Discharge Performance of Impinging Injector for Cavitating Flow

Won Kook Cho* and Chul-Sung Ryu*
Rocket Engine Department
Korea Aerospace Research Institute, Daejeon, Korea 305-333

Abstract

The discharge performance of an impinging-type injector for cavitating flow has been evaluated. The predicted discharge coefficient for cavitating flow agrees well with the measured data showing less than 2% discrepancy. For the case of non-cavitating flow analysis, the disagreement between CFD results and the experimental data is 8%. The discharge coefficient for the cavitating flow decreases with decrease in the Reynolds number. On the other hand, it increases slightly as the Reynolds number increases for the non-cavitating flow because of the reduced viscous effect. The incipience of cavitation is predicted to occur around the cavitation number of 1.3 for fixed Reynolds number flow. In this environment, the discharge performance is proportional to the cavitation number for cavitating flow while it is independent to the cavitation number for non-cavitating flow regime.

Key Word : impinging injector, cavitating flow, discharge performance, CFD-ACE

Introduction

It has been reported that the discharge performance of an injector with high pressure drop is strongly influenced by back pressure[1-5]. The cavitation incipience in the contraction region of the injector hole where the flow accelerates is the major cause for discharge performance deterioration. The increase of pressure drop for cavitating flow in the orifice[6] has been ascertained experimentally *in the early 60's. Recently numerical approaches[3-5] have been reported for cavitating flow through* the injectors.

(a) (b)

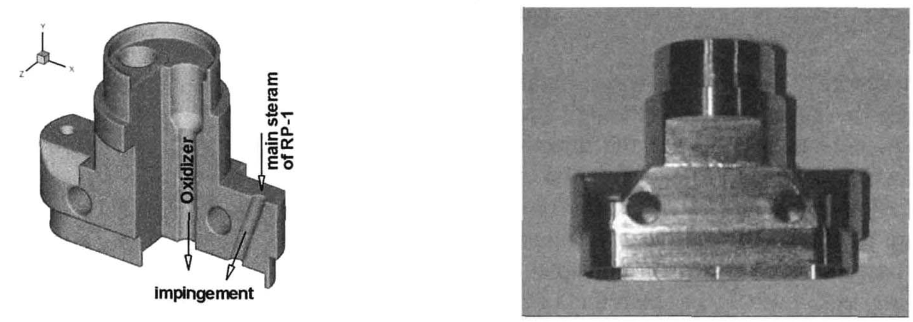

Fig. 1. Impinging type injector; (a) Flow passages inside the injector, (b) Photo of injector

* Senior research engineer
Email : wkcho@kari.re.kr, TEL : 042-860-2937, FAX : 042-860-2602

NOMENCLATURE

A	area
C_d	discharge coefficient, $= \dot{m}/A\sqrt{2\Delta p\rho}$
C_c	coefficient of condensation, 0.01
C_e	coefficient of evaporation, 0.01
f	mass fraction
K	cavitation number, $= (p_{in}-p_v)/(p_{in}-p_e)$
k	turbulent kinetic energy
$\dot{m}$	mass flow rate
p	pressure
p_v	saturation pressure, =3540 pa at 300 K
Re	Reynolds number
$\mathbf{V}$	velocity vector
V_{ch}	characteristic velocity, $=\sqrt{k}$

Greek symbols

Δp	pressure difference
ρ	density
σ	surface tension, =0.0717 N/m

subscripts

e	value at exit
g	gas phase
in	value at inlet
l	liquid phase
v	vapor phase

The injector[4,5] under consideration in the present study is used for liquid rocket engine. No cavitation is expected to occur at the design point of the liquid rocket engine, because of the high back pressure i.e., combustion chamber pressure which is at least ten bars. However, the incipience of cavitation in the injector may be an important issue for the condition of the combustor before ignition or injector water test carried out under atmospheric back pressure. In this context the discharge performance of the injector for cavitating flow is of great importance to analyze the injector water test results and off-design point performance.

