FLUCOME 2009
10th International Conference on Fluid Control, Measurements, and Visualization
August 17-21, 2009, Moscow, Russia

STUDY ON FLOW CHARACTERISTICS OF RADIAL SLIT ELEMENT

Yoichi Okawa[1], Chongo Youn[2], Kenji Kawashima[3], Toshiharu Kagawa[4]

ABSTRACT

Pressure reducing valves are widely used to maintain the pressure of gas reservoirs to specific values. In a normal valve, supply pressure is depressurized with an orifice structure. When highly pressurized air passes through the orifice structure, considerable noise occurs at the downstream side. To solve this problem, we have developed a radial slit element. The micro radial slit element is comprised of disks similar to a cylinder that has been sliced. In this research, the flow characteristics of micro radial slit element are studied. There is difference between the experimental results of flow characteristics of the slit element and the approximation of ISO6358. As the main pressure drop in the slit element occurs by viscosity, the mathematical approximation is not fit well. Therefore, we suggest the newly approximated equation to describe flow characteristics of slit element and it is revealed that this approximation agree well with experimental results more than ISO6358.

Keywords: Radial slit element, Sonic conductance, Critical pressure ratio

NOMENCLATURE

A	:	geometrical area	[m^2]
b	:	critical pressure raio	[-]
C	:	sonic conductance	[dm^3/s/Pa]
D_h	:	hydraulic equivalent diameter	[m]
G	:	mass flow rate	[kg/s]
h	:	height of slit	[m]
L	:	r_2-r_1	[m]
P_1	:	absolute pressure of upstream	[kPa]
P_2	:	absolute pressure of down stream	[kPa]
Q	:	volumetric flow rate	[L/min ANR]
R	:	gas constant	[J/(kg・K)]
r_1 , r_2	:	radius of inner and outer side of disk, respectively	[m]
T	:	temperature	[K]

[1] Corresponding author: Tokyo institute of technology, e-mail: okawa.y.aa@m.titech.ac.jp
[2] Precision and Intelligence Laboratory, Tokyo institute of technology
[3] Precision and Intelligence Laboratory, Tokyo institute of technology
[4] Precision and Intelligence Laboratory, Tokyo institute of technology

u : velocity [m/s]
ρ : density [kg/m^3]
μ : viscosity [Pa・s]

INTRODUCTION

Pneumatic systems are widely used in industrial fields from the viewpoint of low cost and safety. Pressure reducing valves are used to maintain the pressure of gas reservoirs to specific values. In a normal valve, supply pressure is depressurized with an orifice plate. When highly pressurized air passes through the orifice element, considerable noise and pressure fluctuation occurs at the downstream side. Therefore, reduction of noise and pressure fluctuation originating from the valve are required. In some cases, sonic flow occurs even when the pressure ratio b is lower than 0.528. Turbulent and sonic flow can generate considerable noise and shock waves. To solve these problems, we have developed the micro radial slit element. The micro radial slit element is comprised of disks similar to a cylinder that has been sliced. The compressed air enters the center of the disk, and it is exhausted through the slit. The flow of the slit element reduces the noise by suppressing the generation of turbulence and shock wave. Therefore, it has expected that the slit element could reduce noise and pressure fluctuation. In the earlier study, it was revealed that the micro radial slit element has the noise reduction effect about 40 dB more than an orifice and pressure fluctuation is reduced about 1/3 more than an orifice. However it is not investigated that the flow characteristics at the high supply pressure and about directional influence of radial slit element. Thus, in this research, the flow characteristics at the high supply pressure and about directional influence of micro radial slit element are studied.

MICRO RADIAL SLIT ELEMENT

Fig.1 shows a schematic drawing of the slit element. The slit element consists of three disks the outer diameter of which is 60 mm. The upper disk consists of a flow inlet. The middle layer disk of the radial slit element is an upper surface of the radial slit. The inner diameter of middle layer disk is 20 mm. This disk has various channel the depth of which are 30, 50, 70, 100 μm. The right part of Fig. 1 shows the cross section of the element. The lower disk consists of a lower surface of the radial slit.

