Effect of Surface Roughness on Jet Pump Performance*

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The jet pump generally needs a long throat to mix the driving and induced fluids and transfer the momentum of driving fluid to induced fluid. Simultaneously, the energy loses when the fluids flow through the long throat because the friction loss occurs inside of the throat wall. Therefore, it is known that the throat length largely affects the jet pump efficiency. In this study, experimental studies are performed for a typical single nozzle jet pump using water at room temperature. It is revealed that surface roughness located nearer the throat inlet has a greatest effect on the jet pump efficiency because the local skin friction coefficient nearest the throat inlet is the largest. The best efficiency and its flow rate ratio decrease linearly as surface roughness increases. The frictional resistance coefficient in the throat for each roughness is made clear by fitting a one-dimensional theoretical prediction equation to the experimental results.

Key Words: Jet, Pump, Internal Flow, Turbulent Mixing, Efficiency, Surface Roughness, Flow Resistance

1. Introduction

A jet pump is a simple device for controlling entrainment and discharge fluids. It generally consists of a driving nozzle, a suction inlet in the shape of bell-mouth, a mixing throat, and a diffuser. The suction fluid is induced by means of the momentum of the driving jet. The two fluid streams mix in the throat, and then the combined flow is decelerated in the diffuser to discharge pressure and velocity.

The advantage of the jet pump lies in its simplicity, its ability to pump multiphase fluids, and the absence of moving parts. On the other hand, its efficiency is much below a centrifugal pump.

One main reason why jet pump efficiency is low is the large friction loss in the throat, which needs enough length to mix the two fluids. And the optimum throat length exists for each jet pump specification to get best efficiency⁽¹⁾.

Therefore, increasing the surface roughness of the

throat, which causes friction loss, affects jet pump performance whose throat length is optimized.

To obtain fundamental knowledge of the effect of surface roughness on jet pump performance, experimental studies are performed for several surface roughnesses of a typical single nozzle jet pump using water at room temperature. Experimental values of efficiency for the flow rate ratio are compared to a one-dimensional theoretical prediction equation⁽²⁾, and the effect of roughness on the frictional resistance coefficient in the throat for each roughness is investigated.

Nomenclature

C_f : Local skin friction coefficient
 C_l : Equivalent frictional length coefficient
 D : Diameter [m]
 K : Friction loss coefficient
 k_e : Equivalent roughness [m]
 L : Length [m]
 M : Flow rate ratio
 N : Pressure ratio
 P : Static pressure [Pa]
 $\bar{P}$: Total pressure [Pa]
 Q : Flow rate [m³/s]
 R : Area ratio = $(D_n/D_t)^2$
 Re : Reynolds number = $V \times D/\nu$
 V : Mean velocity [m/s]
 x : Distance from throat inlet [m]

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η : Efficiency = $M \times N$
 λ : Frictional resistance coefficient
 ν : Kinematic viscosity [m^2/s]
 ρ : Density [kg/m^3]

Subscripts

b : Best efficiency
 d : Diffuser outlet
 hs : Hydraulically smooth
 n : Driving nozzle
 r : Rough surface
 s : Suction inlet
 t : Throat
 ti : Throat inlet
 to : Throat outlet

2. Experiment

2.1 Experimental apparatus

The experimental set-up of the jet pump performance tests is shown in Fig. 1. The working fluid is water at room temperature. High pressure water pumped by a centrifugal pump flows into the nozzle through the magnetic flow meter from the chamber and is discharged to the throat inlet in the shape of bell-mouth, as the driving jet flow.

The driving jet and induced flow are mixed in the throat and flow out after recovering pressure in the diffuser. They return to the chamber through another magnetic flow meter in the discharge line.

In this study, driving flow rate Q_n is fixed at $6.5 \times 10^{-3} \text{ m}^3/\text{s}$ (nozzle Reynolds number $Re_n = V_n \times D_n / \nu = 4.8 \times 10^5$), and flow rate ratio $M (= Q_s / Q_n)$ is changed from 0.5 to 1.8 (throat Reynolds number $Re_t = V_t \times D_t / \nu = (3.5 \sim 6.6) \times 10^5$). The chamber is pressurized at about 0.35 MPa to prevent the occurrence of cavitation in the jet pump throat.

Figure 2 shows the configuration of jet pump nozzle and throat. The cross section of a jet nozzle is circular, and its exit diameter is $D_n = 17 \text{ mm}$. The throat is an $L_t = 430 \text{ mm}$ straight pipe whose diameter is $D_t = 35 \text{ mm}$. The distance of the nozzle and the inlet of the throat is 0 mm.

The rough surface inside the throat is shaded area shown in Fig. 2. Coated abrasives affixed inside the throat are substituted for the inside surface roughness of the jet pump. In this study, the length of the coated abrasives is $L_r = 50 \text{ mm}$, and the location is varied from $x/L_r = 0 \sim 0.12, 0.20 \sim 0.31, 0.32 \sim 0.43$ in the throat by affixing new coated abrasives after peeling off the previous ones, where x is the streamwise position from the throat inlet.