A typical impinging type injector is shown in Fig. 1. Three-dimensional analysis should be carried out since the flow in an impinging injector may not be regarded as two dimensional. Though a three-dimensional analysis and experiment[5] were carried out for the impinging injector a systematic interpretation of the cavitation effect to the discharge characteristics has not been reported. So the present paper considers the three dimensional numerical analysis and experimental measurement on the discharger performance of the impinging type injector. The major parameters governing the injector orifice performance are propellant, material property, orifice size, transient flow conditions, characteristics of fluid dynamics and heat transfer. The effect of the following parameters to the discharge coefficient is presented: Reynolds number and the cavitation number defined in the following.

Measurement

Discharge coefficient was obtained by measuring the mass flow rate through the injector hole and upstream pressure of the injector. Fig. 2 shows the schematic of the experimental apparatus. It has little impact on the measured upstream pressure to change the pressure transducer location because the flow passage before contraction of which the cross section area is 25 times larger than that of the orifice hole is believed to behave as a plenum chamber. The mass flow rate is calculated from the water weight gathered in the tank and the operation time. The measurement errors of the load-cell and the pressure transducer are less than the manufacturing error

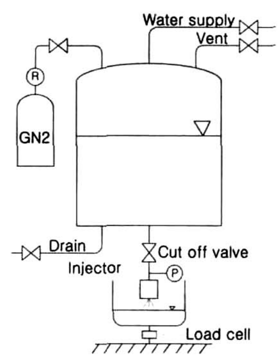

Fig. 2. Schematic of experimental setup

which is less than 0.5%. The pressure of supplying fluid is extremely uniform as the normalized standard deviation of the upstream pressure is less than 0.3% after 12 to 20 seconds preconditioning time.

As shown in Fig. 1, the trace of RP-1 slants against the mainstream which is essential to collide the propellants for generating spray. The RP-1 flow passage is modeled as a slant circular tube with simple contraction in the computation. The mass flow rate and pressure data are averaged from three times measurements. The operating time, mass flow rate and the statistical data about upstream pressure are recorded after experiment.

Numerical Method

Numerical analysis has been performed by using the commercial CFD code, CFD-ACE v6.4[7]. The governing equations are steady state three dimensional Navier-Stokes equations for incompressible flow as the Mach number is much less than unit at the injector orifice where the velocity accelerates the most, e.g., 20 to 30 m/s. The material properties of the working fluid is assumed to be constant and the reference temperature is 300K.

The vaporization mass is described by the eq. (1) of conservation of the vapor mass fraction, f with numerical cavitation model.

$$\nabla(\rho \mathbf{V} f) = \nabla(\Gamma \nabla f) + R_e - R_c \tag{1}$$

where the source and the sink terms are

$$R_e = C_e \frac{V_{ch}}{\sigma} \rho_l \rho_v \left(\frac{2}{3} \frac{p_v - p}{\rho_l} \right)^{0.5} (1-f)$$

$$R_c = C_c \frac{V_{ch}}{\sigma} \rho_l \rho_v \left(\frac{2}{3} \frac{p - p_v}{\rho_l} \right)^{0.5} f$$

The average density of two phase fluid is obtained by the following eq. (2). The density of liquid phase and the vapor phase is assumed to be constant respectively.

$$\frac{1}{\rho} = \frac{f_v}{\rho_v} + \frac{f_g}{\rho_g} + \frac{1 - f_v - f_g}{\rho_l} \tag{2}$$

The density of the non-condensible gas is described by the ideal gas law and its mass fraction, f_g is constant (= 15PPM). The liquid density is 1000 kg/m^3 and the vapor density is 0.0258 kg/m^3.

SIMPLEC algorithm is adopted for pressure-momentum coupling and the second order upwind scheme with flux blending of 10% upwind scheme is used for convective term for stable convergence. The present numerical procedure solves iteratively the governing equations and stops the iteration when the residual of each variable is less than 10^{-3}. Simultaneously confirmed is the state that the variation of all the dependant variables is negligibly small at a prescribed monitoring location.

