000 ft, Q=603 BPD, D1=1.995, D2=0., μ=2.5 cp, G=.38

PFN = 24 psi

8. Calculate the power fluid pressure at the nozzle.

$$PN = PT + GN \times D - PFN$$

$$PN = 3000 + 0.38 \times 5000 - 24 = 4876 \text{ psi}$$

9. Calculate the flow rate of the return fluid.

$$QD = QN + QS$$

$$QD = 603 + 500 = 1103 \text{ BPD}$$

10. Calculate the gradient of the return fluid.

$$GD = \frac{GS\text{x}QS + GN\text{x}QN}{QD}$$

$$GD = \frac{0.4\text{x}500 + 0.38\text{x}603}{1103} = 0.389 \text{ psi/ft}$$

11. Calculate the water fraction for the return fluid.

$$WCD = \frac{GD - GO}{GW - GO}$$

$$WCD = \frac{0.389 - 0.38}{0.45 - 0.38} = 0.129$$

12. Determine the return flow gas liquid ratio.

$$GLR = \frac{QS\ (1\text{-}WC)\ GOR}{QD}$$

$$GLR = \frac{500(1\text{-}0.3)\ 0}{1103} = 0 \text{ scf/bbl}$$

13. Determine the viscosity of the return fluid.

$$\mu_D = WCD \times \mu_w + (1\text{-}WCD) \times \mu_o$$

$$\mu_D = 0.129\text{x}.55 + (1\text{-}0.129)\text{x}2.5 = 2.25$$

14. Determine the pump discharge pressure.

PFD is calculated using Equation 12.
L=6000 ft., Q=1103 BPD, D1=4.892, D2=2.375, =2.25cp, G=0.389
PFD = 3 psi

PD = PWH + GDxD + PFD

PD = 100 + 0.389x5000 + 3 = 2048 psi

15. Calculate a new value of pressure ratio.

$$N = \frac{PD - PS}{PN - PD}$$

$$N = \frac{2048 - 1000}{4876 - 2048} = 0.371$$

16. Based on the value of N, use Figure 3 or Table 1 to determine the optimum area ratio (R).

R = 0.25

17. Using the Performance Design Curve in Figure 3, find a new value of M corresponding to the value of N from STEP 15. Rather than the curve, Equation 7a in the appendix can be used to calculate M, using the value of R found in Table 1.

From the appendix C1=.5, C2=.0556, C3=0.75, C4=1.03

From Equation 7a M=0.876

18. Compare the new value of M to the previous value of M. If the change in M is less than 1%, consider the solution to be converged.

M=0.876, Previous M = 0.873

$$\frac{0.876-0.873}{0.873} \times 100 = .34\ \% < 1\%$$

Convergence - Go To STEP 19

19. Compute the flow ratio at the cavitation limit. ML is determined from Equation 7.

$$ML = \frac{1 - R}{R} \sqrt{\frac{PS}{1.3\ (PN-PS)}}$$

$$ML = \frac{1 - 0.25}{0.25} \sqrt{\frac{1000}{1.3(4876-1000)}} = 1.336$$

20. If M < ML, cavitation is not a problem. Proceed to STEP 24. If M > ML, this solution will result in cavitation and adjustments are necessary. Go to STEP 21.

M = 0.871 ML = 1.336 Therefore cavitation is not a problem. Go to STEP 24

24. Compute the nozzle area required for the calculated power fluid rate. Use Equation 1.

$$AN = \frac{QN}{832\sqrt{(PN-PS)/GN}}$$

$$AN = \frac{603}{832\sqrt{(4876-1000)/.38}}$$

$$AN = 0.0071 \text{ sq. in.}$$

DISCUSSION

The jet pump nozzle that will produce this well with a surface operating pressure of 3000 psi has a flow area of 0.0071 sq.in. It will require 603 BPD of power fluid to produce 500 BPD. The performance curve which will have the highest value of pressure ratio for these conditions corresponds to an area ratio of 0.25. This means the mixing tube area needs to be 4 times that of the nozzle or 0.0284 sq.in. As can be seen from Table 2, Guiberson does not have a nozzle area of 0.0071 sq.in. The closest nozzles to this size are the A nozzle with an area of 0.0055 sq.in. and the B nozzle with an area of 0.0095 sq.in. With the A nozzle, a number 2 mixing tube will give an area ratio of 0.29 and a number 3 mixing tube will give an area ratio of 0.23. With the B nozzle, a number 5 mixing tube will give an area ratio of 0.25.