Fig.2 shows flow direction of slit element. In the forward direction (called Direction-A), the compressed fluid enters from the inner of the middle layer disk. The area of flow channel of the slit is divergent. The compressed air enters from the center of the upper disk and is exhausted outward through the radial slit. In the backward direction (called Direction-B), the compressed fluid enters from the outside of the middle layer disk. The area of flow channel of the slit is convergent.

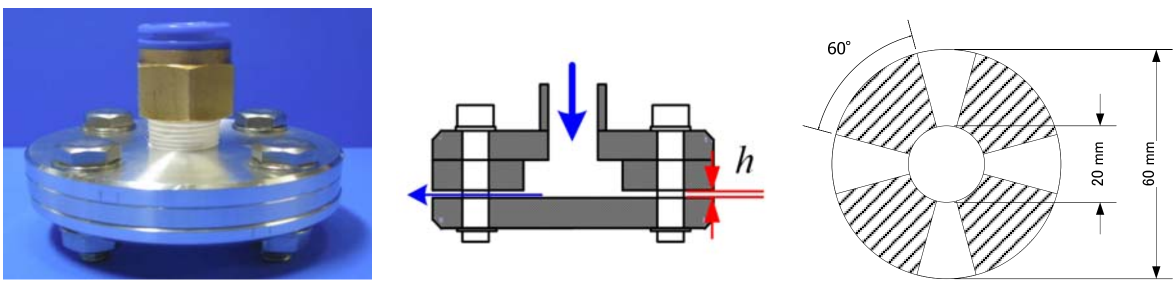

Fig. 1 Schematic structure of slit element

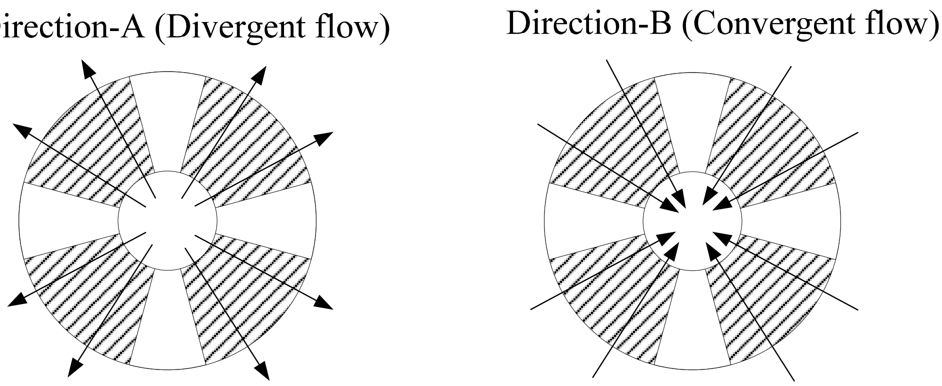

Fig. 2 Flow direction of slit element

FLOW CHARACTERISTICS

Information concerning the flow characteristics of pneumatic components is essential not only for selecting the right component at the design stage, but also for the simulation and the validation of different performances of a circuit. Therefore, ISO6358 standard provides an efficient help to manufacturers to characterize the flow capacity of pneumatic components with a couple of parameters: the sonic conductance *C* and the critical pressure ratio *b*. This standard defines both mathematical approximation of the mass flow rate characteristics and the experimental way to obtain these parameters. Experimental apparatus to measure flow characteristics is shown in Fig.3. The relation between mass flow rate and the sonic conductance in the sonic region is described in Eq.(1) and the subsonic region is approximated by a quarter of ellipse (Eq.(2)). In order to use slit element, it is necessary to obtain flow characteristics.

