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Original Article

Experimental Investigations of Jet Expansion for Hydraulic Nozzles of Different Materials

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Abstract — *A nozzle is an essential part of fluid and pneumatic system to increase or decrease kinetic energy of fluid at the expense of pressure. The convergent-divergent nozzle is most commonly employed in flow measurement, rocket propulsion systems, jet pumps, hydraulic turbines, etc. A convergent type nozzle solely is more useful in the case of a hydraulic system compared to a diffuser type. In the present study, nozzles with different materials and different exit diameters have been investigated. The effect of varying discharge on jet expansion for the same material with different exit diameters as well as different materials for the identical diameter is also studied. More robust the construction and jet with a smaller diameter is stable enough. For a stable jet, the standoff distance is more otherwise. Spreading of jet leads to loss of kinetic energy as air-entrained at the circumference in the free surface of jet. For the nozzle with 17mm diameter but with different materials, more discharge was found in the case with polymer nozzle, whereas less angle of jet expansion was found with stainless steel nozzle. The jet expansion was found more with a larger diameter nozzle for both stainless steel and polymer. With smaller diameter nozzles of 17 mm, it is likely for jet expansion.*

Keywords — *Nozzle, Coefficient of discharge, Jet expansion, Material, Nozzle size, Jet quality.*

I. INTRODUCTION

Nozzles have been employed in almost so many engineering applications since the advent of engineering and technological advancement. It eases the work by accelerating or decelerating the fluid with a change in either pressure or kinetic energy [1]. In an automobile, fluid power sector, various misting processes, sprinklers, injection system of automobiles, the propulsion system of rocket engine so many and so forth everywhere nozzles are used since it is a simple geometry involves no moving parts. Even in pneumatic and hydraulic systems for automation, it is a critical part as based on this feedback is sent to the controlling unit.

In the present study, convergent fluid nozzles are taken under consideration, having a constriction ratio less than 0.5 as it is a useful part of a fluid power system. A thorough understanding makes more efficient use of nozzles in the fluid power section. Here convergent nozzles of different materials are taken under consideration and studied for high head, high Reynolds number and high discharge conditions. The quality of the jet depends on exit conditions, shape or opening velocity, a viscosity of the fluid and surrounding air at an application where the jet is to be employed [2], [3]. A jet issued from the convergent nozzle is studied to bring more clarity about work done. Benedict and Wyler [4] carried out analytical and theoretical studies of ASME flow nozzles in the early 80s, and correlations were established for various pressure tapped nozzles. Rahman et al. [5] and Alam et al. [6] have performed rigorous experimental investigations and stated that for different types of nozzle geometry and curvature, angle affects the end conditions; consequently, contraction of streamlines and the coefficient of discharge get affected. McCarthy and Molloy [7] have stated that by experimentation, the breakup pattern of liquid jets in regimes beyond the surface tension controlled axisymmetric case requires application-based correlations due to the complex nature of the flow. Cui et al. [8] found that smaller-diameter nozzles induce cavitation and hydraulic flip much more easily than larger-diameter ones. In a nozzle with a 10% smaller diameter, the critical pressure P_{crit} required for inducing cavitation and hydraulic flip decreases by approximately 5.9% and 7.5%, and it will further decrease by 14.7% and 12.5% with a 20% smaller diameter. Kiaoulias et al. [9] carried out and found large diameters had small laminar flow jet breakup length, but large for turbulent and Sharp-edge inlets experienced cavitation and varying discharge coefficients. Essien et al. [10] carried out experiments and concluded that the value of maximum C_d for a given flow rate is relative to the flow area used. The coefficient of discharge (C_d) increased with the increasing value of the l/d ratio. Increasing the beta ratio led to a decrease in C_d. The effect of viscosity was