If an operating pressure different from the 3000 psi had been specified, a different pump geometry would have resulted. A lower operating pressure would lead to a larger nozzle size, while a smaller nozzle would require a higher operating pressure. If 2500 psi had been used in the example calculations, the nozzle area would have been 0.0093 sq. in. with an area ratio of 0.30. This geometry matches a Guiberson B-4 jet pump very closely. The choice of a higher operating pressure would have resulted in a closer match with the size A nozzle.

CONCLUSION

The horsepower provided by a hydraulic pump is represented by the pressure and flow rate of the power fluid supplied to the pump. When matching a pump to a specific well, a tradeoff is made between the pressure and rate. In the case of the jet pump this tradeoff is accomplished by moving along the performance curves in Figure 2 or the design curve in Figure 3. As the power fluid rate is increased, the operating pressure will tend to decrease according to the characteristics of the pump. However, as a result of pressure losses in the tubulars, this increase in power fluid rate will tend to increase the operating pressure. In most installations either the pump characteristics or the pressure losses will be significantly dominate over the other.

If the pressure losses dominate the relationship between pressure and rate, the described method will not usually converge for reasonable values of operating pressure. A trial and error method is then required for obtaining a geometry that will work. In some cases, the direct calculation will converge for a high operating pressure and the results used as a starting point for the trial and error process. When the pump performance is dominate over the friction pressure losses, this method of selecting a jet pump geometry is effective.

REFERENCES

1. Petrie, Hal, Phil Wilson, and Eddie Smart, "The Theory, Hardware, and Application of the Current Generation of Oil Well Jet Pumps", Southwestern Petroleum Short Course, April 27-28,1983, Texas Tech University.
2. Petrie, Hal, Phil Wilson, and Eddie Smart, Jet Pumping Oil Wells", World Oil, November and December 1983, January 1984.
3. Coberly, C. J., "Theory and Application of Hydraulic Oil Well Pumps",Kobe,Inc. Huntington Park, Calif., 1961.
4. Cunningham, R. G., A. G.Hansen, and T. Y. Na, "Jet Pump Cavitation", Journal of Basic Engineering, Transactions of the ASME, September 1970.

GLOSSARY

AN Flow area of the nozzle (sq. in.)
D Vertical depth of well (ft)
D1 Inside diameter of tubing or casing (in)
D2 OD of inner tubing in annular flow (in)
GD Gradient of mixed power fluid and produced fluid returning to surface (psi/ft)
GLR Gas-liquid ratio in return flow to surface (scf/bbl)
GN Gradient of power fluid passing through nozzle (psi/ft)
GO Gradient of produced oil (psi/ft)
GOR Gas-oil ratio (scf/bbl)
GS Gradient of well produced fluid (psi/ft)
GW Gradient of water (psi/ft)
KN Nozzle loss coefficient
KTD Throat-diffuser loss coefficient
L Tubing length (ft)
M Dimensionless Mass Flow Ratio
ML Dimensionless Mass Flow Ratio at Cavitation
N Dimensionless pressure recovery ratio
PD Pump discharge pressure (psi)
PF Friction loss in tubing (psi)
PFN Friction loss in power fluid tubing (psi)
PFD Friction loss in return conduit (psi)
PN Pressure at the nozzle entrance (psi)
PS Pump suction pressure (producing bottomhole pressure) (psi)
PT Surface operating pressure (triplex pressure) (psi)
PWH Flowline pressure at the wellhead (psi)
QD Flow rate from pump discharge (BPD)
QN Flow rate through the nozzle (BPD)
QS Flow rate to pump suction (production flow rate) (psi)
R Dimensionless ratio of nozzle area to throat area
WC Production water fraction
WCD Water fraction of return flow
μ Viscosity (cp)
μ_D Viscosity of return fluid (cp)
μ_O Viscosity of oil (cp)
μ_W Viscosity of water (cp)

APPENDIX

The non-dimensional performance of the jet pump as described by Equation 1 is given as pressure ratio being a quadratic function of flow ratio. When the values of flow ratio and area ratio are known, the equation is easy to evaluate for pressure ratio. In the problem of determining an optimum pump, the values of area ratio and pressure ratio are known and the value of flow ratio is needed. To accomplish this, Equation 1 can be arranged as a standard quadratic equation for a fixed value of area ratio. The quadratic formula can then be applied to determine a value of flow ratio for a given value of pressure ratio. The first step is to rewrite Equation 1 in a simpler form by defining new coefficients which are function of area ratio.

$$N = \frac{C1 + C2\ M^2 - C3\ (1+M)^2}{C4 - C1 - C2\ M^2 + C3\ (1+M)^2} \tag{1a}$$

