Design and experimental research of the cryogenic ejector to inject liquid nitrogen

Q M Jia¹², Z Y Li¹, L H Gong¹², L Q Liu¹², W P Zhu¹, M M Zhang¹ and H K Su¹²

¹ State Key Laboratory of Technologies in Space Cryogenic Propellants(Technical Institute of Physics and Chemistry, Chinese Academy of Sciences), Beijing 100190, China

² University of Chinese Academy of Sciences, Beijing 100049, China

E-mail: jqmipc@mail.ipc.ac.cn

Abstract. With the development of cryogenics, the demand of cryogenic liquid increases constantly. However, there are some difficulties to control and to adjust the extraction of cryogenic liquid especially for liquid helium. Compared with the immersed pump, the ejector has huge advantages in pumping the cryogenic liquid from cryogenic Dewar, like stable operation and simple structure. Considering the similarity between liquid nitrogen and liquid helium and the high cost to conduct the liquid helium experiment, this paper reports a research on the cryogenic ejector in the nitrogen temperature range. The experiment platform customized for liquid nitrogen was set up and the experiment of injection was launched. The nitrogen gas, as the primary flow accelerating in the nozzle, injects the liquid nitrogen at the outlet of nozzle. Two flows blend in the mixing chamber and flow out from the diffuser. Based on the ideal gas assumption and energy conservation, the sound velocity can be derived from two kinds of equations, obtaining the critical condition of primary flow thermal properties. Depending on the properties and previous research experience, the structure of ejector is designed and established, which could effectively inject liquid nitrogen from the cryogenic liquid cylinder. The problems and challenges are analyzed. In conclusion, this paper introduces the design method of cryogenic ejector and builds a liquid nitrogen test instrument. This method makes the extraction of cryogenic liquid more convenient, which is of universal significance for the cryogenic research work.

1. Introduction

Cryogenic liquid, which has more cooling capacity than the cryogenic gas, is applied in more and more fields like medical equipment and scientific researches. Small or large-scale cryogenic refrigerators are used to cool down the refrigerant from gas phase to liquid phase so that it can be easily stored in Dewar. Cryogenic liquid can provide cooling capacities in different temperature ranges and by various methods. However, the extraction of cryogenic liquid from cryogenic Dewar is a complex question in some situations, especially in the large cryogenic refrigeration systems. Concretely speaking, it is difficult to control the injected liquid flow rate and to avoid the heat loss in the process of extraction. The cryogenic immersed pump is widely adopted nowadays. Nevertheless, the mechanical motion components of immersed pump lead to an extremely high requirement of
machining especially when working in cryogenic condition. With some inevitable problems, the operational stability and service life is very likely unsatisfactory. In addition, the heat leak from the pump in cryogenic liquid results in a huge cooling capacity loss. Hence, a new kind of pump is researched in this paper to avoid those problems resulting from immersed pump.

The development of ejector has a long history and many researchers proposed valuable theories to present the jet mechanism. Because of structure feature, ejector owns so many advantages, like operating stability, low heat leakage and convenient processing [1, 2], so that it is applied in various industrial fields.

Ejectors are used in the field of refrigeration from 1901, when Leblanc and Parsons proposed an air separating ejector [3]. In 1966, Rietdijk first proposed the application of a jet pump in the cold side of a helium refrigeration system [4]. In 1976, Ageev conducted an experiment on a cryogenic ejector, in which the optimum position of the nozzle exit was found and the reliability of the design method was verified [5]. In 1987, D.L. Johnson proposed a cryogenic ejector used in a closed-cycle refrigerator, which could supply cooling capacity for systems whose temperature was below 4.2 K [6]. In 1985, Rudolf proposed a warm ejector that was used in a liquid helium refrigeration system, and the impact of the nozzle axial position and nozzle shape on the performance was analysed [7]. In 2013, Qing Ni proposed a cryogenic ejector, whose function was to sub-cool the supercritical helium by a method in which high-pressure and low-velocity supercritical helium speeded up in the nozzle and then entrained the helium stream from the subcooler, which was used to decrease the chamber temperature and pressure [8]. In 2009, S. He reviewed the mathematical model of ejector and described the different design methods [9]. In this review, the fundamental principle and model establishment of ejector are introduced, including steady model and dynamic models.