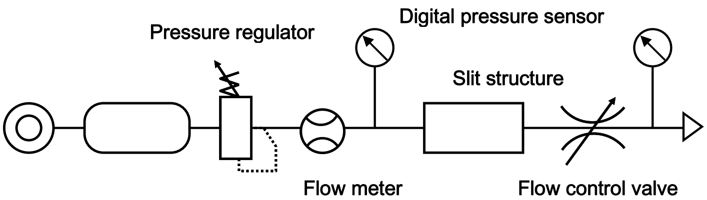

Fig. 3 Experimental apparatus for flow characteristics measurement

$$G = C\rho_0 P_1 \sqrt{\frac{293}{\theta_1}} \qquad \frac{P_2}{P_1} < b \qquad (1)$$

$$G = C\rho_0 P_1 \sqrt{1 - \left(\frac{\frac{P_2}{P_1} - b}{1 - b} \right)^2} \sqrt{\frac{293}{\theta_1}} \qquad \frac{P_2}{P_1} \geq b \qquad (2)$$

The experimental results of flow characteristics of slit element are shown in Fig.4.

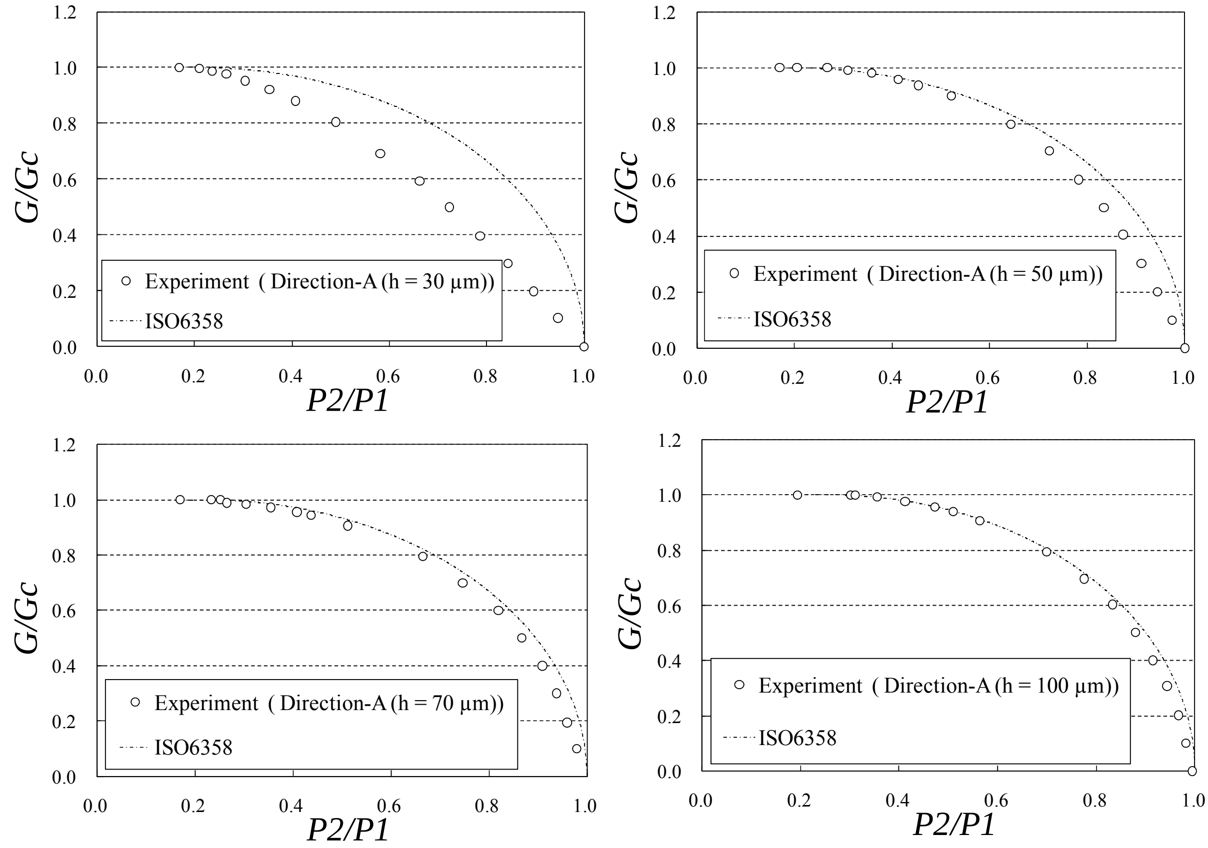

Fig. 4 Experimental results of critical pressure ratio (h = 30 - 100 µm)