Where

$$C1 = 2xR \tag{2a}$$
$$C2 = (1-2R)R^2 /\ (1-R)^2 \tag{3a}$$
$$C3 = (1+KTD)R^2 \tag{4a}$$
$$C4 = 1+KN \tag{5a}$$

Equation 1a can then be rearranged as below.

$$(C2-C3)\ M^2 - (2xC3)\ M + C1 - C3 - (C4\ N\ /\ (N+1)) = 0 \tag{6a}$$

The quadratic formula may then be applied to Equation 6a to yield M as a function of N.

$$M = \frac{C3 - \sqrt{C2xC3 + C3xC1 - C2xC1 + C4(C2-C3)\ N\ /\ (N+1)}}{C2 - C3} \tag{7a}$$

The performance curves in Figure 1 are the half of the function which is defined by the negative sign in the quadratic formula.

Equation 7a can be used along with Equation 2a-5a to calculate a value of flow ratio for given values of pressure ratio and area ratio.

Table 1
Optimum Area Ratios

AREA RATIO	PRESSURE RATIO RANGE
0.60	2.930 - 1.300
0.50	1.300 - 0.839
0.40	0.839 - 0.538
0.30	0.538 - 0.380
0.25	0.380 - 0.286
0.20	0.286 - 0.160
0.15	0.160 -

These values are for the coefficients shown in Figure 1. A similar table can be constructed for different curves by determining the points were the performance curves intersect.

Table 2
Jet Pump Size and Area Ratio Chart

	MIXING TUBE SIZE CODE	NOZZLE SIZE CODE / DIAMETER	2" & 2-1/2" NOZZLE SIZES DD	CC	BB	A	B	C	D	E	F	G	H	I	3" NOZZLE SIZES J	K	L	M	N	P
			.045	.060	.070	.084	.110	.125	.150	.175	.200	.240	.290	.330	.400	.450	.500	.560	.630	.700
2" & 2-1/2" MIXING TUBE SIZES	000	.075	.36	.64																
	00	.095	.22	.40	.54															
	0	.115		.27	.37	.53	.91													
	1	.135		.20	.27	.39	.66	.86												
	2	.155			.20	.29	.50	.65												
	3	.175				.23	.40	.51	.74											
	4	.200					.30	.39	.56	.77										
	5	.220					.25	.32	.46	.63										
	6	.240					.21	.27	.39	.53	.69									
	7	.260						.23	.33	.45	.59									
	8	.290							.27	.36	.48	.68								
	9	.320							.22	.30	.39	.56								
	10	.350								.25	.33	.47	.69							
	11	.390								.20	.26	.38	.55	.72						
	12	.430									.22	.31	.45	.59	.87					
	13	.475										.26	.37	.48	.71	.88				
	14	.525										.21	.30	.40	.58	.73	.90			
3" MIXING TUBE SIZES	15	.576											.25	.33	.48	.61	.75			
	16	.631												.27	.40	.51	.63	.79		
	17	.691												.23	.34	.42	.52	.66	.83	
	18	.758													.28	.35	.44	.55	.69	.85
	19	.831													.23	.29	.36	.45	.57	.71
	20	.911														.24	.30	.38	.48	.59

