



ENGINEERING SCIENCES

Air entrainment and pressure drop in low-cost ejectors

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Abstract: This study investigated experimentally the air entrainment and pressure drop in low-cost ejectors composed of two pieces shaped from PVC bars inserted in a 25 mm T-junction of the same material. The hydraulic behavior was very similar for the different ejector designs, and linear relationships between the water and air flow rates were fitted. However, when a rotameter was installed at the air line, the head losses resulted in a pronounced decrease (3-fold) in the air entrainment rate. The maximum air-water entrainment ratios reached by the low-cost ejectors was 1.7, while the pressure drop was about 80% of the upstream pressure. The results suggest that these ejectors have a better benefit-cost ratio than conventional ones for applications such as aeration and mixing in reactors, tanks and water bodies. Comparing our results with those obtained previously by using water both as primary and suction fluids, it was shown that under gas-liquid flow conditions the entrainment ratio was about 2.5 times larger than that for the single-phase case, while the pressure drop was about 15% higher. This was attributed to the lower density of the air and the higher dissipation of turbulent kinetic energy due to bubble-liquid interactions in the two-phase flow case.

Key words: aeration, hydraulics, jet pumps, mixing, two-phase flow.

INTRODUCTION

Ejectors have long been used for many purposes such as aeration, pumping and evaporation, with application in several areas of agricultural, civil, chemical, environmental and mechanical engineering, including water treatment, mixing, desalination, dredging, refrigeration, among others (Cunningham 1995, Wang & Wypych 1995, Winoto et al. 2000, El-Dessouky et al. 2002, Lima Neto & Porto 2004, Baylar & Ozkan 2006, Kumar & Mani 2007, Balamurugan et al. 2007, Lima Neto et al. 2008a, b, Lima Neto 2004, 2006, 2011, Yuan et al. 2011, Opletal et al. 2018, Park & Yang 2018).

Previous studies on gas-liquid ejectors have focused on the experimental, theoretical and/or numerical analysis of conventional devices, which are usually manufactured from five

metallic parts: driving nozzle, suction nozzle, suction chamber, mixing chamber, and diffuser (Cunningham 1995, Lima Neto et al. 2008a, b, El-Dessouky et al. 2002, Kumar et al. 2007, Lima Neto et al. 2008a, b, Yuan et al. 2011, Opletal et al. 2018). The cost of the commercial ejectors used in these cases ranges from about \$150 to \$500 U.S. dollars for a 25 mm nominal diameter device. With the appearance of the Venturi-type ejectors made from PVC or polyethylene, which are more compact and cheaper than the conventional ejectors, these accessories have been increasingly employed in mixing systems. Lima Neto & Porto (2004) built and evaluated experimentally ejectors composed of two pieces shaped from PVC bars inserted in T-junctions of the same material, with geometry similar to that of conventional and Venturi-type ejectors,

and found comparable mixing efficiencies using water both as primary and secondary fluids. However, these simpler ejectors costed (including materials and labor) only about \$30 U.S. dollars for a 25 mm nominal diameter device.

Earlier experiments on Venturi and conventional gas-liquid ejectors normally investigated the maximum air-water entrainment ratios reached by these devices, which ranged from about 0.3 – 2.5 (Baylar & Ozkan 2006, Yuan et al. 2011, Park & Yang 2017, Opletal et al. 2018). Another parameter normally investigated was the pressure drop over the ejector, which ranged from approximately 0.7 – 0.9 of the upstream pressure (Kumar et al. 2007, Yuan et al. 2011). Large efforts have been made by many of the above-mentioned researchers in order to improve the ejector's design and performance by increasing the air-water entrainment ratio and decreasing the pressure drop for applications such as aeration and mixing.

In this paper, we report an experimental study to investigate the air entrainment and pressure drop in low-cost ejectors designed according to the recommendations of Lima Neto & Porto (2004). However, differently from previous studies on these ejectors (Lima Neto & Porto 2004, Lima Neto 2011), in which both the primary and secondary fluids were water, here we evaluate experimentally the hydraulics of the low-cost ejectors using air as a secondary fluid. We also investigate the impact of rotameters installed at the air suction line on the air entrainment and pressure drop induced by the ejectors. Additionally, we compare the hydraulic behavior of the low-cost gas-liquid ejectors with that of liquid-liquid ejectors. To the authors' knowledge, this is the first study that addresses the above issues.