found significant at low viscosity and reduced as viscosity reduced. Florez et al. [11] have carried out experiments and concluded that the one-equation eddy viscosity turbulence LES model generated an early breakup and was able to reproduce the dynamic interaction between the air and water phases. Staubli et al. [12] and Broujerdi et al. [13] deduced that the quality of water jet depends on the angle of dispersion, deviation from centre, air entrapment on the surface, splashing from the core. Chongji et al. [14] have studied internal nozzle flow and found that the increase in nozzle opening results in greater dispersion of the jet, resulting in a higher hydraulic loss. Sushma et al. [15] have worked on numerical simulation for different nozzles and studied for turbulent mixing on low Mach numbers. Srinivasan et al. [16] have worked on forced liquid jets using a volume of fluid method on stagnant gas.
From the literature survey, the parameters can be listed for further study. As most of the parameters are related to the nozzle geometry like internal flow condition, surface roughness, size of the opening for designed application, aspect ratio, area ratio, constriction ratio (β), annular flow area in the case of a spear which controls the size and streamlines distribution across the nozzle [17], [18]. Moreover, the surrounding parameter leads to a change in jet flow physics. The surrounding air is the main responsible parameter for a jet to deviate or spread and sway [19]. An effort has been made to shape a qualitative relationship between the nozzle shape and the outcoming jet shape. The jet length without the influence of air is useful to get maximum output through it, as in the case of hydraulic turbines [20], [22]. The dispersed jet is least useful as it involves fluid tangles in reversed direction leads to loss of kinetic energy [23]-[25]. The following points are experimentally studied and visualized by photography.

- Effect of nozzle material on the coefficient of discharge and jet quality with same fundamental dimensions of the nozzle. Nozzles with two different materials, viz. stainless steel and polymers with the same diameter, have been investigated.
- Effect of variable flow condition on jet quality with different sizes of a nozzle of the same material.
- Effect of exit diameter of a nozzle on quality of jet, i.e. Jet dispersion angle and the shape of jet and core length by flow visualization through digital photography.

The analytical hydrodynamic access should present realistic plug flow nozzles, where 'water-like' viscosity is observed.

II. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1 for carrying out an investigation on the different nozzles for different flow conditions. The experimental setup consists of several components, as mentioned in the part list. The flow line with 2.5 inches size is used to carry a heavy flow of water. An electric motor of 5 HP is used to run a heavy flow rate through line located at the bottom-most part of the setup sideways. It is attached with a heavy centrifugal impeller capable of delivering flow in the line. It includes all the fittings and valves for the smooth functioning of the apparatus. An electromagnetic digital flow meter with ±0.00069 m^3/hr flow measuring capacity is attached to the line for measuring discharge through a pump. The downcomer nozzle assembly can accommodate different types of nozzles under investigation. A transparent acrylic chamber is made to allow flow visualization. The control panel includes starting and stopping control buttons and the display for power input to the motor.

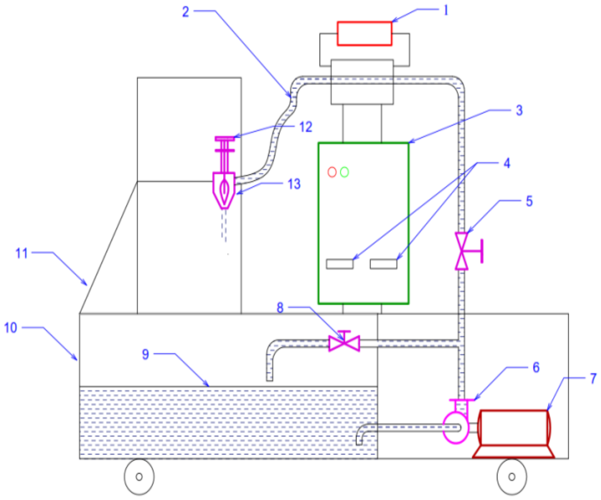

Fig. 1 Experimental setup line diagram for jet analysis

1. Electromagnetic flowmeter
2. Flexible hose for nozzle connection
3. Control panel
4. Speed and power input indicators
5. Head control valve
6. Centrifugal pump
7. Electric motor
8. Bypass valve
9. Sump level
10. Frame for setup
11. Acrylic box for flow/process visualization
12. Knob for gate opening
13. Detachable convergent hydraulic down comer nozzle