2.2 Jet pump parameters

Jet pump performance is generally considered to be a function of the parameters defined as follows.

Flow rate ratio M is the ratio of induced flow to driving flow defined by

$$M = \frac{Q_s}{Q_n}, \quad (1)$$

Fig. 1 Experimental set-up of jet pump performance tests

Fig. 2 Configuration of jet pump nozzle and throat

pressure ratio N is the ratio of the specific energy increase of the induced flow to the specific energy decrease of the driving flow defined by

$$N = \frac{\bar{P}_d - \bar{P}_s}{\bar{P}_n - \bar{P}_d}. \quad (2)$$

Jet pump efficiency η is defined by

$$\eta = MN. \quad (3)$$

2.3 Surface roughness parameters

The surface roughness inside the throat is changed by affixing commercial coated abrasives. In this study, three sizes of coated abrasive grains are used: P150, P240, and P1200 (based on ISO International Standards). The grain size of the 50% frequency distribution is standardized to be $98 \pm 8 \mu\text{m}$ for P150, $58.5 \pm 2.0 \mu\text{m}$ for P240, and $15.3 \pm 1.0 \mu\text{m}$ for P1200. In this study, equivalent roughness k_e is defined as grain size of the 50% frequency distribution.

On the other hand, surface roughness of the acrylic throat affixing no coated abrasives is defined as hydraulically smooth. Its equivalent roughness is presumed to be $k_e = 1.5 \mu\text{m}$, the same as the drawn pipes⁽³⁾.

Figure 3 shows the 3-D surface profile and plane surface of the optical visual inspection using the same lens of magnification ratio 450 for all coated abrasives. The surface roughness (peak to peak) measured by the roughness gauge is about $92 \mu\text{m}$ P-P for P150, $61 \mu\text{m}$ P-P for P240, and $10 \mu\text{m}$ P-P for P1200. These results are almost the same as the standardized grain sizes of the 50% frequency distribution.

Fig. 3 3-D surface profile and plane surface of coated abrasives

Therefore, the three kinds of relative roughness are defined as $k_e/D_t = 0.0028 \pm 0.0002$, 0.0017 ± 0.0001 , and 0.0004 ± 0.00003 , respectively. The relative roughness of the hydraulically smooth is $k_e/D_t = 0.00004$.

Using the $L_t = 50$ mm long coated abrasives ($0.12L_t$), rough surface are located on the entire inside face from $x/L_t = 0$ (at the throat inlet except for bell-mouth) to $x/L_t = 0.12$.

To investigate the effect of rough location on jet pump performance, rough location is changed from $x/L_t = 0$, $x/L_t = 0.20$, and $x/L_t = 0.32$ in the throat on which the induced flow is greatly accelerated, using the relative roughness $k_e/D_t = 0.0028$. In addition to that, the rough at the inlet of the diffuser is also investigated for reference.

3. Results and Discussion

3.1 Effect of rough location

Figure 4 shows the effect of rough location in the throat using coated abrasives P150 (relative roughness $k_e/D_t = 0.0028$) on jet pump performance.

The jet pump efficiency is decreased by surface roughness located in the throat and at the inlet of the diffuser comparing with the hydraulically smooth ($k_e/D_t = 0.00004$) results and surface roughness greatly affects jet pump efficiency η in the higher flow rate ratio M region. In cases of rough location at the inlet of the diffuser, the

Fig. 4 Effect of rough location on jet pump performance (Relative roughness, $k_e/D_t = 0.0028$)

Fig. 5 Effect of rough location on the best efficiency (Relative roughness, $k_e/D_t = 0.0028$)

effect of roughness is smaller than in the throat.

Figure 5 shows flow rate ratio M_b at the best efficiency point and best efficiency ratio $\eta_b/\eta_{b,hs}$, where $\eta_{b,hs}$ is best efficiency of the hydraulically smooth jet pump.

The flow rate ratio M_b and efficiency η_b at the best efficiency point are decreased rapidly as rough location x/L_t is closer to the throat inlet.

From the velocity profile measurement results⁽⁴⁾ in case of hydraulically smooth throat, local skin friction coefficient C_f tended to decrease toward the throat exit and then increase after the transition to the turbulent boundary layer. Apparently roughness in the throat inlet where C_f is larger greatly affects jet pump efficiency.

This study reveals that the surface roughness located nearer the throat inlet has a greater effect on jet pump efficiency.

3.2 Effect of relative roughness

Flow rate ratio M_b at the best efficiency point, and best efficiency η_b are decreased more than the hydraulically smooth results.

Fig. 6 Effect of relative roughness on best efficiency (Rough location, $x/L_t = 0 \sim 0.12$)

cally smooth ($k_e/D_t = 0.00004$) results as relative roughness k_e/D_t increases. Identical to effect of rough location on jet pump performance in Fig. 4, relative roughness k_e/D_t greatly affects jet pump efficiency η in the higher flow rate ratio M region.