MATERIALS AND METHODS

The experiments were performed in the apparatus shown schematically in Fig. 1. A square tank with a width of 50 cm and a height of 100 cm was filled with tap water up to a height of 80 cm. A centrifugal pump of 2.0 hp withdrew water from 5 cm below the water surface and then supplied the different low-cost ejectors (A1, A2, A3 and B) shown in Fig. 2, which were built from two pieces shaped from a PVC bar inserted in a T-junction of the same material, following the dimensions recommended by Lima Neto & Porto (2004) and Lima Neto (2011). Each ejector design is summarized in Table I, in which D is the nominal diameter of 25 mm. The resulting gas-liquid mixture was then injected at the base of the tank by using a nozzle with diameter of 1 cm, producing a bubbly jet. The volumetric flow rates of water (Q_w) and air (Q_a) were measured with rotameters (models 440 and DK48, Conaut, Brazil), while the pressures upstream (P_u) and downstream (P_d) the ejectors were measured with digital manometers (models PM 1010, Conaut, Brazil). Details of the measurement parameters, instruments and their ranges and accuracies are presented in Table II. Different values of Q_w (10-70 l/min) and P_u/γ (1-20 m) were adjusted through a globe valve. This resulted in different combinations of Q_w , Q_a , P_u/γ and P_d/γ for each ejector design.

Additional experiments were also performed without the rotameter at the air suction line, in order to assess that impact of this device on the air flow rate (Q_a) induced by the ejectors. In both cases, with or without the rotameter, measurements of the mean axial water velocity (u_w) were taken at 20 cm above the nozzle exit in the bubbly jet region (see Fig. 1), by using an electromagnetic propeller anemometer (MiniWater20, Omni Instruments, UK). These

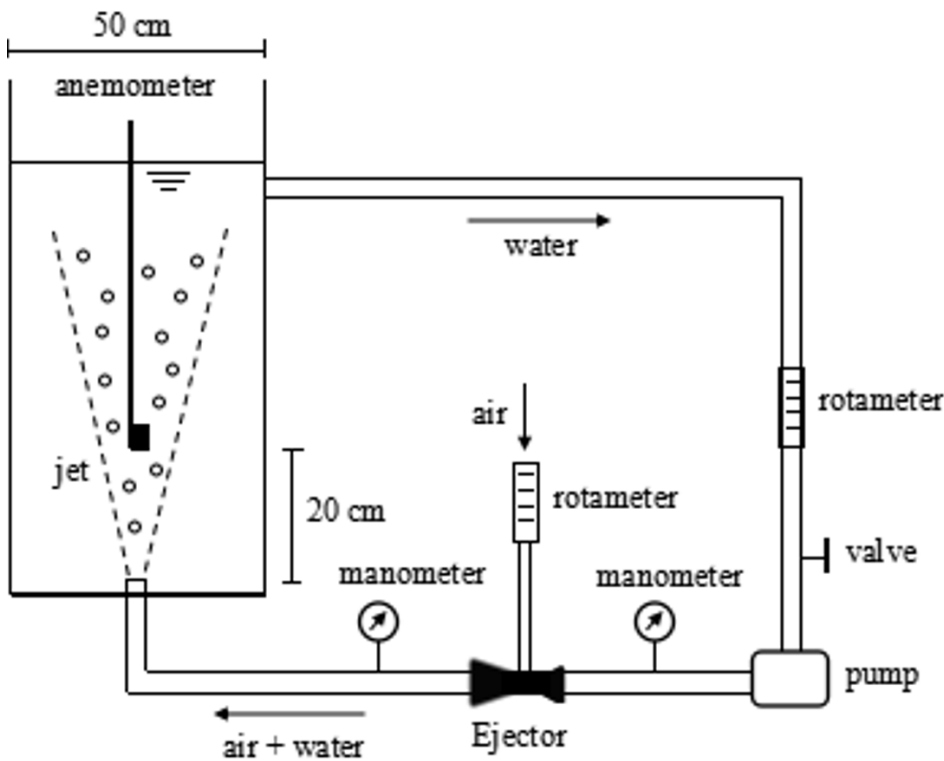


Figure 1. Schematic of the experimental apparatus, indicating the process of air entrainment induced by the ejector and the discharge of the resulting bubbly jet in the tank.

measurements allowed the validation of the bubbly jet model of Lima & Lima Neto (2018).