Table 1 Experimental result of critical pressure rate and sonic conductance

	Direction-A	
Height [µm]	Critical pressure rate [-]	Sonic conductance [$dm^3/(s\cdot bar)$]
h	*b*	*C*
30	0.21	0.0008
50	0.20	0.0028
70	0.22	0.0050
100	0.26	0.0079

The result of the sonic conductance C and critical pressure ratio b which express characteristics of pneumatic device are measured from experimental result is shown in Fig.4 and Table 1. In the case of the h was small, the mathematical approximation is not fit well because the main pressure drop in the slit element occurs by viscosity. So it needs considered about the way to obtain the sonic conductance C and critical pressure ratio b of the slit element.

SUGGESTION OF APROXIMATED EQUATION OF FLOE CHARACTERISTICS

As the subsonic region of slit element is not approximated by a quarter of ellipse, it is necessary to use substitute equation. In order to consider the mathematical model, relation between Reynolds number and friction coefficient was determined.

A Reynolds number is defined by

$$\mathrm{Re} = \frac{\rho u D_h}{\mu} \tag{3}$$

where

$$D_h = 4\frac{2\pi r_{in}\alpha h}{2(2\pi r_{in}\alpha + h)} \cong 2h \tag{4}$$

In Darcy-Weisbach equation, friction coefficient is defined by

$$\lambda = \frac{P_2 - P_1}{\left(\rho u^2/2\right)}\frac{D_h}{L} \tag{5}$$

In this research, to investigate relation Reynolds number and friction coefficient, it is hypothesized that friction coefficient is defined by

$$\lambda = \frac{l}{\mathrm{Re}} + \left(-\frac{i}{(\mathrm{Re}-k)} + j\right) \tag{6}$$

The following equations is derived from Eq.(5) and Eq.(6).

$$\frac{Lj}{\mu}(\rho D_h)^2 u^3 + \rho L(l - jk - i)D_h u^2 - \left\{\mu lLk + \frac{2\rho D_h{}^3(P_1 - P_2)}{\mu}\right\}u + 2D_h{}^2 k(P_1 - P_2) = 0 \tag{7}$$

where

$$u = \frac{G}{\rho A} \tag{8}$$

$$A = 2\pi r h\alpha \tag{9}$$

$$\alpha = \frac{cross\ \ section\ area}{360^\circ} = \frac{240^\circ}{360^\circ} \tag{10}$$

In this research, adequacy of this hypothesis to describe flow characteristics with new number *i*, *j* and *k* was investigated by experiment.

The results of relation between Reynolds number at inner radius of slit element and friction coefficient are shown in Fig.5.

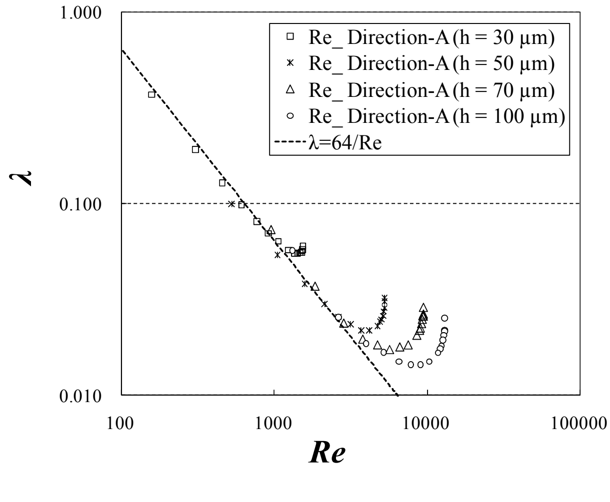

Fig. 5 Relation between Reynolds number and friction coefficient (h = 30 - 100 μm)

Experimental results presented are for l = 64. It is expected that the flow steady of the region that is described by λ = 64/Re is laminar and occur turbulent transition as Reynolds number increases. Then, other correction numbers that calculated using experimental results i, j and k is shown in Table 2. As one can see in Table 2, the correction number i increases considerably with an increase in height of slit. Approximation of flow characteristics using these correction numbers are shown in Fig.6. Eq.(7) was fit well with experimental result. In order to expand Eq.(7) for various slit components of which height is unknown, it is necessary to obtain relation between h and these parameters.