Although the flowing and mixing mechanism of ejector is researched for a long history, the cryogenic ejector entraining cryogenic liquid is rarely researched. Due to the particularity of cryogenic fluid properties, designed structure of cryogenic ejector needs to be adjusted for adopting the two-phase flow in some cases. The two-phase flow increases the design difficulty for disclosing the complicated flow mechanism in the nozzle and intricate mixing process in the mixing chamber.

2. Design of cryogenic ejector

2.1. The fundamental principle

The primary flow in high pressure flows through the nozzle and turns out to be low-pressure and high-speed. Then the secondary flow is entrained in suction chamber because of the low pressure zone causing by the primary flow. The suction flow and primary flow mix together in mixing chamber and the mixed fluid decelerates in diffuser chamber. The design theory of cryogenic ejector is based on the following assumptions. In nozzle, the flow speed is extremely high with rare heat loss. Hence, the flow process in nozzle is considered to be isentropic. To simplify the flow problems, many factors are ignored in engineering design. The gas is regarded as the ideal gas so that the simplified functions of ejector can be used.

Figure 1. Schematic diagram of a cryogenic ejector.
0-primary flow inlet, 1-secondary flow inlet, t-nozzle throat, 2-nozzle exit, 3-suction chamber, 4-mixing chamber, 5-diffuser chamber
The continuity equation, momentum equation, energy equation and sound speed equation are shown in equations (1-4).

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}
\]

\[
\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}
\]

\[
\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i}(u_i(\rho E + P)) = \vec{V} \left( a_{eff} \frac{\partial T}{\partial x_i} \right) + \vec{V} \left( u_i(\tau_{ij}) \right) \tag{3}
\]

\[
c = \left(-\nu^2 \left( \frac{\partial P}{\partial u} \right)_S \right)^{1/2} \tag{4}
\]

The ideal gas equation and the sound velocity equation of ideal gas are shown in equations (5, 6).

\[
\rho = \frac{P}{RT} \tag{5}
\]

\[
c = (\gamma R g T_c)^{1/2} \tag{6}
\]

The continuity equation and energy equation can be simplified to the equations (7, 8).

\[
\rho_0 u_0 A_0 + \rho_1 u_1 A_1 = \rho_5 u_5 A_5 \tag{7}
\]

\[
\left( h_{0g} + \frac{u_0 g^2}{2} \right) + \left( h_{1t} + \frac{u_1 t^2}{2} \right) = \left( h_{5g} + \frac{u_5 g^2}{2} \right) + \left( h_{5t} + \frac{u_5 t^2}{2} \right) \tag{8}
\]

The nomenclatures in above equations are introduced below. \( \rho, t, \tau, P, c, v, R, \gamma, T, u, A, h \) are density, time, heat, pressure, sound velocity, specific volume, gas constant, specific heat ratio, temperature, flow speed, area and specific enthalpy, respectively. The subscripts in above equations are listed below. Subscript ‘0-5’ indicates different positions of the ejector, which is specifically shown in Table 1. The simplified function provides a valid guidance for researches in the situation of lacking design experience and experimental data.

2.2. Design method of cryogenic ejector

As shown in the Table 1, the parameters of cryogenic ejector are listed in the table. Because of the possibility of two-phase flow in the inner of ejector, the physical property, quality, is noted to denote.