III. PROCEDURE

A laminated A4 size graph paper is attached with marking on it in the present study in order to measure jet expansion angle. The effect of exit diameter and interaction with atmospheric air was studied. The atomization of the jet or spreading of the jet is less likely in a case when high kinetic energy at impact is required. In order to avoid the splashing of water, a front activity door can be screwed and unscrewed at the time of replacing the nozzle. In the case of different percentages of valve opening, a valve is operated in or out to vary the flow condition at the nozzle. The valve handle and the pointing bar have been marked on them to vary the discharge. The complete nozzle assembly is rested up firmly on an acrylic chamber with metallic frame support to sustain heavy jerks and flowing fluid pressure. The readings were taken from full valve opening to gradually decreased flow area by operating knob over the assembly.

Table 1 shows the nozzles of different materials and diameters, as well as orifice plates, are used for experimentation. It was coded with specifications.

Table 1. Geometrical Parameters of Tested Nozzles and Material

Sr No.	Nozzle and its Specification	Size (D_i) mm	Material
1	S1	17	Stainless steel
2	S2	22	Stainless steel
3	PY1	17	Polymer
4	PY2	18	Polymer
5	PY3	19	Polymer
6	PY4	25	Polymer

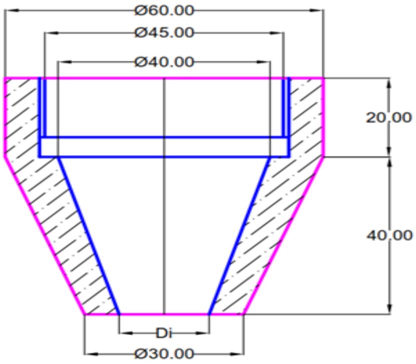

Fig. 2 Cross-sectional view of a nozzle

Fig. 2 shows the cross-sectional view of the nozzle. Consider a jet of water issuing from a convergent nozzle with exit diameter D_i as shown in Fig. 3. Let the jet travels a horizontal distance of length 'Z' and have a core radius (r) at the exit. Since the jet is impinging in still air, it is subjected to atmospheric pressure on the outer surface and surface tension to act on it. Let the jet expansion angle be 'α'.

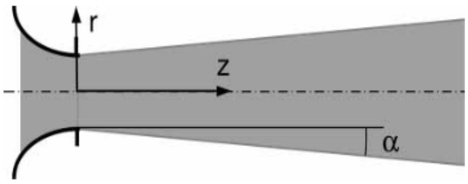

Fig. 3 Jet flow with expansion in horizontal configuration [26]

Fig. 4 and Fig. 5 show the convergent nozzles of different diameters made from stainless steel and polymers, respectively.

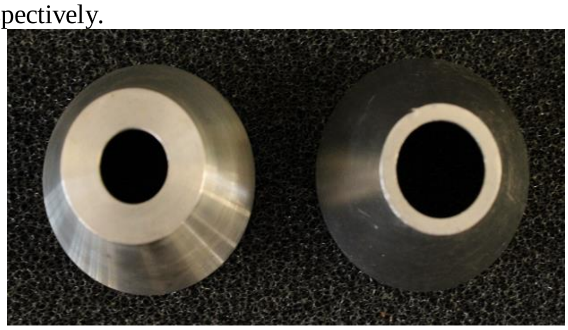

Fig. 4 Stainless Steel convergent nozzle top view left to right a) D_i=17 mm b) D_i=22 mm

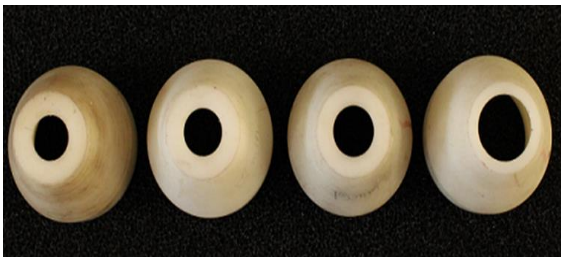

Fig. 5 Polymer convergent nozzle top view left to right a) D_i=17 mm b) D_i=18 mm c) D_i=19 mm d) D_i=25 mm