Table 2 Result of corrected number *i, j* and *k*

h	i	j	k
30	1.0	0	1595
50	5.4	0.0008	5546
70	9.8	0.0026	9940
100	16.0	0.0030	14000

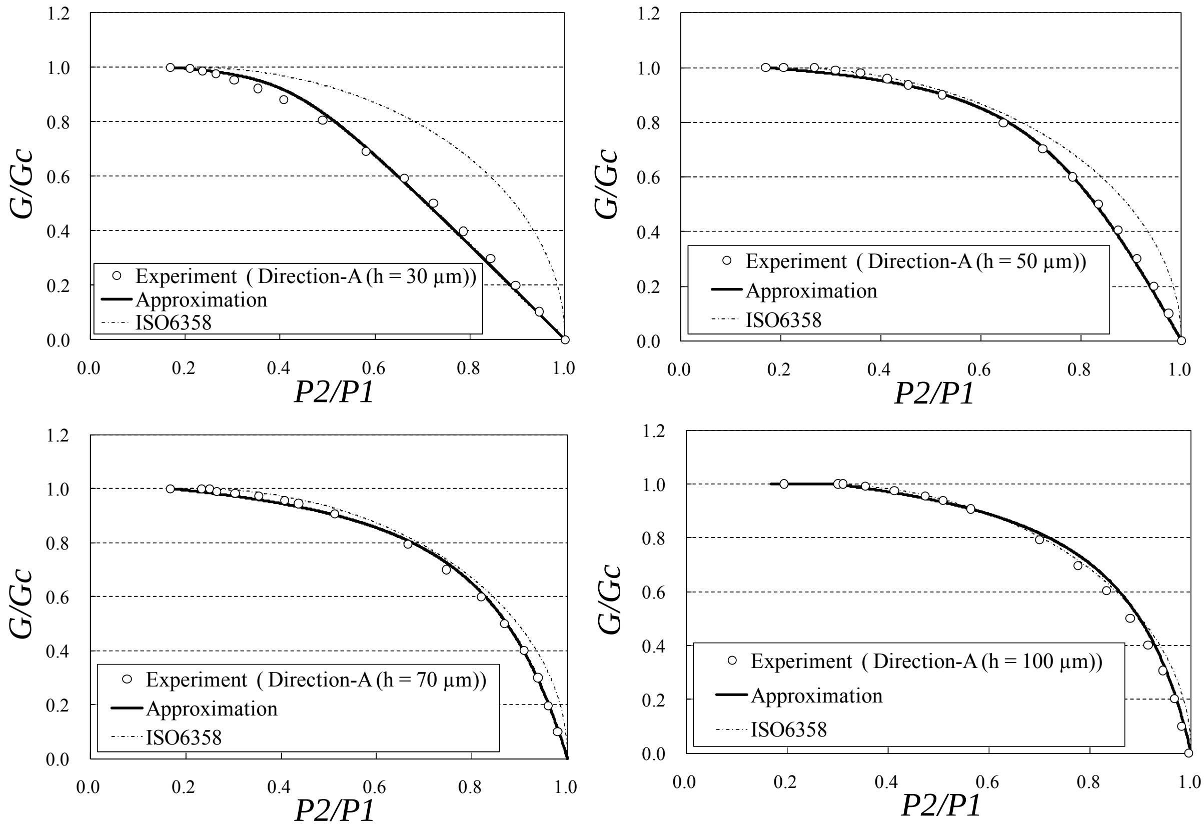

Fig. 6 Flow characteristics (h = 30 - 100 µm)

DIRECTIONAL INFLUENCE OF MICRO RADIAL SLIT ELEMENT

The directional influence of radial slit element was investigated. The results of relation between pressure and volumetric flow rate are shown in Fig.7. Compare to the same pressure and heights, the flow rate of direction-A was higher than one of direction-B in all cases.