| Position          | \( P \) (kPa) | \( T \) (K) | \( h \) (J/kg) | Density (kg/m\(^3\)) | Quality | Flow rate (m/s) | Mass flow rate (g/s) |
|-------------------|---------------|-------------|----------------|------------------------|---------|----------------|----------------------|
| 0 inlet of nozzle | \( P_0 \)     | \( T_0 \)   | \( h_0 \)     | \( \rho_0 \)           | \( q_0 \) | \( v_0 \)     | \( m_p \)            |
| 1 inlet of injection | \( P_1 \) | \( T_1 \) | \( h_1 \) | \( \rho_1 \) | \( q_1 \) | \( v_1 \) | \( m_s \) |
| t throat of nozzle | \( P_t \) | \( T_t \) | \( h_t \) | \( \rho_t \) | \( q_t \) | \( v_t \) | \( m_p \) |
| 2 outlet of nozzle | \( P_2 \) | \( T_2 \) | \( h_2 \) | \( \rho_2 \) | \( q_2 \) | \( v_2 \) | \( m_p \) |
| 3 suction chamber | \( P_3 \) | \( T_3 \) | \( h_3 \) | \( \rho_3 \) | \( q_3 \) | - | - |
| 4 mixing chamber  | \( P_4 \) | \( T_4 \) | \( h_4 \) | \( \rho_4 \) | \( q_4 \) | \( v_4 \) | \( m_m \) |
| 5 outlet of diffuser | \( P_5 \) | \( T_5 \) | \( h_5 \) | \( \rho_5 \) | \( q_5 \) | \( v_5 \) | \( m_m \) |
The working conditions of cryogenic ejector are regarded as prerequisites for structure design including ejector inlet, ejector outlet, secondary inlet pressures and temperatures. The mass flow rate of primary flow and entrainment flow is requisite as well. The radius of primary pipe is determined by system requirement, which influences the inlet flow rate. Firstly, the inlet flow rate can be calculated by the known mass flow rate and inlet sectional area. Stagnation condition is deduced by the entropy and flow rate of inlet flow, in which the velocity is zero and the entropy of stagnation point equals to the inlet entropy. In most instances, the stagnation condition is similar with the inlet initial condition if the inlet velocity is not extremely high so that the inlet velocity can be ignored. In order to get various physical parameters in stagnation condition, the parameter, enthalpy, need to be obtained by energy equation as shown in equation (9).

\[
h^* = h_0 + \frac{c_0^2}{2}
\]  

Assuming the specific heat at constant pressure is invariable, equation (10) is obtained to indicate the velocity at nozzle throat. If the fluid is looked upon as ideal gas, equation (11) can be obtained. Achieving sound speed at nozzle throat is the basic requirement of nozzle design. Therefore, \(v\) equals to \(c\).

\[
v = \left(2C_p(T^* - T_t)\right)^{1/2}
\]  

\[
c = \left(\gamma R_g T_t\right)^{1/2}
\]  

The relation between the pressure at nozzle throat and the pressure at stagnation condition can be obtained, as is shown in equation (12). \(\gamma\) is adiabatic exponent and \(k\) is revision coefficient.

\[
\frac{P_t}{P^*} = \left(\frac{2}{\gamma + 1}\right)^{\gamma + k - 1}
\]  

Temperatures at nozzle throat and sound speed are determined by equation of physical property rather than the ideal gas equation. By this method, the speed at nozzle throat can be presented in two forms, the calculated velocity value by energy equation and calculated sound velocity by physical property equation. Via comparing two values, the validity of assumptions can be verified. Further, the radius of nozzle throat is calculated by equation (13).

\[
r_t = \left(\frac{m_p}{\pi \rho_t v_t}\right)^{1/2}
\]  

The outlet pressure of nozzle is assumed to be the same with the secondary flow pressure, which guides us to design the appropriate radius of nozzle exit.

\[
\frac{P_2}{P_t} = \left(\frac{T_2}{T_t}\right)^{\gamma - 1}
\]  

\[
r_2 = \left(\frac{m_p}{\pi \rho_2 v_2}\right)^{1/2}
\]  

The contraction section of nozzle is with the angle between \(60^\circ - 90^\circ\). The divergent section of nozzle is with the angle between \(3^\circ - 8^\circ\) [10].

The radius of mixing chamber is confirmed on the prerequisite of simplified mixing process. In the assumption, the energy and momentum loss is ignored and equations (16-18) can be obtained.

\[m_p v_2 + m_s v_1 = m_m v_4\] (16)
\[ r_4 = \left( \frac{m_p + m_s}{\pi \rho_2 v_4 + \pi \rho_1 v_4} \right)^{1/2} \]  
(17)

\[ T_4 = \frac{m_p C_{p1} T_2 + m_s C_{p2} T_1}{m_p C_{p1} + m_s C_{p2}} \]  
(18)

The function of diffuser chamber is to decelerate and pressurize the mixing flow. The radius of diffuser chamber exit decides the velocity and pressure of outflow. Thus the appropriate radius is adopted with the assumption of isentropic flow, which is shown in equations (19-21). \( k_2 \) is the polytropic exponent.

\[ \frac{T_4}{T_5} = \left( \frac{P_4}{P_5} \right)^{\frac{k_2-1}{k_2}} \]  
(19)

\[ v_5 = \left( 2C_{p3}(T_4 - T_5) + \frac{v_4^2}{2} \right)^{1/2} \]  
(20)

\[ r_5 = \left( \frac{m_s}{\pi \rho_5 v_5} \right)^{1/2} \]  
(21)

The main parameters of ejector are determined by the assumption of ideal case, which is shown in the equations above. In practice, some key parameters maybe need to be adjusted for conforming the working condition.