IV. RESULTS AND DISCUSSION

A. Effect of nozzle material

Variation of coefficient of discharge with Reynolds number (R_e) has been shown in Fig. 6 for comparing both identical diameter nozzles. It shows almost the same variation, which can be seen from the graph. A higher coefficient of discharge (C_d) is achieved for a lower value of Reynolds number (R_e) with stainless steel nozzle compared to polymer nozzle. With a higher value of Reynolds number (R_e), the coefficient of discharge (C_d) is higher. This is quite reasonable with the same amount of valve opening. High flow velocity may be likely to erode the polymer surface, which is not likely to occur in stainless steel nozzle.

B. Jet expansion

The angle of expansion up to a certain length of a jet can be measured by an online angle protector. Here, CAD software was adopted to measure the angle of expansion, as shown in Fig. 7. Jet expansion angle measured for included angle was found to be 1° in a case with Di = 17 mm and 2° for Di = 22 mm for full valve open condition.

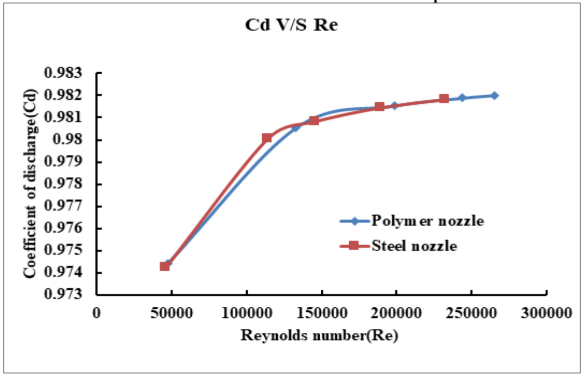

Fig. 6 Variation of coefficient of discharge (C_d) with Reynolds number (R_e) with Di = 17 mm

A small shift is also seen at a larger diameter nozzle, which is due to acceleration and spear effect at the nozzle. Increased diameter is no more useful here, i.e. Di = 22 mm, since higher expansion and shift is associated with it. The jet expansion study is carried out for stainless steel and polymer nozzles of different diameters under identical conditions. From Fig 7, it can be seen that variable jet expansion occurs. The jet expansion increases with restriction inflow or either closing valve gradually. The retardation of flow leads to less momentum transfer between the particles as a result of that while making contact with air get deviated from the path originated from the nozzle exit.

