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Original Article

Experimental investigation of jet pump performance used for high flow amplification in nuclear applications

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ABSTRACT

The jet pump can be used in a test device of a nuclear reactor for high flow amplification as it reduces inlet flow requirement and thereby size of the process components. In the present work, a miniature jet pump was designed to meet high flow amplification greater than 3. Subsequently, experiments were carried out using a test setup for design validation and performance evaluation of the jet pump for different parameters. It was observed that a minimum pressure of 0.6 bar (g) was required for the secondary fluid inside the jet pump to ensure cavitation free performance at high amplification. Spacing between the nozzle tip and the mixing chamber entry point had significant effect on the performance of the jet pump. Variation in primary flow, temperature and area ratio also affected the performance. It was observed that at high flow amplification, the analytical solution differed significantly from experimental results due to very large velocities encountered in the miniature size jet pump.

1. Introduction

The jet pump is a device in which the energy of a primary motive fluid is transferred to a secondary fluid through momentum transfer. It does not have any moving parts and has wide industrial applications like deep well pumping, booster pumping, aeration etc. [1,2]. One of the main design parameter for jet pump is the ratio between the secondary flow and the primary flow (termed as flow amplification or flow ratio). In the nuclear industry, jet pump is mainly used for achieving flow amplification in primary recirculation system of Boiling Water Reactor (BWR) [3]. Jet pumps for these conventional applications normally have low to moderate flow ratios (0.5–2.0). Analytical, numerical and experimental results are available in the open literature for jet pumps with low to moderate flow ratios. For some special applications in nuclear industry, jet pumps are used for achieving very high flow ratios (>2.5) with miniature sizes. Studies reported in open literature on miniature jet pumps are limited. Performance of this type of jet pump and its dependency on various parameters can significantly differ from conventional jet pumps. Experimental investigation on performance of the miniature jet pump for high flow ratio will provide useful data for understanding the behavior of jet pumps used for special nuclear applications.

1.1. Description of jet pump

Jet pump differs from other categories of pump basically due to its principle, in which energy to the induced (secondary) fluid is imparted through the kinetic energy of inducing (primary or driving) fluid instead of via rigid moving parts (e.g., impeller, piston). The simplified diagram of the jet pump is shown in Fig. 1. It mainly consists of a nozzle, a mixing chamber and a diffuser. Fig. 1 also shows various geometric parameters, process parameters and performance parameters.

As indicated in Fig. 1, the primary fluid flow (Q_1) is supplied at high pressure through the nozzle. Because of the high velocity at the nozzle tip and associated pressure dip at this location, secondary flow (Q_2) is drawn towards the tip and it enters into the mixing chamber. The primary and secondary flow merges together in the mixing chamber and subsequently pressure recovery takes place in the diffuser provided at the outlet of the mixing chamber.

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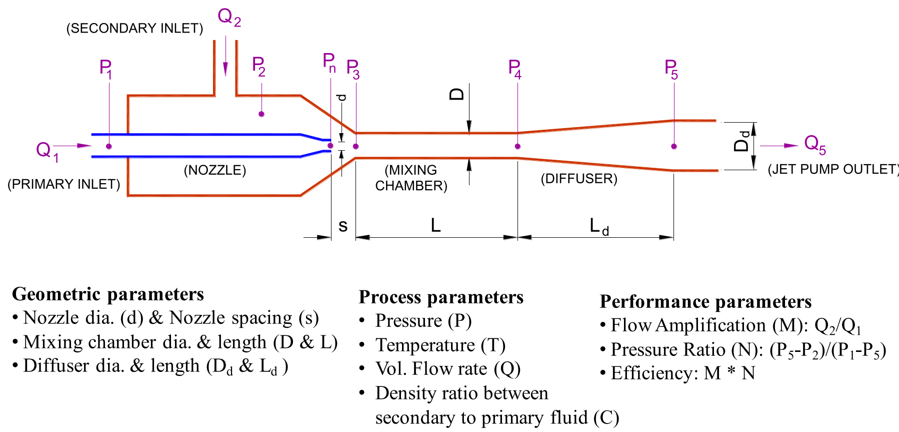


Fig. 1. Simplified diagram of a jet pump.

Typical pressure profile for the secondary fluid along the length of the jet pump is shown in Fig. 2, which shows the pressure drop from P_2 to P_n and subsequently to P_3. Further downstream to this pressure increases to P_4 due to momentum mixing with primary fluid and finally recovery of pressure in the diffuser from P_4 to P_5.

The performance of jet pump is evaluated based on the following main parameters:

$$\text{Flow amplification or flow ratio}, M = \frac{\text{Volumetric flow rate of secondary fluid } (Q_2)}{\text{Volumetric flow rate of primary fluid } (Q_1)} \quad (1)$$

$$\text{Pressure ratio}, N = \frac{\text{Pressure gained by secondary fluid } (P_5 - P_2)}{\text{Pressure loss by primary fluid } (P_1 - P_5)} \quad (2)$$

$$\text{Efficiency}, \eta = M * N \quad (3)$$

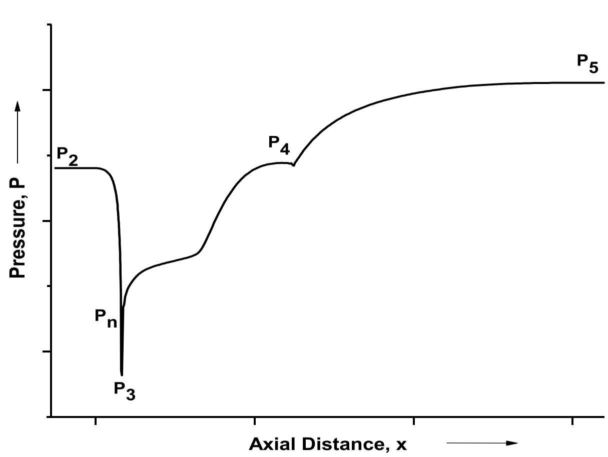


Fig. 2. Typical axial pressure profile for secondary fluid in the jet pump.

1.2. Motivation for the present study

The jet pump used in conventional applications generally works with flow amplification less than 2. However, in some special application like in the test device of a nuclear reactor, jet pump is used to amplify the flow required for nuclear heat removal. This helps to reduce the process flow requirements of the cooling system resulting in size reduction of equipment, piping, associated control & instrumentation and accessories. This also reduces the floor space requirement, active fluid hold up and capital & operating cost of the process system. The flow amplification requirement for these jet pumps is higher than 2.5. This high flow amplification can be achieved by low area ratio (<0.1) of nozzle to mixing chamber. Since the total flow rate requirement in the test device is comparatively small and because of space constraints, miniature size jet pump with nozzle diameter of 1–1.2 mm is required for this type of application.

