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The role of backpressure on discharge coefficient of sharp edged injection orifices

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ABSTRACT

Sharp edged injection orifices used in thrust chambers and thermal regulation system of liquid rocket engines have to maintain a steady flow to ensure optimum performance. These orifices are subjected to backpressure and elevated temperature during actual operation. The sharp edged orifices do not always run full due to the orifice geometry and/or flow conditions. In some cases, the flow may change its characteristics from attached to detached flow or vice versa. Length of the orifice in relation to its diameter and the backpressure have been observed to play an important role in the abrupt changes in the flow characteristics. In order to comprehensively characterize this phenomenon and to clearly identify the governing parameters, discharge characteristics were determined experimentally for sharp edged injection orifice of 0.6 and 1.4 mm diameters with length-to-diameter ratios in range between 1.4 and 11.5. Cavitation numbers were varied in the range of 0.06 to 20.9 while Reynolds numbers were varied in the range of 13 000 to 62 500. The backpressure for the injection orifice was varied upto 3.6 MPa. The effect of backpressure, Reynolds number, cavitation number, length-to-diameter ratio, and injection pressure drop-to-backpressure ratio on discharge characteristics was brought out. The experimental investigation gives the detailed flow characteristics of sharp edged orifices in the presence of backpressure.

1. Introduction

Sharp edged cylindrical orifices are used for injection of liquids into gaseous media as they are easy to fabricate and not sensitive to inlet radius. Impinging-jet injectors of liquid rocket engines employ multiple numbers of such orifices to achieve required spray characteristics. Sharp edged orifices are also used for accurate metering of water into the thermal regulation system. The thermal regulation system is employed in liquid rocket engines to provide gas at constant temperature to gas motor of the gimbal control system. A small quantity of hot gas is bled to the convergent of the thermal regulation system that mixes with the water injected at the throat. The cold gas from the divergent of the thermal regulation system is admitted into the gas motor.

The entry radius of a sharp edged orifice is generally lower than one-seventh of the orifice diameter. In a sharp edged orifice, liquid is separated from the wall at the vena contracta, which generally reattaches if the length of orifice is more than its diameter. Cavitation occurs in orifices when the static pressure at the vena contracta falls below vapour pressure due to high velocity.

Ohrn et al. [1] showed that the discharge coefficient of sharp edged orifices is always lower than its equivalent contoured-inlet orifice. The studies on the sharp edged orifices have identified two regimes [2,3] viz. attached flow to the orifice wall and detached flow from the orifice wall. The transition from attached to detached flow is known as hydraulic flip. The flow in a sharp edged orifice can be either turbulent, cavitating or hydraulic flip [4,5]. In turbulent flow, discharge coefficient is a function of Reynolds number [6] while in cavitating flow, discharge coefficient mainly depends on the cavitation number for sharp edged orifices [7]. Malavasi and Messa [8] used computational fluid dynamics to simulate the flow through orifices with different geometrical characteristics for various inlet flow velocities. They have identified self-similarity region for single hole orifices in the pressure drop coefficient versus pipe Reynolds number plot.

Yu et al. [9] have investigated the effect of backpressure on the discharge coefficient of the tapered inlet nozzle. They have varied the pressure drop and obtained the relationship between the discharge coefficient and Reynolds number in the turbulent regime and between discharge coefficient and cavitation number in the cavitation flow regime. They showed that upto a critical Reynolds number, discharge coefficient is constant in flip flow. An empirical relationship for the critical value of cavitation number separating turbulent flow from cavitation flow is given in [10] and

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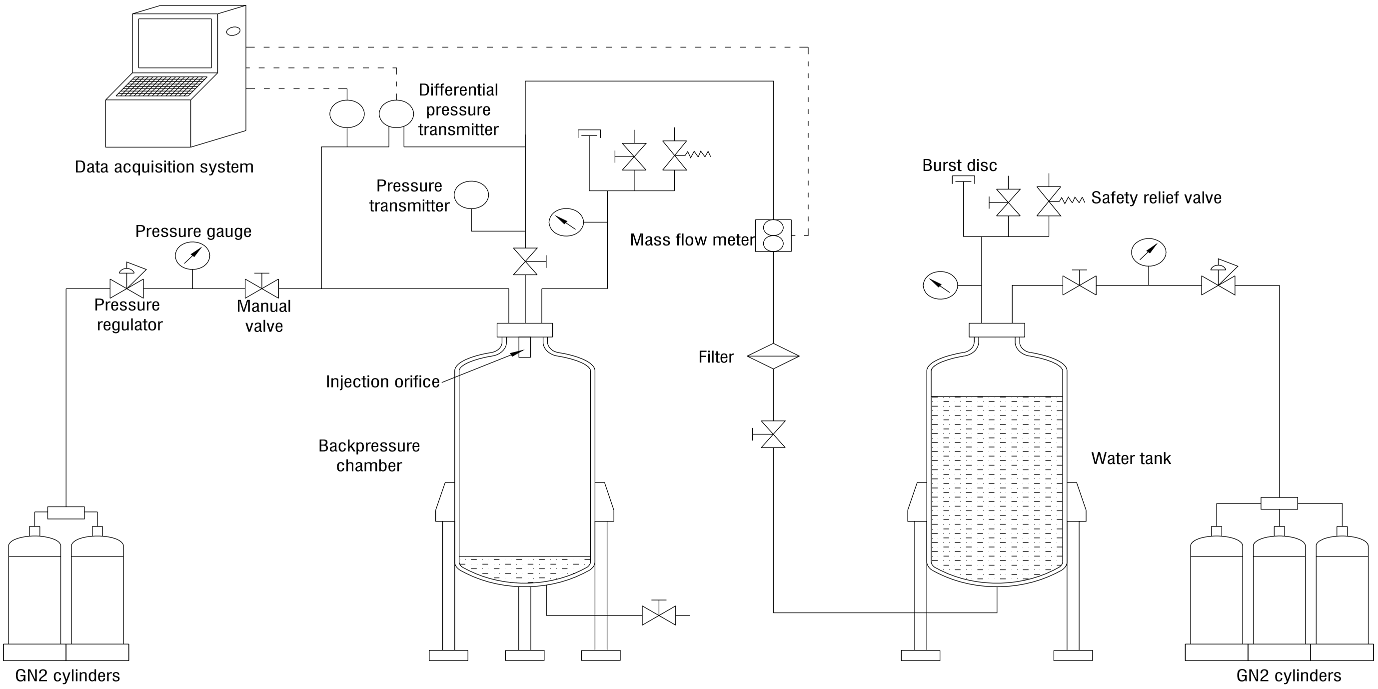

