STUDY ON THE HIGH-PRESSURE GAS FLOW MEASUREMENT SYSTEM OF ORIFICE USED IN ROCKET

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Abstract. In Abstract: In order to improve the reliability of rockets, owing to the simple structure and having no moving parts, more and more orifice plates with steady performance are adopted to replace the traditional gas regulators in the propellant pressurization system. However, it has been found that, different from the normal ones, orifice plates' inlet pressure here is so extremely high, and they do not show the regular theoretic flow performance any more. Based on that background, in this paper, a kind of high-pressure gas flow measurement system of Venturi nozzles and Positive Pressure Facility pVTt has been developed, and numerical analysis of orifice plates and Venturi nozzles were carried out. The results and conclusions of this study will benefit the use of orifice plates in future rocket pressurization systems.

1. Introduction

As the important part of the rocket propellant providing system, rocket propellant pressurization system is used for compelling propellant properly to enter the thrust chamber of rocket engine. As is known, the failures of the propellant pressurization system have been happened sometimes, some of which were caused by gas regulators, which couldn’t control exactly the flow discharged from the high-pressure gas-storage tank and fail to keep properly the pressure in the rocket propellant tank, as a result, the flow rate of propellant transmitted to the thrust chamber of rocket engine was error. For the sake of keeping a target ullage pressure in propulsions tanks and enhancing the exactly of the flow rate, orifice plates with steady performance are adopted, instead of traditional gas regulators, in the propellant pressurization system. For the present study, the orifice plate tested in the experiment comes from a practical rocket propellant pressurization system and the structure is showed in Figure 1.
2. Theoretical and CFD analysis

Analysis of the orifice plate mass flow rate starts with the Reynolds transport equation, which is idealized for potential flow conditions along a streamline, and commonly accepted in the fluid dynamics literature.

\[
\frac{\partial}{\partial t} \int_{CV} \rho \, dV + \int_{CS} \rho \vec{V} \cdot \vec{n} \, dA = 0
\]

With additional idealizations, including a flat velocity profile, non-viscous, no friction losses, and constant fluid density, the classic ideal orifice plate relation can be derived by integrating the Reynolds transport equation over the fluid flow cross-section. Under the critical-flow circumstance, the gas flow accelerates to the critical velocity at the throat (this being equal to the local sonic velocity). At the critical velocity, the mass flow-rate of the gas flowing through the ideal orifice plate is the maximum possible for the existing upstream conditions. The ideal mass flow rate of one-dimensional inviscid flow is:

\[
Q_{\text{ideal}} = \frac{\pi}{4} d^2 \frac{C_v}{\sqrt{\gamma \, M}} \frac{p_0}{\sqrt{T_0}}
\]

According to the structure, the relation between orifice plates’ Mach number with its work condition also has been analyzed by CFD.

However, real applications are not ideal and orifice plate structure is not compliant to ISO standards, for a case, without standard geometries, and special work conditions may also make difference, as a result of a deviation exists between ideal flow and real flow, which is defined as discharge coefficient.

\[
C_D = \frac{Q}{Q_{\text{ideal}}}
\]

The discharge coefficient is a dimensionless ratio of the actual flow-rate to the ideal flow-rate of non-viscous gas that would be obtained with one-dimensional isentropic flow for the same upstream stagnation conditions. This coefficient corrects for viscous and flow field curvature effects. For each type of orifice plate design and installation conditions specified in International Standard, it is only a function of the throat Reynolds number, but to this special, it may be show a different circumstance.