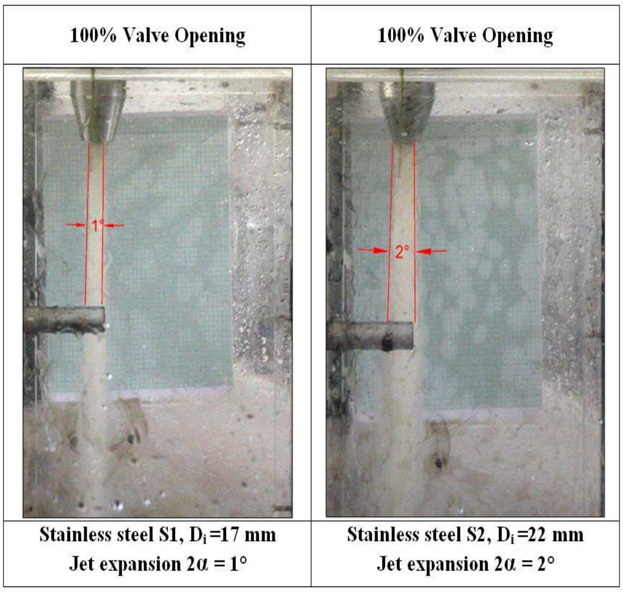

Fig. 7 Stainless steel nozzles with full valve opening under investigation

As shown in Fig. 7, stainless steel nozzle with above described Di = 17 mm and Di = 22 mm with full valve opening were tested further for variable % age valve opening as mentioned. It has been found from an investigation that flow should not be restricted in nozzle since undesirable effects like shifting are more prone to occur in retarded flow. As it can be seen from Fig. 8, a jet deviation is major with 20% valve in a case with Di = 17 mm smaller diameter nozzle too. The momentum is thus higher in the case of Di = 17 mm compared to Di = 22 mm when acted upon a plate with high kinetic energy and ultimately results in higher force due to change in momentum.

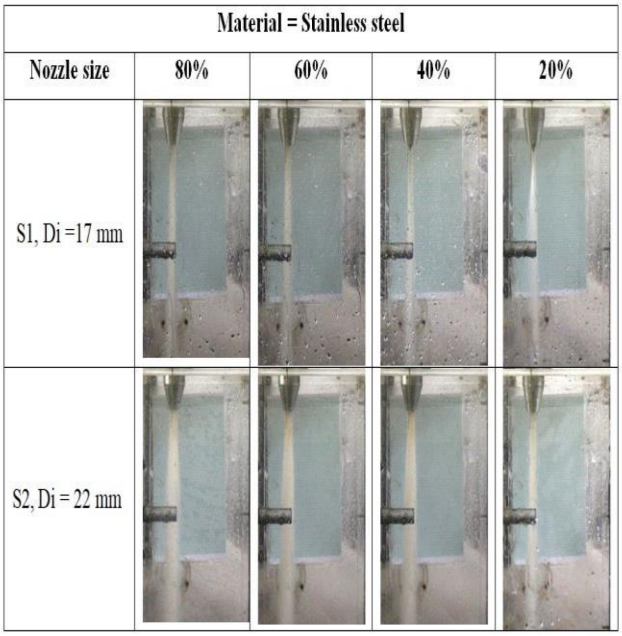

Fig. 8 Stainless steel nozzles with %age valve opening (VO) under investigation

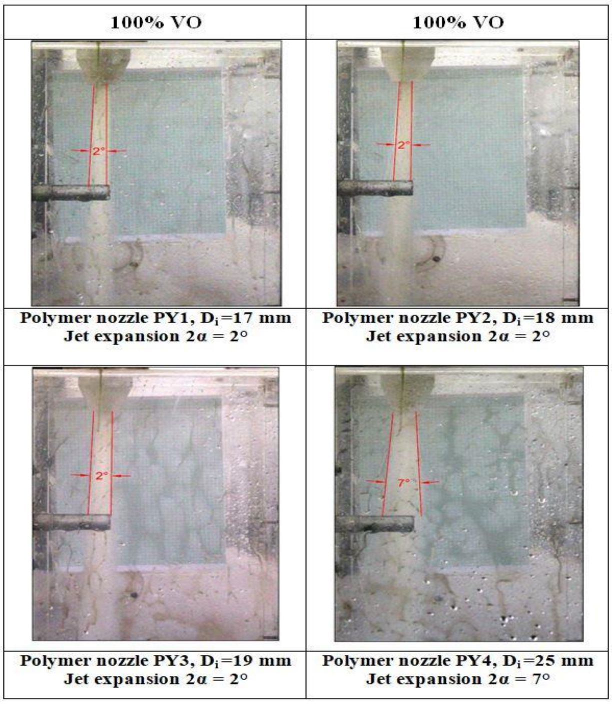

Fig. 9 Polymer nozzles with full valve opening (VO) under investigation

Fig. 9 depicts a polymer nozzle of different diameters with jet expansion values. Four sets of nozzles with a different diameter under consideration were tested and found expansion as depicted. The angle measurements were carried out by CAD software. In fact, an accuracy issue is concerned with such a method, and this is a primary study and very useful to compare options available. The present study gives a brief idea about the change in expansion of jet with change in diameter. In a case with nozzle exit diameter of Di =17, 18, 19 mm, it has been found that the jet expansion included angle is equal to 2°.