Computational grid of 39,000 finite volumes shown in Fig. 3 is confirmed fine enough to give a grid insensitive solution as a finer grid of 99,840 volumes gives only 0.3% difference of pressure drop for same flow condition. Five blocks can construct the whole flow domain to ensure orthogonal grid. The iterative numerical procedure terminates after about 1000 iteration for single phase flow while twice iteration is needed for cavitating flow. Nearly 8-second CPU of SGI Octane (300MHz) is consumed for one iteration.

Results and Discussions

The orifice diameter is 1.6mm and the area contraction ratio is 1/25. The aspect ratio, i.e.,

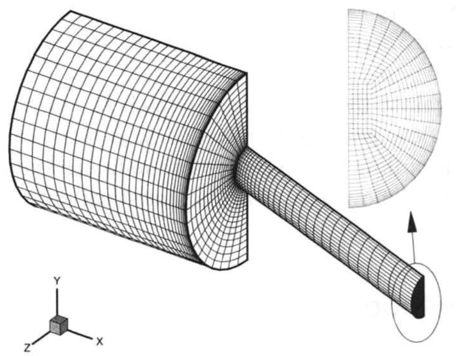

Fig. 3. Computational grid

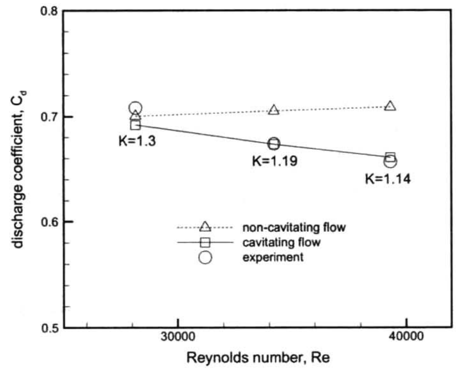

Fig. 4. Discharge coefficient versus Reynolds number for atmospheric back pres- sure

the ratio of injector hole length and the diameter is 5.3 which is sufficiently large for pressure recovery[1]. The velocity is uniform at the inlet with 10% turbulence intensity, and the pressure at the exit is atmospheric as given for the experimental condition if not specified. Only half of the physical domain is solved because of the symmetric geometry.

The discharge coefficient variation with respect to the flow rate is described in Fig. 4 for atmospheric back pressure with which the measurement is carried out. In the figure the Reynolds number is defined with the average velocity through the injector hole and the hole diameter. Cavitation numbers specified in the figure for each flow condition cannot be controled independently because the back pressure, inlet pressure and vapor pressure are fixed for each test condition.

The results of numerical analysis for both single phase flow and cavitating flow give almost same discharge performance for the flow with little cavitation of which the Reynolds number is less than 3×10^4. The numerical analysis method of cavitating flow gives accurate data about the discharge characteristics as the discrepancy between the analysis and the measurement is less than 2%. However the incipience of cavitation severely affects the discharge performance for large Reynolds number flows. One can conclude that the single phase flow analysis dose not give accurate results any more under this circumstance because the discharge coefficient is over-predicted by 8% for the Reynolds number of 3.9×10^4. On the other hand, the cavitation model accurately predicts the pressure drop through the injector orifice as shown in the figure. In the single phase flow, the discharge coefficient slightly increases as the Reynolds number increases. This can be interpreted as the reduced viscous effect for high Reynolds number flows. On the contrary, the discharge coefficient decreases for cavitating flow as the Reynolds number increases because the vapor bubbles from cavitation suppress the pressure recovery through the injector hole. Bunnel and Heister[3] reported about the water discharge performance of long injector passage without slant angle through 3-dimensional CFD analysis under laminar flow assumption. The discharge coefficient was predicted to decrease by 10% due to cavitation for Reynolds number of 85,400.