Literature is available for liquid-liquid jet pumps having area ratios 0.15–0.6 and nozzle diameter above 5 mm, which are generally used for conventional applications. Kundrika and Gluntz [3] carried out both analytical and experimental studies for the development of jet pump for BWR. The nozzle diameter and area ratio of the jet pump considered were 83 mm and 0.166 respectively.

For low area ratio (<0.1) jet pumps, very few studies have been reported. Sanger [4] carried out experimental evaluation for jet pumps with area ratio of 0.066 and 0.197. The pressure profile inside the jet pump was experimentally measured. The performance deterioration because of cavitation was also studied. The nozzle diameter considered was 8.8 mm. Yapici et al. [5,6] carried out numerical optimization for different parameters like nozzle spacing, mixing chamber length etc. for a wide range of area ratios

(0.06–0.5). They also investigated the effect of dimension scale and roughness on the performance of jet pump. The nozzle diameter considered was 15 mm.

For low area ratio with miniature size nozzle, Marini et al. [7] carried out theoretical and experimental studies pertaining to aircraft fuel engine application. These studies were carried out for nozzle diameters from 0.5 to 1.45 mm and area ratios 0.01 to 0.172. They had studied the behavior of jet pump for aircraft fuel having molecular viscosity much different than that of water. It was reported that loss coefficients recommended in literature for analytical design of the jet pump are applicable for limited range of flow ratio only.

The low area ratio jet pump is energy inefficient (~10–20%) compared to conventional area ratio jet pump (~25–35%). Due to limited literature available on low area ratio miniature size water jet pump, the performance study was carried out earlier for one typical case of jet pump to compare the numerical (using standard k- ε turbulent model) and experimental results [8].

This paper presents the performance evaluation of the miniature size low area ratio jet pump through experiments under various operating conditions to find the minimum required pressure to avoid cavitation. Experiments were carried out for different nozzle spacings and recommended spacing was established for better performance of the jet pump. Parametric study was done by varying primary flow, temperature and area ratio. The results are compared with the reported findings of previous researchers for conventional jet pumps.

2. Analytical model

The analytical model [1,2] for the pressure ratio (N) obtained using 1-D mass balance and momentum balance equations for incompressible flow is shown below.

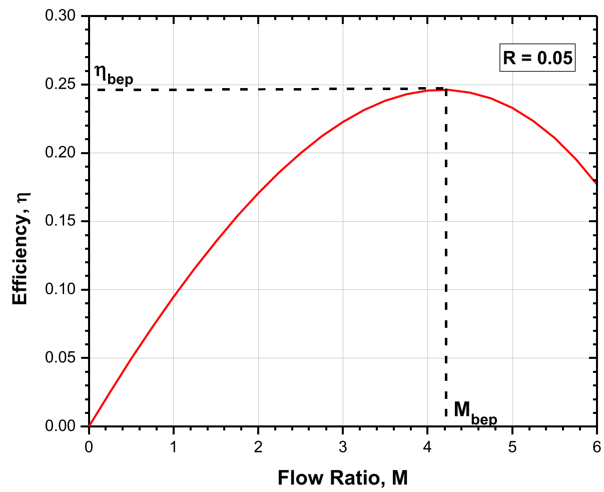


Fig. 3. Performance curve from analytical model for area ratio (R) = 0.05.

given area ratio (R). Using the typical loss coefficients values (K_n = 0.04, K_s = 0.1, $K_m + K_d$ = 0.25) at high Reynolds number obtained from literature [1] and equal density ratio (C = 1), efficiency (η) vs. flow ratio (M) curve is generated as shown in Fig. 3 for the area ratio (R) of 0.05 (as an example). At best efficiency point (bep) from Fig. 3, maximum efficiency (η_{bep}) is found to be about 0.25 and corresponding flow ratio (M_{bep}) is about 4.2. Similar calculations were carried out for different values of area ratio (R) to find the best efficiency point for each case. The best efficiency (η_{bep}) and corresponding flow ratio (M_{bep}) vs. area ratio (R) plot is generated as shown in Fig. 4. It can be seen that design the area ratio (R) is to be kept less than 0.1 for designing a jet pump to obtain

$$N = \frac{2R + \left(\frac{2CM^2R^2}{(1-R)}\right) - R^2\left(1 + K_m + K_d + a^2\right)(1+M)(1+CM) - \left(\frac{CM^2}{S^2}\right)(1+K_S)}{1 + K_n - 2R - \left(\frac{2CM^2R^2}{(1-R)}\right) + R^2\left(1 + K_m + K_d + a^2\right)(1+M)(1+CM) + (1-j)\frac{CM^2}{S^2}(1+K_S)} \tag{4}$$

The efficiency of the jet pump is defined as multiplication of M and N as mentioned in equation (3).

At very high flow ratio, if pressure is not sufficiently above the vapor pressure at the nozzle exit region, there may be cavitation due to pressure dip. In order to ensure cavitation free flow, the design flow ratio is to be kept below the cavitation limiting flow ratio (M_L) for the given suction pressure (P_2). The cavitation limiting flow ratio (M_L) is predicted from the following equation [9]:

$$M_L = \frac{(1-R)}{R}\sqrt{\frac{(P_2 - P_v)}{Z\sigma}} \tag{5}$$

The analytical model assumes uniform velocity profile at entry and complete mixing inside mixing chamber. It is derived for a zero nozzle spacing and therefore does not consider variation in nozzle spacing. Also, there are additional uncertainty associated with the loss coefficients (K_n, K_s, K_m & K_d), which are input to the analytical model [1]. The performance is quite sensitive towards these loss coefficients used in modelling of the jet pump.