The validated bubbly jet model of Lima & Lima Neto (2018) was used to estimate the air flow rate (Q_a) for the experiments without the rotameter at the air suction line. It was possible because this model needs both the air and water flow rates as input data. Hence, as Q_w was already measured, the model provided the values of Q_a that better fitted the experimental data of mean axial water velocity (u_w). This fitting was performed by minimizing the standard deviations between measured and modeled values of u_w . Note that the model of Lima & Lima Neto (2018) is based on the integral approach for bubble plumes and bubbly jets (see Lima Neto 2012a, b).

The above-mentioned procedures allowed the analysis of the impact of ejector design on two relevant dimensionless parameters: the

air-water entrainment ratio (Q_a/Q_w) and the pressure drop over the ejector ($\Delta P/P_u$). The effect of the rotameters at the air suction line on these two dimensionless parameters (Q_a/Q_w and $\Delta P/P_u$) was also investigated and compared with the previous case (without rotameter).

The repeatability of the experimental results (triplicate) was also assessed for the tests with the ejector A1, and the standard deviation was calculated for both flow rate and pressure data.

RESULTS AND DISCUSSION

Figure 3 shows the mean axial water velocity u_w measured inside the bubbly jets (see Fig. 1) as a function of the water flow rates Q_w that fed each ejector (A1, A2, A3 and B). The increase of u_w with Q_w was expected, as the air entrainment rates Q_a were also directly proportional to Q_w , as observed by Lima & Lima Neto (2018) using a

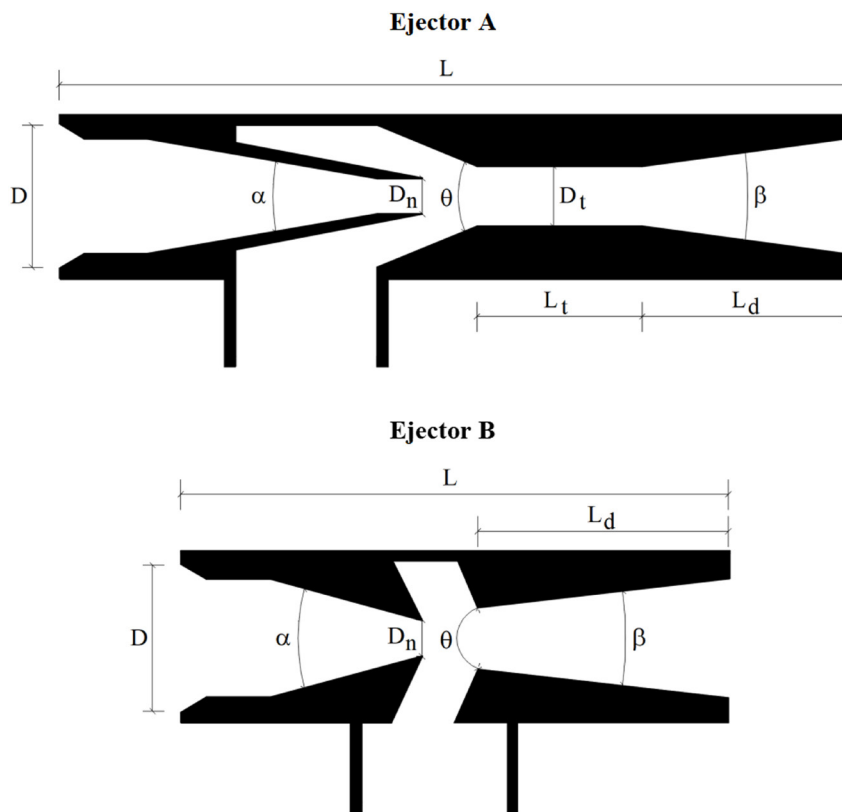


Figure 2.
Schematic of the
different ejector
designs.