Figure 6 shows the effect of relative roughness k_e/D_t located from $x/L_t = 0$ to 0.12 in the throat, where jet pump performance is extremely affected, on jet pump efficiency. Flow rate ratio M_b at the best efficiency point and $\eta_b/\eta_{b,hs}$ is linearly decreased as relative roughness k_e/D_t increases.

3.3 Theoretical prediction

Regarding the effect of relative roughness k_e/D_t located near the throat inlet on jet pump performance, the effect on frictional resistance coefficient λ in the throat is investigated for each roughness by a one-dimensional theoretical equation⁽²⁾ which is consisting of an application of energy, momentum, and continuity equations across the jet pump. The energy equations at the driving nozzle, suction

Fig. 7 C_l distribution for hydraulically smooth jet pump

inlet, and diffuser are

$$\bar{P}_n - \bar{P}_{ti} = K_n \frac{\rho V_n^2}{2}, \quad (4)$$

$$\bar{P}_s - \bar{P}_{ti} = K_s \frac{\rho V_s^2}{2}, \quad (5)$$

$$\bar{P}_{to} - \bar{P}_d = K_d \frac{\rho V_t^2}{2}, \quad (6)$$

the momentum equation which is applied for the throat is

$$P_{to} - P_{ti} = \rho \{ R V_n^2 + (1 - R) V_s^2 - V_t^2 \} - K_t \frac{\rho V_t^2}{2}. \quad (7)$$

Equation (7) assumes that momentum is fully transferred in the throat.

Mean velocity V at suction inlet and throat are described as follows using continuity equations

$$V_s = \left(\frac{R}{1 - R} \right) M \times V_n, \quad (8)$$

$$V_t = R(1 + M) \times V_n. \quad (9)$$

Therefore, a one-dimensional theoretical equation of jet pump efficiency η becomes

$$\eta = M \times \frac{\bar{P}_d - \bar{P}_s}{\bar{P}_n - \bar{P}_d} = -M \times \frac{(1 + K_s) \left(\frac{RM}{1 - R} \right)^2 - 2R - \frac{2R^2 M^2}{1 - R} + R^2 (1 + M)^2 (1 + K_t + K_d)}{(1 + K_n) - 2R - \frac{2R^2 M^2}{1 - R} + R^2 (1 + M)^2 (1 + K_t + K_d)}. \quad (10)$$

Although friction loss coefficient K is generally defined by $K = \lambda \times (L/D)$ for straight pipe flow, in this study friction loss coefficient K_t in the throat, where flow is not fully developed, is defined by

$$K_t = \lambda \times \frac{C_l L_t}{D_t}, \quad (11)$$

where C_l is the equivalent frictional length coefficient for a hydraulically smooth jet pump, λ is the frictional resistance coefficient obtained from Colebrook's equation of the Moody diagram⁽³⁾ using k_e/D_t , and throat Reynolds number Re_t .

The values of K_n , K_s and K_d in Eq. (10) are 0.01, 0.02 and 0.16, respectively, which are obtained by the experimental result and the general literature.

Figure 7 shows C_l distribution which are calculated by Eqs. (10), (11) and the experimental result. C_l decreases linearly as M increases. This means that as increasing M the deviation from the friction resistance coefficient λ for fully developed pipe flow increases. To investigate how the frictional resistance coefficient λ is affected by relative roughness, λ for three relative roughnesses are evaluated by Eqs. (10), (11) and C_l in Fig. 7.

In Fig. 8 λ for three relative roughnesses are drawn on the Moody diagram⁽³⁾. Figure 8 also has λ which are obtained

Fig. 8 Effect of relative roughness on jet pump throat (Rough location, $x/L_t = 0 \sim 0.12$)

by Colebrook's equation in case of the fully developed pipe flow for $k_e/D_t = 0.0028$, 0.0017 , 0.0004 and 0.00004 .

From λ distribution in Fig. 8, λ is not affected very much by relative roughness in lower Re_t . However, λ increases as increasing Re_t and becomes almost the same as the dashed line, which is Colebrook's equation calculated from Re_t and k_e/D_t for fully developed pipe flow. Although the rough surface is a part of the throat, the roughness located nearer the throat inlet affects as the same increases of λ as the entire area roughness of the throat in larger Re_t .

In this study, the frictional resistance coefficient in the throat for each roughness becomes obvious by fitting a one-dimensional theoretical prediction equation to the experimental results.

4. Conclusions

To obtain fundamental knowledge of the effect of surface roughness in the throat on jet pump performance, experimental studies are performed for a typical single nozzle jet pump by affixing commercial coated abrasives onto

the throat's inner surface. The following results are obtained:

(1) Surface roughness located nearer the throat inlet has a greater effect on the jet pump efficiency because the local skin friction coefficient nearest the throat inlet is the larger.

(2) The flow rate ratio at the best efficiency point and best efficiency decrease linearly as surface roughness increases, especially surface roughness greatly affects jet pump efficiency in the higher flow rate ratio regions.

(3) The frictional resistance coefficient in the throat for each roughness becomes obvious by fitting a one-dimensional theoretical prediction equation to the experimental results.

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