Eqns. (3) and (4) are used to generate the performance curve i.e., pressure ratio (N) and efficiency (η) vs. flow ratio (M) curves for a

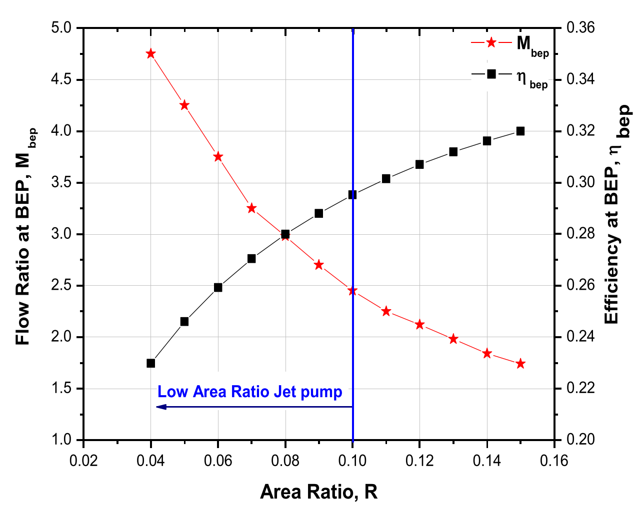


Fig. 4. Flow amplification & efficiency at best efficiency point (M_{bep} & η_{bep}) vs. area ratio (R) from the analytical model.

Table 1
Experimental parameters for miniature jet pump.

Parameter	Value
Mixing chamber diameter (D)	4.5 mm
Nozzle tip diameter (d)	**1.0**/1.1/1.2 mm
Area ratio (R)	**0.05**, 0.06, 0.07
Diffuser diameter (D_d)	9 mm
Diffuser half angle (ϕ)	5°
Nozzle spacing (s)	0, 1, 2, 3, 4, 5 mm
Secondary fluid pressure (P_2)	0, 0.2, 0.3, 0.6, 1.0, 2.0, 3.0 bar(g)
Primary fluid flow (Q_1)	0.6, 1.0, 1.4, **1.8** lpm
Temperature (T)	22, 43, 55 °C

flow ratio greater than 2.5.

3. Jet pump configuration & experimental parameters

Table 1 gives the jet pump dimensions and experimental parameters used for achieving high flow amplification (3–4.5). From the analytical solution (Fig. 4), area ratios (R) 0.05, 0.06 & 0.07 are chosen. The required primary flow rates (Q_1) range from 0.6 to 1.8 lpm for the applications under consideration and corresponding nozzle diameter (d) required are small (1–1.2 mm). The sizes of the nozzles are selected based on the geometrical constraints, velocity required, erosion issues and chocking probability. Temperature during the experimental study range from 22 to 55 °C. Other dimensions (diffuser angle & diameter) are chosen as per conventional design guideline.

For a prospective application, required primary flow (Q_1) is 1.8 lpm and flow amplification is 4.2. This will require an area ratio of 0.05 and nozzle diameter of 1 mm. These are considered as nominal parameters (shown in bold fonts in Table 1) for the optimization/sensitivity study considered in this work.

Experimental sequence and parameters from Table 1 are chosen based on the following criteria.

- Pressure (P_2 or P_t): Due to high flow amplification, it is required to establish the adequacy of suction pressure (P_2) so that cavitation will not take place for selected experimental temperature conditions. Also, experimental determination of cavitation limiting flow ratio (M_L) for different suction pressure (P_2) will give value of cavitation parameter (σ) for miniature size nozzle. The experiments are carried out at zero nozzle spacing (s) as it is more prone to cavitation. Further experiments are carried out keeping suction pressure (P_2) sufficiently above the minimum required pressure.
- Nozzle spacing (s): Optimum value of nozzle spacing (s) needs to be established for the nominal primary flow (Q_1) and area ratio (R). The experiments are carried out for obtaining the jet pump performance curve (N vs. M and η vs. M) at different value of nozzle spacing (s).

Additionally, using the required value of pressure (P_2) and nozzle spacing (s), sensitivity studies are carried out for different values of following parameters:-

- Primary flow (Q_1): To study effect of the nozzle Reynolds number (Re_n) by predicting the performance curves at different primary flow conditions.
- Temperature (T): To study the effect of molecular viscosity and thus skin friction on jet pump performance.
- Area Ratio (R): Since flow amplification at best efficiency point is very much dependent on area ratio, effect of area ratio on performance of jet pump is considered in the experimental study.

The cross section details and photographs of the jet pump assembly & the nozzle are shown in Fig. 5.

4. Experimental setup & procedure

Fig. 6a shows the flow diagram and Fig. 6b is the photograph of the experimental test setup. The centrifugal pump draws water

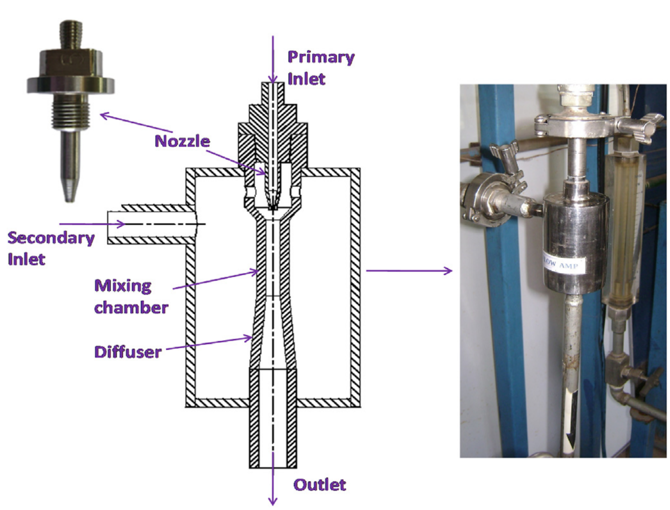


Fig. 5. Details of jet pump assembly.