Venturi type ejector. However, it is clearly seen that the presence of the rotameter at the air suction line significantly reduced the water velocity of the bubbly jets, as compared to the experiments without this device. This was attributed to the minor head loss caused by the rotameter, which resulted in a pronounced decrease (3-fold) in the air entrainment rate, as will be seen later in Fig. 4. For the experiments with the rotameter, the measurements allowed the validation of the bubbly jet model of Lima & Lima Neto (2018), with deviations between measured and predicted values of u_w of up to about $\pm 20\%$. Model simulations are also shown in Figure 3. For the experiments without this rotameter, we were able to estimate the air entrainment rates Q_a by fitting the bubbly jet model results to the measured values of u_w . The error bars in Figure 3 indicate a standard

deviation of $\pm 17\%$ obtained from repeatability of the tests with ejector A1.

Figure 4 shows that the ejector design caused little impact on the air entrainment rates Q_a , which allowed the fitting of general linear relationships between the water and air flow rates for the experiments with or without the rotameter at the suction line [Eqs (1) and (2)]. The error bars indicate a standard deviation of $\pm 12\%$ obtained from repeatability of the tests with ejector A1. It is also interesting to note that all ejectors started inducing air entrainment for water flow rates $Q_w > 12$ l/mim (and upstream pressure heads $P_u/\gamma > 1.25$ m). These results indicate that the effect of the ejector type on the air entrainment rates was negligible, which implies that the shortest and simplest ejector (B) has advantage with respect to the other devices (A1, A2 and A3). This contrasts with the results

Table I. Ejector dimensions. The nominal diameter D = 25 mm.

Ejector	α	β	θ	D_n/D	$R=(D_n/D_t)^2$	L_i/D	L_d/D	L/D
A1	20°	10°	38°	0.25	0.25	2.5	1.8	6.9
A2			44°		0.35	2.1	2.2	7.1
A3			49°		0.53	1.7	2.7	7.3
B			140°		0.35	-	2.2	4.2

reported by Lima Neto & Porto (2004), in which type A ejectors presented higher entrainment rates than type B ejectors when water was used both as primary and suction fluids.

$$Q_a = 0.902 Q_w - 10.444 \text{ (with rotameter)} \quad (1)$$

$$Q_a = 2.843 Q_w - 35.671 \text{ (without rotameter)} \quad (2)$$

Figure 5 shows the dimensionless pressure drop $\Delta P/P_u$ as a function of the air entrainment ratio Q_a/Q_w for each ejector type. The error bars indicate a standard deviation of $\pm 9\%$ obtained from repeatability of the tests with ejector A1. For $Q_a/Q_w < 0.5$, $\Delta P/P_u$ had a little variation (0.70-0.85) for the different experimental conditions, but for $Q_a/Q_w > 0.5$, $\Delta P/P_u$ tended to a constant value of about 0.8. Hence, a simple relationship of $\Delta P/P_u = 0.8$ [Eq. (3)] together with Eq. (2) can be taken as design criteria for such ejectors. Observe that pressure drops of about 80% of the upstream pressure were also obtained in previous studies on conventional gas-liquid ejectors (Kumar et al. 2007, Yuan et al. 2011). On the other hand, all the ejectors reached air entrainment ratios of up to about 1.7, which is within the maximum values of 0.3 – 2.5 reported by previous researchers using from standard Venturi to more sophisticated types of ejectors (Baylar & Ozkan 2006, Yuan et al. 2011, Park & Yang 2017, Opletal et al. 2018). Again, no significant performance variation was observed for the different ejector types, which suggests that the shortest and simplest ejector (B) has a better benefit-cost ratio than

the others (A1, A2 and A3). Although the length of the ejector can also impact oxygen transfer efficiency, we focused our discussion on the two dimensionless parameters Q_a/Q_w and $\Delta P/P_u$, as bubble dynamics and aeration efficiency in reactors, tanks and water bodies can be controlled by the discharge nozzle design and air/water flow rates (see Lima & Lima Neto 2018). Thus, in these cases, the optimization of the ejector will be important to induce a high air-water entrainment ratio and a low pressure drop, while the discharge nozzle will be important to produce small bubbles and improve air-water mass transfer.

$$P/P_u = 0.8 \text{ (with and without rotameter)} \quad (3)$$

Comparing our results with those obtained by Lima Neto & Porto (2004) with the same ejector types (A1, A2, A3 and B), but using water as suction fluid (Figure 5), we can see that under gas-liquid flow conditions the entrainment ratio Q_a/Q_w is about 2-3 times larger while the pressure drop $\Delta P/P_u$ is about 15% higher. This suggests that gas-liquid ejectors aspirate more fluid than single-phase liquid ejectors, but induce higher head losses. The higher entrainment rate is attributed to the lower density of the air as compared to that of water, while the higher head loss is attributed to the higher dissipation of turbulent kinetic energy due to bubble-liquid interactions.