R

$$R = \frac{AN}{AT}$$

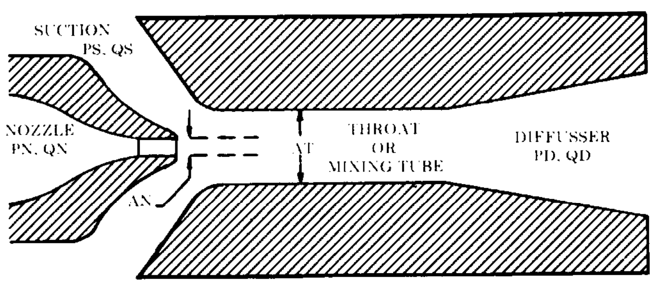

Figure 1 - Jet pump nomenclature

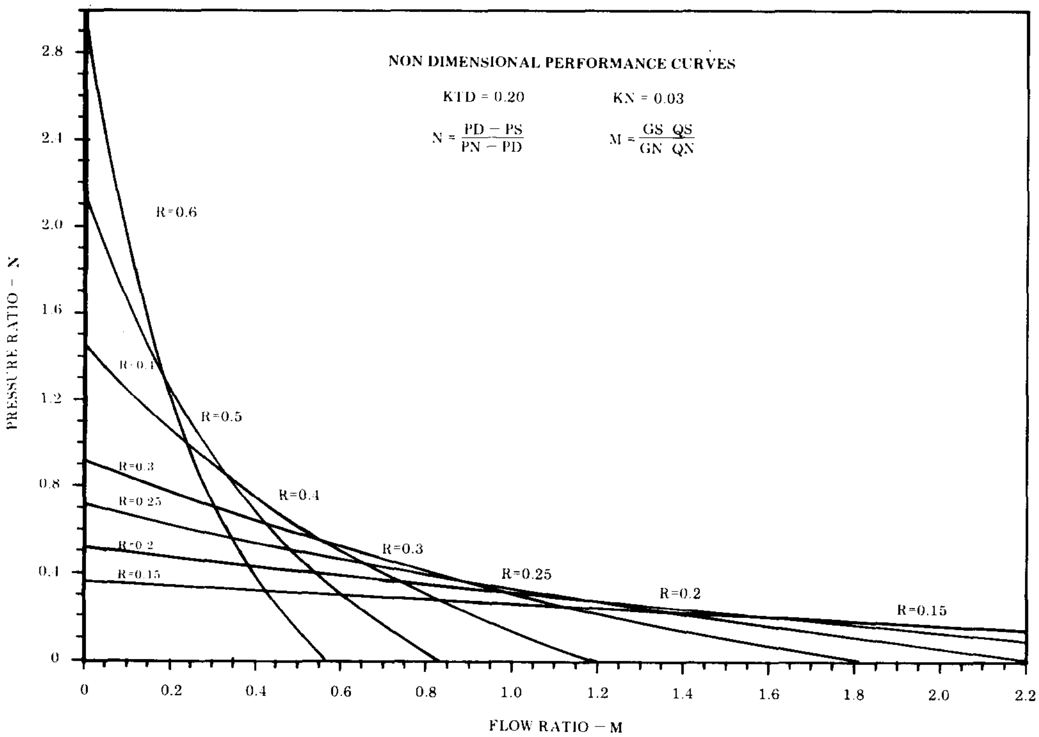

Figure 2

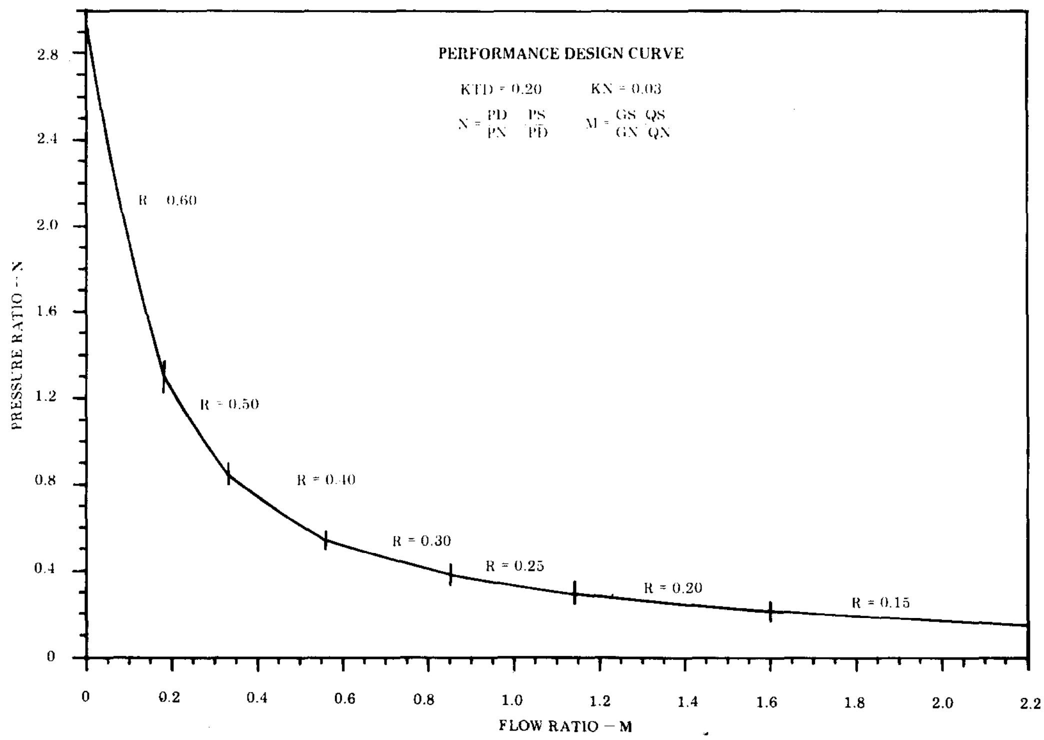

Figure 3