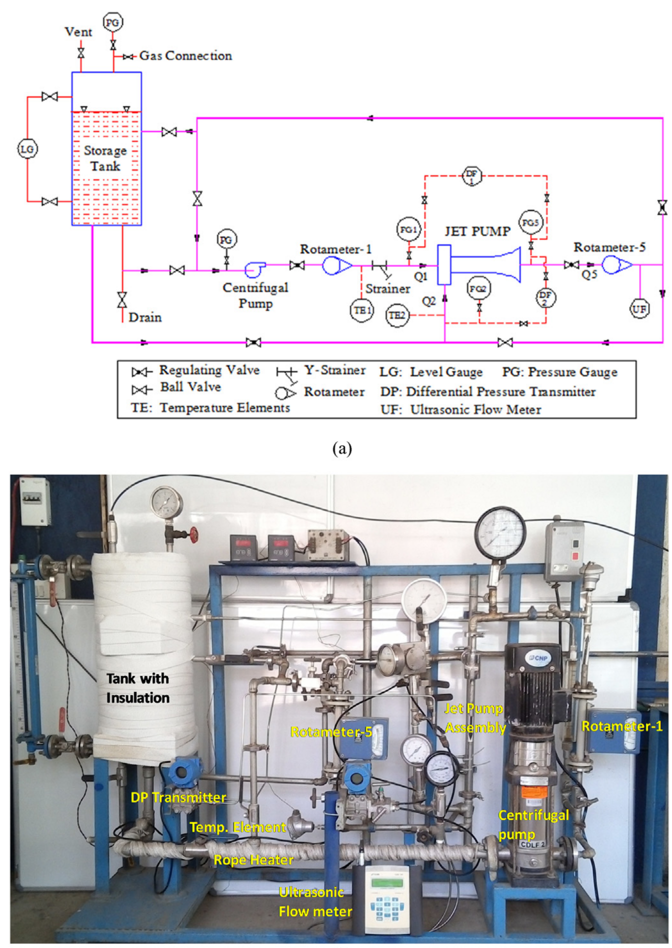


Fig. 6. (a) Flow diagram and (b) photograph of the experimental setup.

from the storage tank and injects water (primary fluid) to the nozzle of the jet pump for flow amplification. The secondary flow is induced by primary flow and transversely drawn into the jet pump assembly. Both the flows get mixed in the mixing chamber and after pressure recovery in the diffuser, exit from the jet pump. Pressure in the tank (P_t) is controlled by applying air pressure above the water level. The pressure gauges PG1, PG2 & PG5 are used to measure pressure at the primary inlet (P_1'), secondary inlet (P_2') and jet pump outlet (P_5') respectively.

Differential pressure transmitters are used to measure $(P_5 - P_2)'$ and $(P_1 - P_5)'$. These data are corrected for frictional drop to evaluate actual pressures (P_1, P_2, P_5) and pressure differentials $(P_5 - P_2)$ & $(P_1 - P_5)$ for characterizing the jet pump. Primary flow rate (Q_1) and total flow rate (Q_5) are measured through the rotameter-1 and rotameter-5 respectively. These flow rates can be controlled through regulating valves provided at the upstream of these rotameters for changing the flow ratio (M). Additionally, total flow rate (Q_5) is measured through ultrasonic flow meter as an independent measurement. Temperature elements are provided to measure the primary and secondary fluid temperatures (T_1 & T_2). The temperature in the system (up to max. 55 °C) can be achieved through the pump heating by continuously operating the system for few hours and also through rope heater provided at the pump suction. The instruments used are calibrated and accuracy of the same is mentioned in Table 2.

4.1. Experimental procedure

Following steps were followed for carrying out the experiments.

a. Fill & vent the system along with storage tank with DM water
b. Pressurize the system using compressed air at the top of the storage tank
c. Check the valve status for ensuring proper flow path
d. Open the valve provided at the upstream of rotameter-5
e. Start the centrifugal pump. Primary flow can be adjusted through the pump discharge valve provided at the upstream of rotameter-1
f. Note down the parameters: primary flow rate Q_1, total flow rate Q_5, pressure P_1', P_2' & P_5', differential pressure $(P_5 - P_2)'$ and $(P_1 - P_5)'$
g. Throttle the valve at upstream of rotameter-5 to vary the total flow rate Q_5 (and thus flow ratio M) and note down all the above parameters
h. All the pressure data & differential pressure data are corrected for taking into account frictional drop between measurement point to the point of interest for predicting characteristics of jet pump
i. Evaluate the following performance parameters as defined equations (1) to (3)
   - Flow ratio $(M) = \frac{Q_2}{Q_1} = \frac{Q_5 - Q_1}{Q_1}$
   - Pressure ratio $(N) = \frac{P_5 - P_2}{P_1 - P_5}$
   - Efficiency $(\eta) = M*N$

Table 2
Accuracy of instruments used in experimental setup.

Instrument	Accuracy
Pressure Gauge	1%
Rotameter	1.5%
Ultrasonic flow meter	0.5%
DP transmitter	0.2%
Temperature sensor	0.2 °C

j. Experiments were carried out varying the following parameters:
   - Pressure (by changing the storage tank compressed air pressure)
   - Nozzle spacing (by providing the washers at the threaded joints between nozzle and jet pump assembly)
   - Primary flow rate (by throttling rotameter-1 upstream valve)
   - Temperature (by continuous operating the system & adding pumping heat and heating through rope heater provided at pump suction line)
   - Area ratio (by changing the nozzle with different diameter in jet pump assembly)

5. Results and discussion

Experiments were carried out to predict the jet pump performance curve (N vs. M and η vs. M) for the combination of parameters of the jet pump as explained in section 3. The effect of various parameters on the performance is described hereunder in details.

5.1. Effect of secondary fluid pressure

The experiments are carried out to find the minimum secondary fluid pressure required to avoid cavitation. The secondary water entry pressure to the jet pump (P_2) is very near to the tank pressure (P_t). The effect of pressure (P_t) on performance curve is shown in Fig. 7. The other parameters are d = 1.0 mm, s = 0.0 mm, $Q_1 = 1.8$ lpm and $T_1 = 43$ °C. It can be seen from figure that for flow ratio greater than 3, the performance of the jet pump is significantly degraded when pressure is less than 0.3 bar (g). The degradation of jet pump performance is due to cavitation at the exit of the nozzle tip at higher value of flow ratio M.

The plot of efficiency (at highest flow ratio M obtained for a given pressure) vs. tank pressure (P_t) is shown in Fig. 8. In order to have pressure independent performance of jet pump, minimum pressure of 0.6 bar (g) is required in the tank. Further experiments are carried out for tank pressure of 2 bar(g) to avoid any chances of cavitation.

The cavitation parameter σ mentioned in Eq. (5) depends on nozzle spacing, internal profile at nozzle and secondary fluid entry. Cunningham et al. [9] summarized the experimentally observed value of cavitation parameter by different researchers and it was found in the range of 0.8–1.67 for most of the cases. However, for the specific cases, Mueller [10] observed higher value of cavitation parameter (6.9–7.7) due to restricted entry of secondary flow by the nozzle and considerable thickness of nozzle tip. For the present case, observed value of M_L is found to be 2.96 and 3.19 for $P_t = 0.0$ and 0.2 bar(g) respectively based on sharp decrease in efficiency (Fig. 7b). Estimated values of σ from equation (5) are 4.5 & 4.2 respectively by using corresponding values of secondary entry pressure (P_2), jet dynamic pressure (Z), vapor pressure (P_v) and area ratio (R). The higher observed value of cavitation parameter may be due to considerable size of nozzle tip thickness of 0.7 mm compared to other dimensions, conical entry for secondary fluid instead of stream line entry (due to fabrication limitation in miniature size jet pump) and fully inserted nozzle (s = 0).