Figure 2. Simplified schematic diagram for the system of cryogenic ejector.

2.3. Parameters of cryogenic ejector experimental system
As shown in Fig. 2, the experimental system is composed of cylinder group, valve, rotameters, tank, heat exchanger coil, cold box, package, ejector and vaporizer. The data collection system consists of 3706 system switch multimeter by KEITHLEY and industrial computer of 610 H by ADVANTECH. Due to the different phases between the primary flow and the second flow, the flow rate of outlet flow is huge; the flowmeter is chosen the volumetric flowmeter. The heat exchanger coil is chosen the
copper tube to achieve the better heat transfer effect. The tank is filled with liquid nitrogen for precooling the primary flow to the designed temperature, which is 100 K in this experiment. The main structure parameters of cryogenic ejector are listed below. The diameters of nozzle throat and nozzle exit are 2 mm and 2.6 mm. The diameter of ejector exit is 15.3 mm.

3. Analyses of the cryogenic ejector experimental results

3.1. The relation between the primary pressure and flow rate

High pressure nitrogen gas from the cylinder group flows through the tank filled with liquid nitrogen to cool down the primary flow. Then, the primary flow entrains the liquid nitrogen from the package and the two flows mix together to rewarm in the vaporizer. In the experiment, the primary pressure is regulated by the valve from 400 kPa to 700 kPa. The outlet flowrate is larger than the inlet flowrate, which indicates the liquid nitrogen from package is entrained by this cryogenic jet pump. Compared with the experimental data of package liquid level, the error of increased flowrate, less than 15%, is in a tolerant range considering cryogenic measurement. The feasibility of this design method is verified. The entrainment flowrate nearly increases with primary pressure rising. Primary fluid flows through nozzle for depressurization and acceleration, which will have a higher velocity if its pressure is higher in a certain range. More suction flow can be carried out by higher speed flow. As shown in Figure 3, experimental flowrate and calculated flowrate are presented, and the error becomes larger at high primary pressure due to the problems brought by the gas-liquid two phase flow.

![Figure 3. Flow rate in the cases of different primary pressures.](image)

3.2. Pressure change from the ejector

With the increase of primary pressure, the outlet pressure increase nearly linearly. The largest outlet pressure is 177 kPa when the primary pressure is 696 kPa. The pressure of secondary flow is regarded as atmospheric pressure because the cavity inner is connected to the atmosphere by inlet pipe to maintain the pressure. Pressure ratio, which is equal to inlet pressure divided by outlet pressure, also rises as the primary pressure increases. The maximum pressure ratio is 3.9.
3.3. The efficiency of ejector

As an important index reflecting the performance of ejector, the entrainment ratio is shown in Figure 5. The dryness of primary flow at the exit of nozzle decreases with the increase of primary pressure, resulting in the decrease of secondary flow. Meanwhile, the primary flow rate increases in a larger primary pressure. Hence, the entrainment ratio decreases. When primary pressure increases further, primary flow turns into liquid phase totally resulting in the entrainment ratio increase again.

The primary flow speeds up from subsonic velocity to sound speed in nozzle contraction section, so that the isentropic efficiency shows the flow loss in this section to indicate the core efficiency of nozzle. In the nozzle contraction section, the primary flow is still gas phase. Based on the experimental data and calculation, the nozzle contraction efficiency is obtained. Due to the variation of flow loss is negligible, a larger primary pressure reduce the influence of flow loss on efficiency of nozzle contraction section. The flow condition in divergent section of nozzle needs a further analysis because of the two phase flow problems.

4. Conclusion

In this paper, a cryogenic jet pump in the range of liquid nitrogen temperature is designed. Based on the ideal gas assumption, a method is proposed for simplifying design process in the application of engineering. A liquid nitrogen experiment system is built to verify the design method. By analyzing
experimental data, liquid nitrogen is entrained by low temperature and high pressure inlet flow. This research can solve many problems for helium temperature ejector design. And it is promising that the ejector can be used to take liquid helium out of Dewar, to adjust the refrigeration capacities of liquid helium refrigerators and to extract high-pressure helium gas from cryogenic cavities.

5. References
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