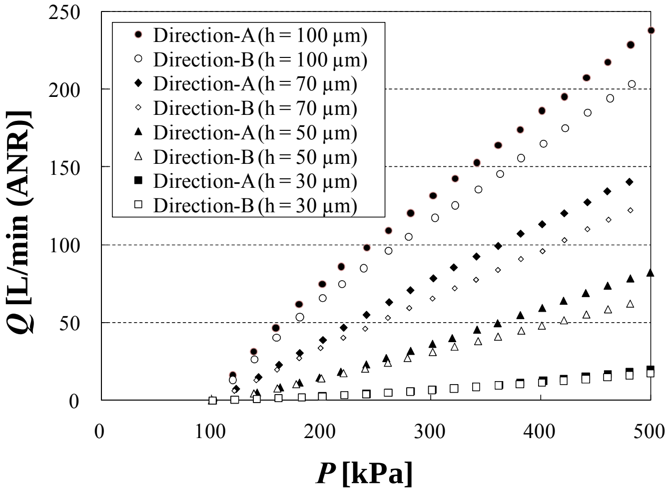

Fig. 7 Relation between pressure and volumetric flow rate (h = 30 - 100 μm)

It is attempted that Eq.(7) expand into direction-B. Therefore, relation between Reynolds number at outer radius of slit element and friction coefficient was determined the same way of direction-A. Fig.8 suggests it might prefer to use *l* = 192 for Eq.(6) in direction-B.

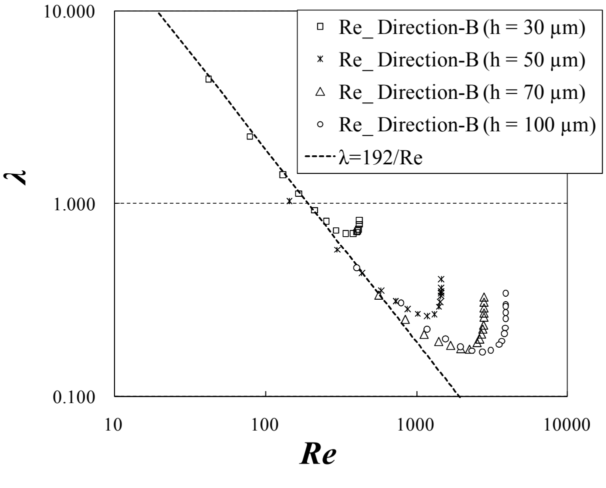

Fig. 8 Relation between Reynolds number and friction coefficient (h = 30 - 100 μm)

It is obtained flow characteristics in direction-B shown in Fig.8. Approximation used Eq.(6) agree better than ISO6358 with experimental results. Therefore, it is suggested usefulness of using Eq.(6) to describe flow characteristics of slit element.