5.2. Effect of nozzle spacing

The effect of nozzle spacing (s) on the performance of the jet pump is significant as reported in the open literature. However, it greatly depends on other parameters also. It is required to optimize the nozzle spacing to give maximum efficiency for the selected parameters & geometry of the jet pump. If secondary fluid entry loss is not significant and mixing chamber length is optimum, best

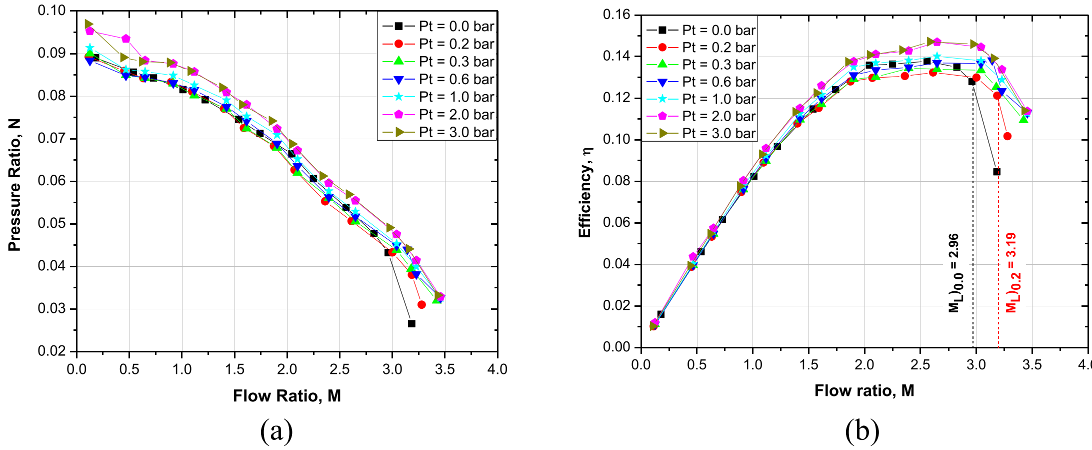


Fig. 7. Effect of pressure on performance of jet pump (d = 1.0 mm, s = 0.0 mm, Q_1 = 1.8 lpm, T_1 = 43 °C).

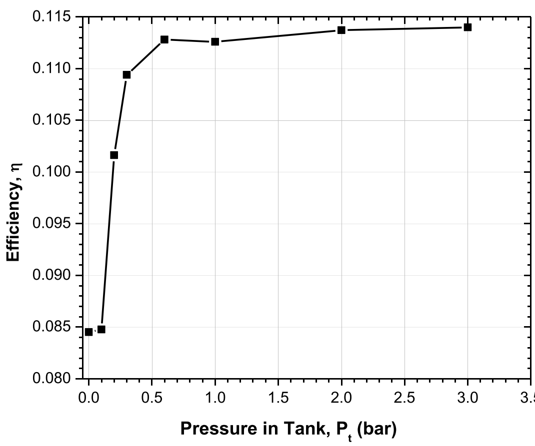


Fig. 8. Plot of efficiency at maximum flow ratio vs. tank pressure.

efficiency is generally obtained for fully inserted nozzle (s = 0). This is due to absence of jet loss i.e., energy loss of jet from the nozzle exit to mixing chamber entrance without doing any work. Nozzle spacing also affects the energy loss (at secondary fluid entry to mixing chamber), which decreases with increase in spacing. Effect of the same is specifically more dominating at higher flow ratio, which is of specific interest for our application.

Generally, nozzle spacing is represented relative to either nozzle diameter (d) or mixing chamber diameter (D). Fig. 9 depicts the effect of relative nozzle spacing (s/d) on the performance of the jet pump with other parameters as: d = 1.0 mm, Q_1 = 1.8 lpm, T_1 = 43 °C, P_t = 2.0 bar.

It can be seen that as relative nozzle spacing (s/d) is increased from 0.0 to 1.0, the performance is observed to deteriorate. It may be due to increase in the jet loss. At s/d = 2.0, the performance improves and is similar to that of fully inserted nozzle (s/d = 0.0). For s/d = 3.0 onwards, the effect of reduction in secondary fluid entry frictional loss starts dominating and performance improves. For s/d = 4.0 & 5.0 performance are similar and better than that for s/d = 3.0.

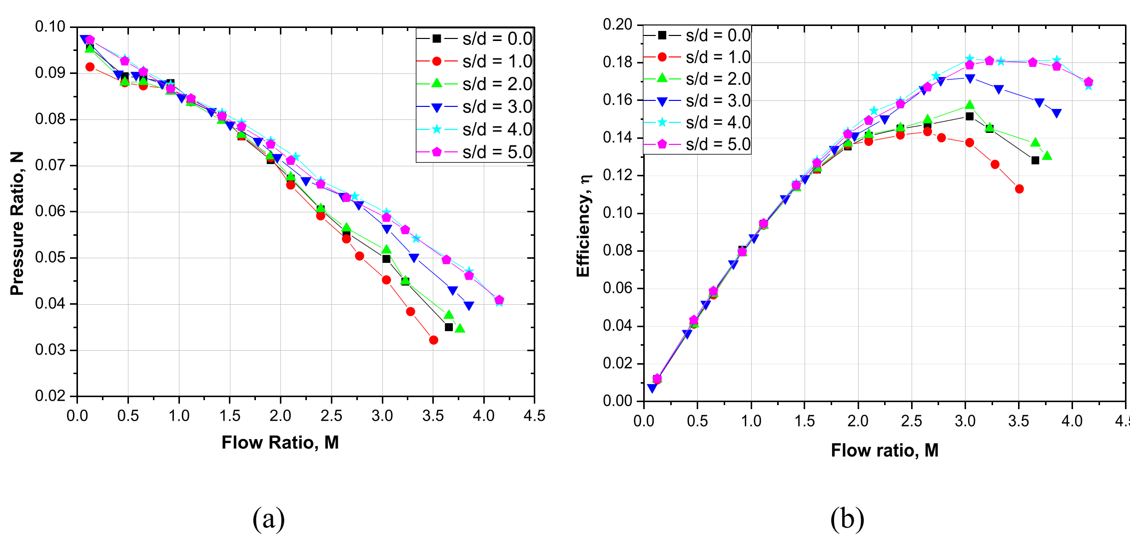


Fig. 9. Effect of nozzle spacing on performance of jet pump (d = 1.0 mm, Q_1 = 1.8 lpm, T_1 = 43 °C, P_t = 2.0 bar).