3. Measurement System

In order to study the discharge coefficient, a kind of high-pressure gas flow measurement system has been developed. A simplified schematic of the measurement system is shown in Figure 4, which
consists of three parts. The first part is the Gas-source system; nitrogen is stored and pressurized in a tank, which is used to provide high-pressure gas for experiment from the beginning to the end. The second part named as the pressure control system. On the basis of the wide variable-pressure working condition, ranging from 2 MPa to 30 MPa, design in parallel and branch is necessary for different flow passing through test orifice plate. Besides, a pressure controller, including a commander and three flow execution counterparts, is adopted and cooperated with cut off valves to control and regulate the pressure of the pipe chosen. Ensuring constant pressure ahead of the test orifice plate and realizing the start perfectly, feedback control was added into the system. The third part, measurement system, is used to accurately measure experimental data of valuable parameters such as the temperature, pressure both front and back of the test orifice plate, and mass flow rate is provided by Venturi nozzles arranged in parallel to cover a wide range of flow rate, which is calibrated at its work conditions by positive pressure facility $pVT_t$, and according to the structure of orifice plates with its work conditions, and in order to calibrate the discharge coefficient of each Venturi nozzle at its work condition, some Venturi nozzles and positive pressure facility $pVT_t$ of 2.5m³ are designed. Data acquisition was implemented in National Instruments Field-Point hardware, and an experimental platform is developed based on Labview software for automatic collecting and controlling.

![Measurement System](image1)

![Positive pressure facility of $pVT_t$](image2)

### 4. EXPERIMENT RESULT AND ANALYSIS

The experiment has been developed with Table 1. The positive discharge coefficient experiment of Venturi nozzle of 2.004 mm throat is showed in Table 2, Table 3 is one of the experiment data of orifice plates. The results of the experiment are illustrated in Fig.7.

| Orifice plate Diameter D(mm) | Inlet Pressure (MPa) |
|-----------------------------|----------------------|
| 2.89, 3.39, 3.82, 4.29, 4.68, 5.18 | 30, 20, 10, 5.2 |

Table 2: Positive discharge coefficient of Venturi nozzles of 2.004 mm throat
| Stagnation pressure of (MPa) | Stagnation temperature(K) | Mass flow of positive pressure pVTt (kg/s) | \( \frac{\pi}{4} d^2 \frac{C_d}{R} \sqrt{\frac{p_0}{M}} \) | Positive discharge coefficient \( C_d \) |
|-----------------------------|--------------------------|------------------------------------------|---------------------------------|------------------|
| 4.0                         | 298.52                   | 0.029483                                 | 0.029913                        | 0.98563          |
| 3.6                         | 298.48                   | 0.026505                                 | 0.026913                        | 0.98484          |
| 2.4                         | 298.55                   | 0.017626                                 | 0.017927                        | 0.98321          |
| 1.8                         | 298.54                   | 0.013195                                 | 0.013424                        | 0.98296          |
| 1.2                         | 298.50                   | 0.0087820                                | 0.0089356                       | 0.98281          |

Table 3: Throat diameter 5.18mm of orifice plate with its work conditions

| Inlet pressure of orifice plate (MPa) | Venturi nozzles mass flow (kg/s) | \( Q_{ideal} \) (kg/s) | Discharge coefficient |
|--------------------------------------|---------------------------------|------------------------|----------------------|
| 2                                    | 0.08631                         | 0.09958                | 0.8667               |
| 5                                    | 0.2148                          | 0.2493                 | 0.8616               |
| 10                                   | 0.4301                          | 0.4994                 | 0.8612               |
| 20                                   | 0.8615                          | 0.9997                 | 0.8618               |
| 30                                   | 1.274                           | 1.500                  | 0.8493               |

Figure 6. The relation between discharge coefficient and Inlet pressure

From the Figure 6, the increment of inlet pressure yields a reduction of the \( C_d \) under the critical circumstance, and the discharge coefficient of this kinds of orifice plates within the limits of 0.82–0.87. The results of this paper assist in improving understanding of the use of orifice plates in rocket pressurization systems. Besides, the method and the modeling of Venturi nozzles positive pressure facility \( pVTt \) described in detail in this paper will make a good contribution to high-pressure gas flow measurements.

References
[1] Hobbs JM, Humphreys JS. The effect of orifice plate geometry upon discharge coefficient. Flow Measurement and Instrumentation 1990; 1(3):133–40
[2] ISO 9300-2005, Measurement of gas flow by means of critical flow Venturi nozzles.
[3] JJG 619-2005, Gas Flow Calibration Facility to p.V.T.1 Technique.