Table II. Measurement parameters, instruments and their ranges and accuracies.

Measurement parameter	Instrument	Range	Accuracy
Water flowrate (Q_w)	Rotameter	0-67 l/min	$\pm 1.0\%$
Air flowrate (Q_a)	Rotameter	0-83 l/min	$\pm 1.0\%$
Driving pressure (P_d)	Manometer	0.5 MPa	$\pm 0.1\%$
Discharge pressure (P_d)	Manometer	0.5 MPa	$\pm 0.1\%$

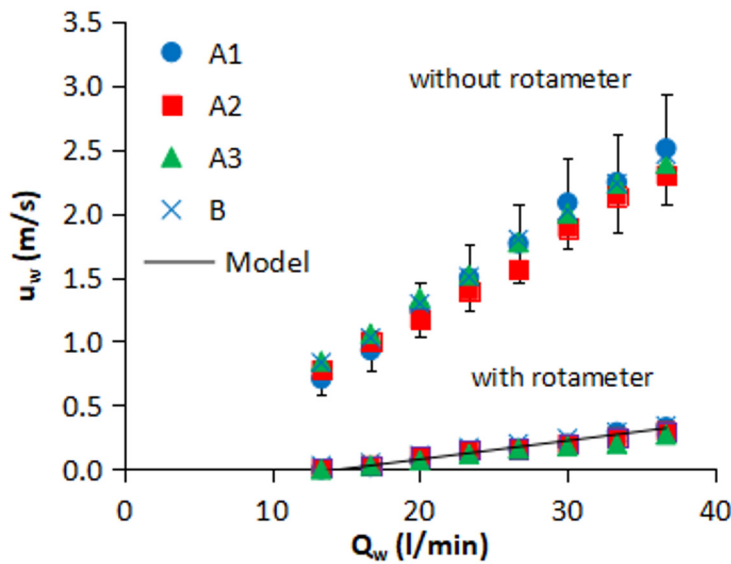


Figure 3. Variation of the bubbly jet velocity above the nozzle exit as a function of the primary flow rate for the experiments with or without the rotameter at the air line and for different ejectors types (A1, A2, A3 and B). The solid line indicates the fitting of the bubbly jet model of Lima and Lima Neto (2018) to the experimental data for ejector A1. Error bars indicate a standard deviation of $\pm 17\%$ obtained from repeatability of the tests with ejector A1.

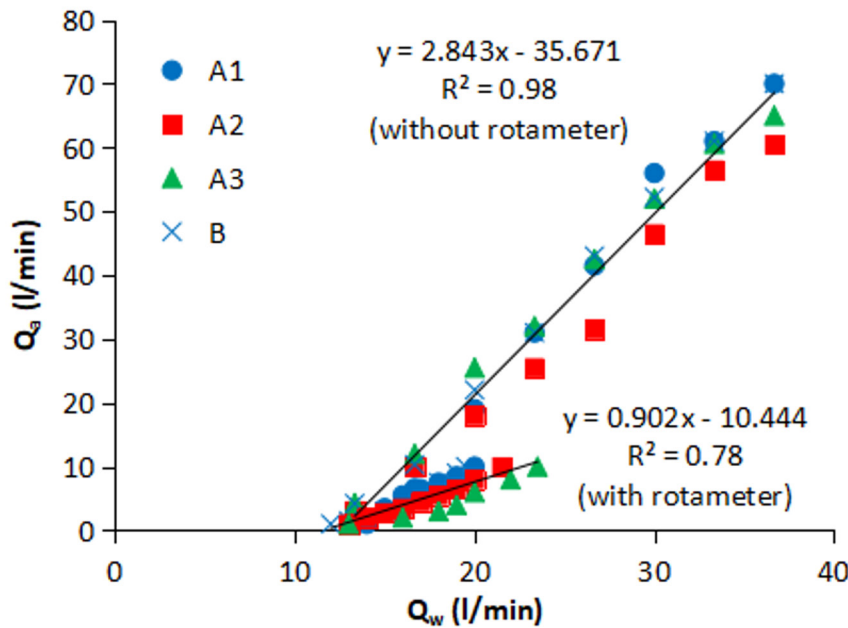


Figure 4. Linear relationships between the water and air flow rates induced by each ejector type (A1, A2, A3 and B) and for the experiments with or without the rotameter at the suction line. Error bars indicate a standard deviation of $\pm 12\%$ obtained from repeatability of the tests with ejector A1.