Fig. 10 shows the plot of relative nozzle spacing on efficiency at maximum flow ratio. It is observed that for low area ratio jet pump with miniature nozzle, optimum performance is achieved for relative nozzle spacing (s/d) of the order of 4–5 for the considered experimental parameters. With relative to mixing chamber diameter (D), optimum relative nozzle spacing (s/D) is ~1.0.

Comparing with the experimental observations reported for the conventional jet pump, Hammoud A.H. [11]. found optimum value of 's/d' as 1.25 for experiments with flow ratio less than 1. Yapici et al. [5] observed optimum value of s/D as 0.74 for jet pump having area ratio of 0.125 with conventional size nozzle. El-Sawaf et al. [12] observed optimum value of s/d as 1.0 for the jet pumps with area ratios of 0.155, 0.25 & 0.4 with nozzle diameter of 10 mm.

The difference in observation for the current experimental results is due to unconventional dimensions of the jet pump along with conical entry for secondary fluid for which entry frictional loss is more dominating than the jet loss.

5.3. Effect of primary fluid flow rate

Flow rate of primary fluid decides the nozzle velocity and thus affects turbulent mixing inside the mixing chamber. At much lower operating velocity than the design velocity, nozzle loss coefficient also increases. Fig. 11 depicts the variation in performance of the jet pump for various primary fluid flow rates keeping other experimental parameters as: d = 1.0 mm, s = 4.0 mm, T_1 = 43 °C and P_t = 2.0 bar. It can be seen that at very low primary fluid flow rate of Q_1 = 0.6 lpm (Re_n = 20,434), performance is poor as compared to other flow rates for all values of flow ratio, due to inefficient suction of secondary fluid and associated mixing. For higher primary fluid flow rates, the performance is almost similar but marginally better for Q_1 = 1.4 lpm (Re_n = 47,681) at higher flow ratio (M > 3.0) due to comparatively less friction loss in the jet pump.

Effect of jet Reynolds number on maximum efficiency for different area ratios from 0.1 to 0.6 was experimentally and analytically studied by Cunningham et al. [13]. It was found that jet Reynolds number (Re_n) doesn't significantly affect the maximum efficiency at Re_n greater than 10,000. The difference observed in the current study may be due to lower area ratio and higher flow ratio, where mixing has to extend more lateral distance in mixing chamber and needs higher jet Reynolds number for the same. Additionally, it may also be due to different nozzle loss coefficient variation with jet Reynolds number because of miniature size nozzle.

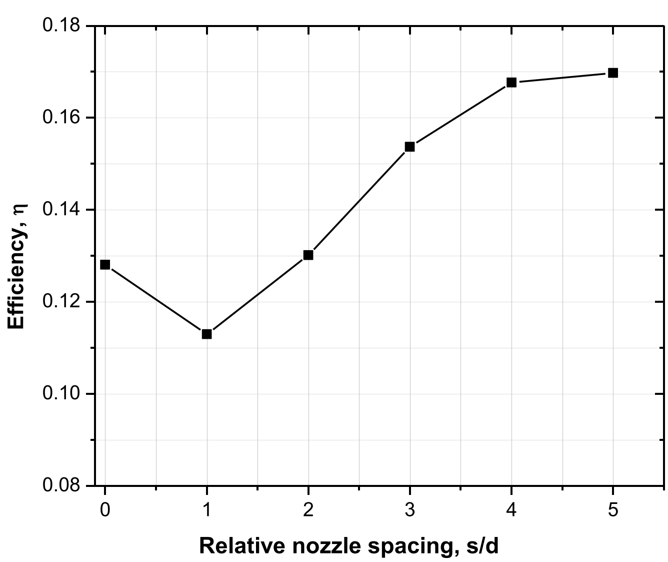


Fig. 10. Plot of efficiency at maximum flow ratio vs. nozzle spacing.

5.4. Effect of temperature

The temperature affects the molecular viscosity and density of the fluid (thus, mixing chamber Reynolds number), which changes the turbulent mixing, viscous dissipation and frictional loss in the jet pump. Performance of the jet pump was evaluated at three different temperatures (22 °C, 43 °C and 55 °C). The other parameters were kept as: d = 1.0 mm, s = 4.0 mm, Q_1 = 1.8 lpm and P_t = 2.0 bar (Fig. 12). Due to design limitation, temperature in the setup could not be increased further. Viscosity of water decreases from 0.95 cP to 0.5 cP by changing the temperature from 22 °C to 55 °C and hence reduces the skin friction energy loss at the jet pump wall. The results clearly show better performance at higher temperature (lower molecular viscosity).

Effect of mixing chamber loss coefficient on performance of conventional jet pump was studied through analytical model by Fredrik Liknes [14] and found that increase in mixing chamber loss coefficient decreases the maximum efficiency as well as optimum flow ratio. It was also observed that the effect of mixing chamber loss coefficient at higher flow ratio is more significant.