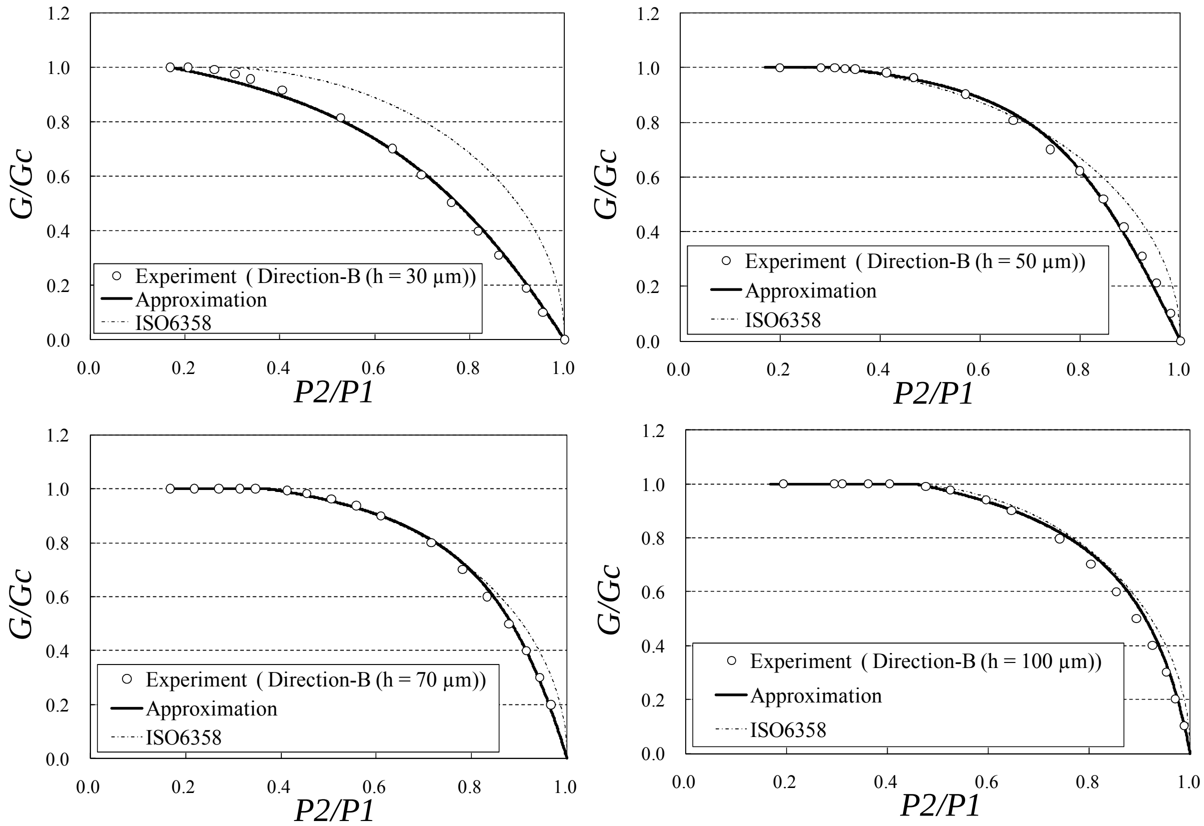

Fig. 9 Flow characteristics (h = 30 - 100 µm)

CONCLUSION

The flow characteristics at the high supply pressure and about directional influence of micro radial slit element were investigated. As the main pressure drop in the slit element occurs by viscosity, the mathematical approximation of ISO6358 was not fitted well with experimental flow characteristics result. Therefore, we suggested new approximation equation to express the flow characteristics of radial slit. The approximation equation uses the relation between Reynolds number and friction coefficient. It was revealed that this approximation agree well with experimental results more than ISO6358. In laminar region, the friction coefficient was inversely proportional to Reynolds number. Additionally, we confirmed that flow characteristics of reverse direction could be fitted well with approximation equation

REFERENCES

Boger, H. W., "Designing Valves and Downstream Devices as Low Noise Pack-ages," Heat./Piping/Air Cond. (1971)

Bell, L. H. (1993), "Industrial Noise Control," Mech. Eng. (Am. Soc. Mech. Eng.), **88**, 417-426.

Amini, A., and Owen, I. (1995), "A Practical Solution to the Problem of Noise and Fluctua-tion in a Pressure-Reducing Valve," Exp. Therm. Fluid Sci., **10**, 136-141.

Davies, P. O. L. A., Harrison, M. F., and Collins, H. J. (1997), "Acoustic Modeling of Mul-tiple Path with Experimental Validations," J. Sound Vib., **200**(2), 195-225.

Youn, C., Kawashima, K., and Kagawa, T. (2003), "Fundamental Analysis of Super Low Noise Control

Restriction for Compressible Fluid," The 18th I.C.H.P., 387-394
Kawashima K., Chongho Y., Kagawa T. (2000), "Development of a Nozzle-flapper Type Servo Valve using a Slit Element," Trans. ASME Journal of Fluid Engineering, **129**(5), 573-578.
Stone, C.R., and Wright, S.D. (1994), "Nonlinear and Unsteady Flow Analysis of Flow in a Viscous Flowmeter," Trans. Inst. Meas. Control(London), 16(3), 128–141.
International Standard ISO6358 (1989), "Pneumatic Fluid Power – Components using Compressible Fluids – Determination of Flow-rate Characteristics", 15