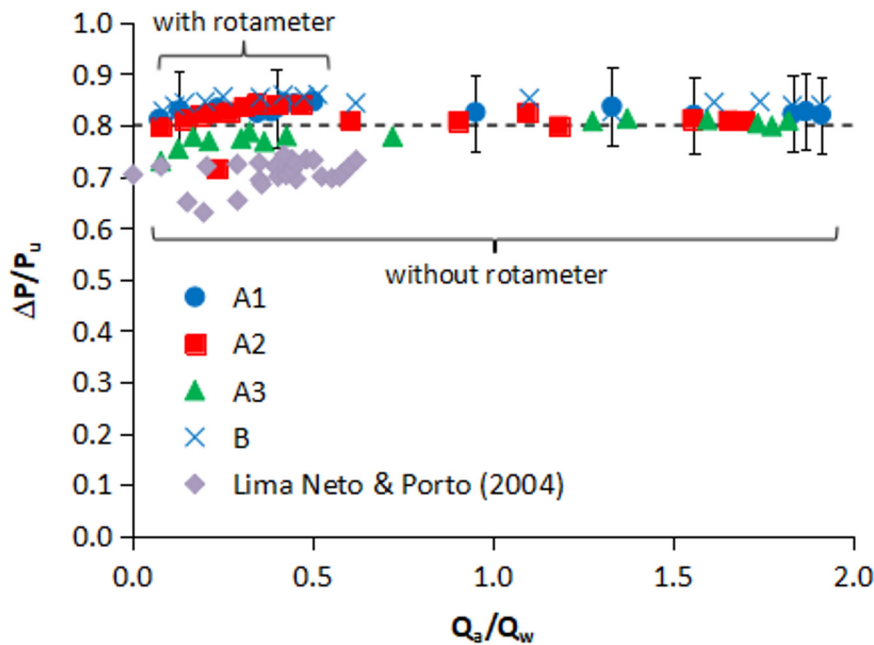


Figure 5. Dimensionless pressure drop as a function of the air entrainment ratio for each ejector type and for the experiments with or without the rotameter at the suction line. Error bars indicate a standard deviation of $\pm 9\%$ obtained from repeatability of the tests with ejector A1. Experimental results of Lima Neto and Porto (2004) obtained by using water both as primary and suction fluids are also shown for comparison.

CONCLUSIONS

The present paper investigated experimentally the air entrainment and pressure drop in low-cost ejectors with different designs. Linear relationships between the water and air flow rates were fitted for tests with or without a rotameter at the suction line, and no significant variation was observed for the different ejector designs. On the other hand, the minor head loss at the rotameter reduced by about 3-fold the air entrainment rates. All the ejectors reached air-water entrainment ratios of up to about 1.7, which is within the maximum values of 0.3 – 2.5 reported in the literature for standard Venturi and more sophisticated types of ejectors. Additionally, the pressure drop produced by the ejectors was about 80% of the upstream pressure, independently of the ejector design. Therefore, as no significant performance variation was observed for the different ejector types, we can conclude that the shortest and simplest ejector

built in the present study had a better benefit-cost ratio than the others, and is recommended here for practical engineering applications such as aeration, mixing, among others. Observe that for the aeration case, the optimization of the ejector design will be important to promote a high air-water entrainment ratio and a low pressure drop, while the discharge nozzle will be important to generate a jet with small bubbles, in order to improve oxygen transfer to the water. Comparison of our results with those available in the literature using water both as primary and secondary fluids also demonstrated that under gas-liquid flow conditions, the entrainment ratio was about 2.5 times larger while the pressure drop was about 15% higher. These trends were attributed to the lower density of the air as compared to that of water (resulting in higher entrainment) and to the higher dissipation of turbulent kinetic energy due to bubble-liquid interactions (resulting in higher head loss).

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