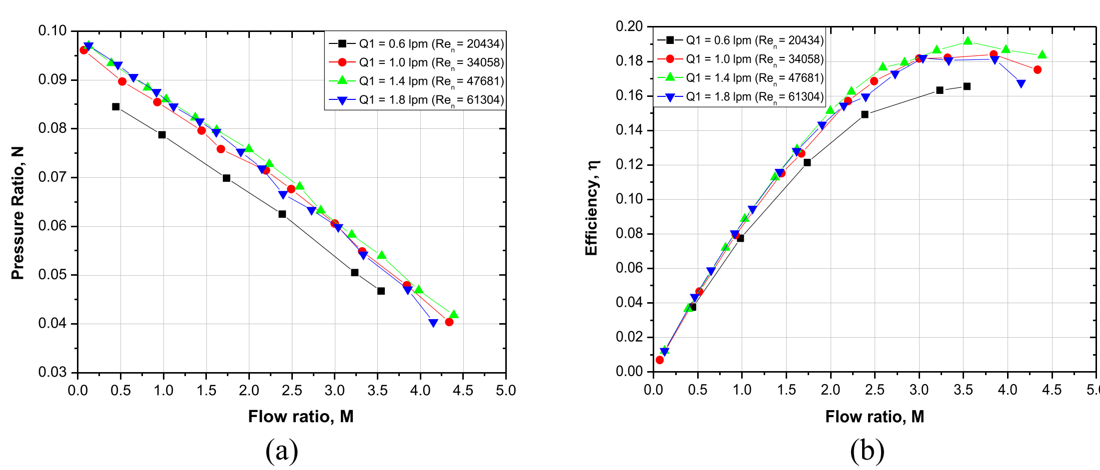
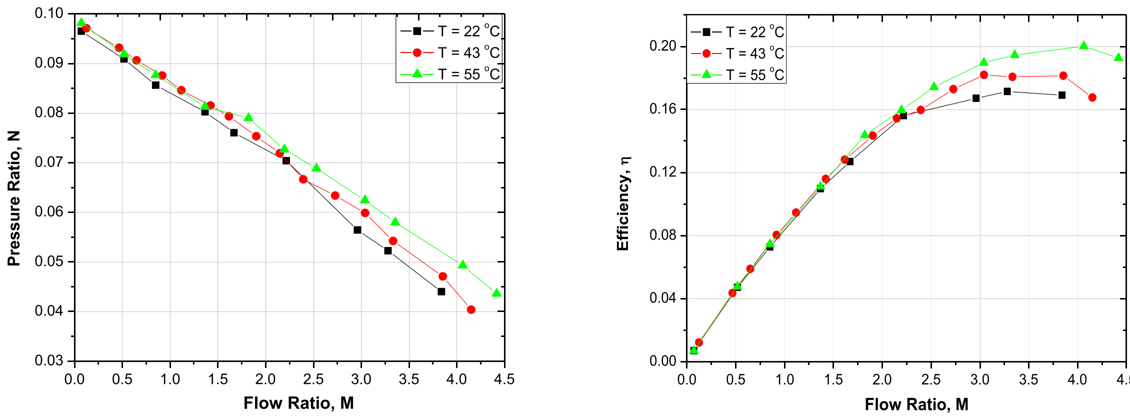


Fig. 11. Effect of flow rate of primary fluid on performance of jet pump (d = 1.0 mm, s = 4.0 mm, T_1 = 43 °C, P_t = 2.0 bar).



(a) (b)

Fig. 12. Effect of temperature on performance of jet pump (d = 1.0 mm, s = 4.0 mm, Q_1 = 1.8 lpm, P_t = 2.0 bar).

5.5. Effect of nozzle diameter

Area ratio (R) is a very important parameter for the jet pump design, which is decided based on required flow ratio (see Fig. 4). Due to very high velocity at the nozzle tip (~38 m/s) at flow rate of 1.8 lpm, erosion may take places during sustained operation, which increases the nozzle tip diameter. Performance studies were carried out for three nozzle diameters (d = 1, 1.1 & 1.2 mm) & thus, the corresponding area ratios (R = 0.05, 0.06 & 0.07). The performance curves for all the three are shown in Fig. 13 keeping other parameters unvaried i.e., Q_1 = 1.8 lpm, T_1 = 43 °C, P_t = 2.0 bar and s = 4.0 mm. It can be seen that increase in nozzle tip diameter has significant effect on the performance. It can also be seen from Fig. 13 that as the area ratio (R) increases, slope of pressure ratio vs. flow ratio changes significantly and also maximum efficiency increases. However, the optimum and maximum achievable flow ratio decrease.

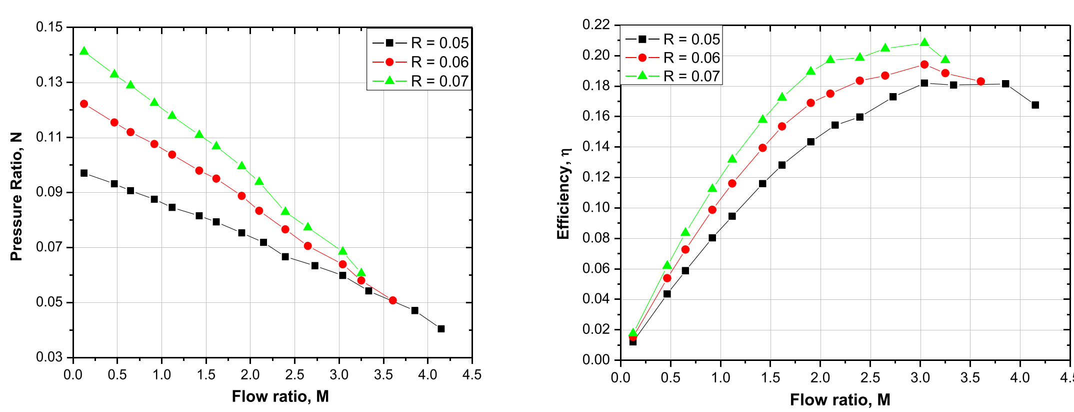
The maximum efficiency is about 20% for area ratio 0.07. However, for the current setup, flow ratio of more than 4.0, can be achieved by using area ratio (R) of 0.05 with a lower efficiency of about 17%.

Yapici et al. [5] carried out study for the jet pump with wide range of area ratios from 0.06 to 0.5. It was found that as the area ratio increases, maximum efficiency (η_{max}) increases but corresponding flow ratio at maximum efficiency decreases. For the jet pump with area ratio 0.06, η_{max} is found to be about 27% at flow ratio (M) near to 4.0. Mixing chamber diameter in the study was 101 mm. Sanger [4] carried out experimental study for jet pump with nozzle diameter of 8.8 mm for two area ratios 0.066 and 0.197 and found maximum efficiency as 29.5% and 35.7% respectively. The efficiency in the present study for similar area ratio (0.06) is about 18%, which is lesser than reported by the earlier researchers due to miniature size. Effect of scale was numerically studied by Aldas K. et al. [6] and found lower dimension scale of the jet pump deteriorates the efficiency significantly due to more turbulent energy dissipation at lower dimension scale.

6. Comparison with analytical solution

The analytical solution is obtained using equations (3) and (4) for typical case of nozzle diameter 1.0 mm (Area Ratio R = 0.05) with Q_1 = 1.8 lpm, T_1 = 43 °C, P_t = 2.0 bar and s = 0.0 mm (as analytical model is applicable for s = 0). Based on the Reynolds number, value of loss coefficients taken from literature are mentioned in Table 3.

The performance curve obtained through analytical solution is compared with experimental results and shown in Fig. 14. It may be seen that analytical solution is in good agreement with the experimental value for flow ratio (M) less than 1.5. This indicates the limitation of analytical model to predict the performance for



(a) (b)

Fig. 13. Effect of area ratio on performance of jet pump (Q_1 = 1.8 lpm, T_1 = 43 °C, P_t = 2.0 bar and s = 4.0 mm).