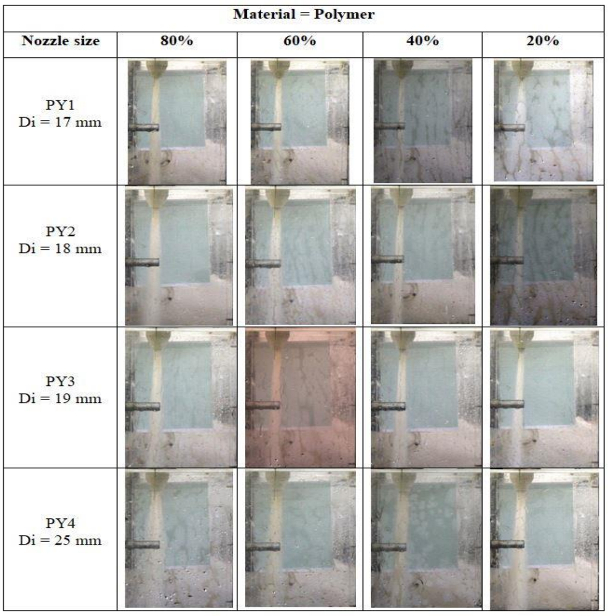

Fig 10: Polymer nozzles with %age valve opening under investigation

All four polymer nozzles with nozzle exit diameter D_i = 17,18,19 mm and D_i = 25 mm were tested further for gradually reducing flow area by the closing valve, as shown in Fig. 10. In these cases, no differentiable expansion was found since polymer nozzle is better in discharge compared to stainless steel nozzles. Although the value of jet expansion is more in the case of polymer nozzle compared to stainless steel nozzle because of frictional losses in polymer nozzles are more. The micro irregularities are mainly responsible for retarded flow in a case with a polymer nozzle.

V. CONCLUSION

The effect of nozzle diameter and flow path obstruction is detrimental to jet quality. The restricted flow may lead to jet deviation and more dispersion compared to fully obstacle-free flow, and the dispersion leads to inferior performance due to less momentum transfer on end striking elements like turbine buckets or plates, as may be the case in hydraulic and pneumatic systems. Following conclusions have been drawn after experimentation.

- Lesser the diameter, more concentrated flow with a less mass flow rate in a case with fully opened flow path as in the case with a nozzle of stainless steel having 17 mm diameter.
- A stainless steel nozzle of 22 mm diameter with a fully opened flow path performs better than the nozzle of 17 mm diameter with half obstructed flow path and tend to deliver more force on end elements to which it is striking.
- More jet expansion beyond the four times of Di depth is observed wherein air entrapment is more on jet surfaces and tangle induced flow.
- Polymer nozzle with 17 mm exit diameter has shown more deviation and jet expansion compared to stainless steel nozzle with the same diameter under identical conditions. Maximum expansion found with polymer nozzle of 25 mm exit diameter and jet shifting too even at fully opened flow path.

With smaller aperture and rigid body of nozzle has shown remarkable jet diameter conformity with least deviation and spreading of a jet. Furthermore, it was also found that the tangle-free flow on the exterior envelope of jet and less jet surface diffusion in a surrounding which otherwise could be of inferior quality as in case with its counterpart.

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NOMENCLATURE

Q - Volumetric flow rate, m^3/sec
D_o - Inlet diameter of nozzle or pipe diameter, m
D_i - Exit diameter of the nozzle, m
β - Constriction ratio (D_o/D_i)
R_e - Reynolds number
C_c - Coefficient for contraction
C_d - Coefficient of discharge
L - Length of nozzle
L/D_i - Nozzle aspect ration
V- Velocity of fluid, m/s
P_{crit} - Critical pressure, N/mm^2
c - Speed of sound in a fluid under consideration, m/s
Z - Length of a jet from nozzle exit, mm
α - Angle of jet dispersion, degree

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