Fig. 1. Schematic of backpressure test facility.

[11]. Ruiz and He [3] identified supercavitation as the cause for detached flow in sharp edged orifices and Williams [12] correlated this to hydraulic flip. Hydraulic flip can lead to variation in mixture ratio in the combustion chamber and degradation in engine performance. The instantaneous variation in flow rate also has ramifications in flow control [13]. Tamaki et al. [14,15] observed that the disturbances associated with the reattachment of the flow in an orifice can promote atomisation of cylindrical jets. Hydraulic flip can also lead to unsteadiness in the liquid jets causing spray pulsations [16] as well as turbulence which affect the breakup of liquid sheets formed by impinging-jet injectors [17]. Cavitation is more likely in high pressure drop injection orifices and was postulated to be the reason for hydraulic flip [18].

Holt et al. [19] analysed the dissipation and cavitation efficiency of baffle plates in circular pipes for evaluating the pressure losses in noncavitating conditions. In the absence of cavitation, pressure loss coefficient is influenced by the geometry of the square edged plate with holes of uniform size. They also found that the incipient cavitation number of perforated plates increases with orifice-to-pipe diameter ratio. Malavasi et al. [20] showed that incipient cavitation number is strongly affected by the diameter ratio of orifice-to-pipe. A lower value of the diameter of orifice to pipe results in a delayed onset of cavitation. The incipient cavitation number increases with thickness-to-diameter ratio when fully separated-flow occurs.

The injection orifices of liquid rocket engines are calibrated using water at ambient conditions. The density and viscosity corrections are invariably applied to determine the flow rate under actual operating conditions. However, corrections for backpressure are not introduced for the determination of flow rate through these injection orifices. The effect of backpressure on the discharge coefficient of the tapered inlet nozzle is reported by Yu et al. [9] but similar results are not available for sharp edged cylindrical orifices. In order to determine discharge coefficient under backpressure corrections, comprehensive characterization of injection orifices in the presence and in the absence of backpressure is to be carried out. The influence of Reynolds number, cavitation number, injection pressure drop-to-backpressure ratio, and length-to-diameter ratio on discharge coefficient is determined experimentally. The results of the experimental investigation conducted on different sharp edged orifices are presented in this paper.

2. Experiments

The experimental setup consists of a cylindrical tank containing demineralized (DM) water, pipe lines, the injection orifice and a backpressure chamber as shown in Fig. 1. Nitrogen gas stored in a gas cylinder was used to pressurize the DM water between 0.1 and 5 MPa through a pressure regulator. The pressurized water was fed to the injection orifice through the pipeline via a series of flow control valves, a mass flow meter and filters. The injection orifice was positioned vertically downwards and the water jet was injected into the ambient gas for experiments without backpressure.

The experiments were also conducted in the presence of backpressure. The injection orifice was mounted on a backpressure chamber with 0.5 m^3 capacity. The backpressure chamber is pressurized upto 3.6 MPa using nitrogen gas stored in gas cylinders. The pressure in backpressure chamber is maintained with the help of a pressure regulator.

2.1. Sharp edged orifice

Sharp edged orifices were machined from stainless steel cylindrical rods into which 0.6 and 1.4 mm holes were drilled. A schematic of the sharp edged orifices is shown in Fig. 2. The details of the orifices used for the experiments are given in Table 1. The length-to-diameter ratio (L/d) is varied upto 6.67 for the 0.6 mm orifice and is varied upto 11.43 for the 1.4 mm orifice.

2.2. Measurements

The flow rate of water through the sharp edged orifice was varied by adjusting the upstream pressure. The mass flow rate ($\dot{m}$) was measured by a high precision Micromotion mass flow meter with an accuracy of ±0.1% on measured value. The pressure of water at the inlet of the orifice (P_i) was measured using a