Table 3
Loss coefficients for analytical solution.

Component for Loss coefficient	Corresponding Reynolds number	Value [Ref.]	Remark
Nozzle (K_n)	6.7×10^4	0.058 [1]	–
Suction (K_s)	$1.3–5.4 \times 10^4$	0.73–0.36 [1]	For M = 0.125–3.65. Extrapolation at lower Re_s
Mixing Chamber (K_m)	$1.7–7.0 \times 10^4$	0.198–0.175 [15]	For M = 0.125–3.65. Roughness = 15 μ
Diffuser (K_d)	–	0.1275 [16]	Based on diffuser diameter ratio (a) and angle (ϕ)

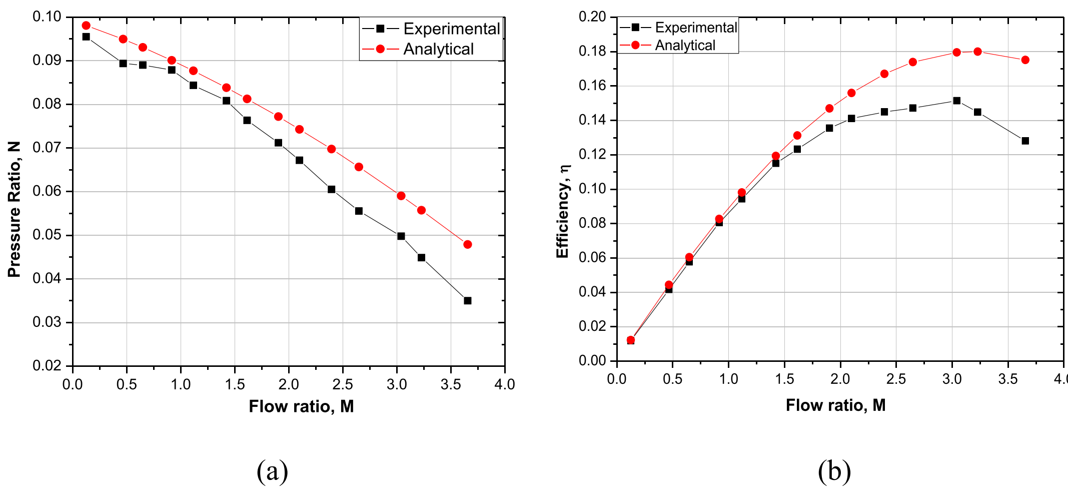


Fig. 14. Comparison of performance obtained from analytical solution with experiments (Q_1 = 1.8 lpm, T_1 = 43 °C, P_t = 2.0 bar and s = 0.0 mm).

miniature size jet pump at high flow ratio. The deviation at higher flow ratio may be due to simplified assumptions in analytical model as well as uncertainty associated with the loss coefficient specifically K_s and K_m on which analytical solution is sensitive at higher flow ratio.

7. Summary & conclusions

In the present study, effect of pressure, nozzle spacing, primary flow, temperature and area ratio on the performance of jet pump having low area ratio and small nozzle diameter was experimentally investigated. It was observed that the minimum secondary fluid suction pressure required for the jet pump operating at room temperature application is about 0.6 bar(g) to avoid performance degradation at higher flow ratio due to cavitation. The cavitation parameter (σ) was estimated for fully inserted nozzle and it was found to be higher than the generally observed values for conventional jet pumps. This is due to the restricted & conical entry of secondary fluid to mixing chamber and significant dimension of nozzle thickness at its tip compared to other dimensions due its miniature size. For the experimental parameter under study, optimum nozzle spacing is found to be about 4–5 times the nozzle diameter (s/d ~ 4 to 5), which is comparatively higher than conventionally observed value. This is due to secondary fluid entry loss being more dominating than the jet loss. Moreover, it is observed that very lower primary flow rate and thus, nozzle velocity significantly deteriorate the performance of jet pump. Minimum jet Reynolds number required to minimize its dependency on performance is found to be higher compared to other conventional area ratio jet pump. Jet pump performance is significantly improved by increasing the temperature and thus, reducing molecular viscosity. The effect of temperature is found to be more at higher flow ratio. As the operating area ratio (R) increases, maximum efficiency increases but maximum achievable flow ratio decreases. For the similar area ratio, efficiency is found to be lower for miniature size due to higher turbulent dissipation. For the typical case, comparison of jet pump performance obtained from analytical model with the experimental observation shows larger deviation at higher value of flow ratio (M > 1.5). From all these parametric studies, it is observed that the performance and its dependency on different parameters for miniature size low area ratio jet pump is different than the conventional jet pumps. Findings of this experimental study can be used for design and optimization of miniature size jet pumps for nuclear reactor applications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature

a	Diffuser area ratio
A	Flow area
C	Density ratio (Density of Secondary fluid to Primary fluid)
d	Primary nozzle diameter
D	Mixing chamber diameter
j	Jet loss coefficient
K	Loss coefficient
l	Characteristics dimension (For the current case it is diameter)
L	Mixing chamber length
M	Flow ratio/amplification (Secondary fluid volumetric flow to primary fluid volumetric flow) = Q_2/Q_1
M_L	Cavitation limiting flow ratio
N	Pressure ratio (Pressure gain by secondary fluid to Pressure loss by primary fluid) = $(P_5–P_2)/(P_1–P_5)$

P	Pressure in the jet pump
P′	Pressure at the measured location
P_v	Vapor pressure
Q	Volumetric flow rate
R	Flow Area ratio between nozzle to mixing chamber (A_n/A_m) = $(d/D)^2$
S	(1-R)/R
Re	Reynolds no. = $\rho Vl/\mu$
s	Nozzle spacing (distance from nozzle to mixing chamber entry)
T	Temperature
V	Velocity
Z	Dynamic pressure of jet ($\rho V_n^2/2$)

Greek symbol

η	Jet pump efficiency (M*N)
Ø	Diffuser angle (Half)
ρ	Density
σ	Cavitation parameter
μ	Kinematic viscosity

Subscripts

1	Primary inlet
2	Secondary inlet (suction)
3	Mixing chamber inlet
4	Mixing chamber outlet
5	Diffuser outlet
bep	Best efficiency point
d	Diffuser
m	Mixing chamber
n	Nozzle/nozzle exit location
s	Secondary

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