The cavitation number playing an important role for cavitating flow is given in the nomenclature. The numerator means static pressure while the denominator does dynamic pressure. Small cavitation number implies the condition readily produces cavitation because liquid vaporizes easily in low static pressure environment. It cannot be concluded that the variation of the discharge coefficient is purely due to the Reynolds number though the discharge performance is investigated in Fig. 4 for different Reynolds numbers with atmospheric back pressure because the cavitation number is not fixed. It needs to observe systematically the effect of the incipience of cavitation to the pressure drop in the injector because the cavitation number is one of the most important parameters in the cavitating flow. Fig. 5 depicts the discharge performance variation vs. the cavitation number for fixed Reynolds number which simulates various back pressure or vapor pressure with fixed flow rate. Invariant discharge coefficient is seen for the cavitation number greater than 1.3 regardless of the Reynolds number. Various injectors show different initiation points of cavitation which is concluded as one of the injector characteristics. However all the slopes of the discharge coefficient in the figure are nearly same for cavitating condition which is reported to be proportional to the square root of the cavitation number by Nurick[2]. A little bit higher discharge coefficient is predicted for higher Reynolds number before the incipience of cavitation because of relatively less viscous effect for high Reynolds number flow. After cavitation initiation, however, the discharge character is close to same for same cavitation numbers regardless of the Reynolds number. From this it can be concluded that the cavitation number plays the most important role for cavitating flow regime.

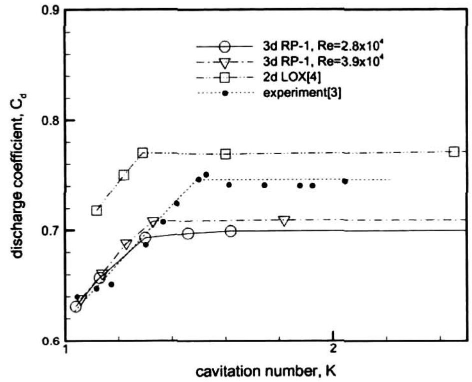

Fig. 5. Discharge coefficient variation for variable cavitation number with fixed flow rate.

Conclusions

An experimental and numerical analysis has been made on the discharge performance of the impinging type injector. The discharge coefficient increases slightly as the Reynolds number increases for non-cavitating flow while it decreases for higher Reynolds number for cavitating flow. The discrepancy of discharge coefficient reaches up to 8% for $Re=3.9\times10^4$ when cavitation is not considered. On the other hand the difference completely disappears for cavitating flow analysis. The incipience of cavitation is predicted to occur around $K=1.3$ with constant Reynolds number. The discharge performance depends on cavitation number for fully cavitating flow regardless of the Reynolds number.

Acknowledgement

The present study is a part of research efforts of KSLV-I program that is supported by the Ministry of Science and Technology, Korea.

References

1. G.S. Gill and W.H. Nurick, *Liquid rocket engine injectors*, NASA SP-8089, 1976.

2. W.H. Nurick, Orifice cavitation and its effect on spray mixing, *J. Fluids Eng.*, v98, pp.681-687, 1976.

3. R.A. Bunnell and S.D. Heister, Three-dimensional unsteady simulation of cavitating flows in injector passages, *J. Fluids Engng.*, v122, pp.791-797, 2000.

4. Won Kook Cho, Chul-Sung Ryu and Young-Mog Kim, Injector discharge characteristics of liquid rocket engine (in Korean), *J. Korean Soc. Propulsion Engineers*, Vol. 5, No. 4, pp.12-19, 2001.

5. Won Kook Cho, Chul-Sung Ryu and Daesung Lee, Cavitating flow in an impinging-type injector (in Korean), *J. Korean Society for Aeronautical and Space Sciences*, v31, pp.80-86., 2003.

6. F. Numachi, M. Yamabe and R. Oba, Cavitation effect on the discharge coefficient of the sharp-edged orifice plate, *J. Basic Engng.*, v82, pp.1-10, 1960.

7. *CFD-ACE v6.4 manual*. 2001.