
SHORT COMMUNICATION

Design factors for “linear” ball valve: theoretical and experimental studies

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Abstract

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Generic non-linear flow characteristics of the conventional ball valve limit the applications of flow modulation in fluid processes. This work presents the flow characteristics of fluid flowing through the conventional and modified ball valves for feasibility of a “linear” ball valve. Theoretical studies are discussed for determining explicit and implicit factors on the valve coefficient, which modulates the flow rate of fluid when the ball valve is operated in flow control processes. In experiment, the cross-sectional opening area at various opening degrees, the shape, and the location of the hole passage in valve ball are examined for complicated relations dependent to the flow rate of fluid. It can be concluded that those factors cause the modulation of flow rate when the ball is turned at different opening degree. In extended design of flow characteristics for linearity, they are to be taken into account.

Keywords : ball valve, flow characteristics, flow control valve, linear valve

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บทคัดย่อ

ธนัญชัย ลีภักดีปรีดา

ปัจจัยออกแบบสำหรับลิ้นเม็ดกลมเชิงเส้น: การศึกษาเชิงทฤษฎีและทดลอง

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ลักษณะควบคุมอัตราการไหลของของไหลให้ไหลผ่านลิ้นปิดเปิดชนิดเม็ดกลมที่ไม่เป็นเชิงเส้นทำให้การใช้งานของลิ้นชนิดนี้เพื่อการปรับลดหรือเพิ่มระดับอัตราการไหลในกระบวนการต่าง ๆ ของของไหลได้ถูกจำกัดลง งานวิจัยนี้ได้ทำการศึกษาลักษณะการไหลผ่านลิ้นเม็ดกลมที่ใช้กันอยู่และที่ได้ปรับเปลี่ยนดัดแปลง ในการศึกษาเชิงทฤษฎีนั้น ให้ได้ทราบถึงปัจจัยโดยชัดแจ้งและโดยปริยายที่ผลต่อสัมประสิทธิ์ตัวลิ้นซึ่งเป็นตัวทำการปรับลดหรือเพิ่มระดับอัตราการไหลเมื่อลิ้นเม็ดกลมได้ถูกปรับเปลี่ยนไปตามตำแหน่งเปิดต่าง ๆ ใน การทดลองนั้น พื้นที่หน้าตัดเปิด รูปร่าง และตำแหน่งของช่องผ่านของลิ้นเม็ดกลมได้ทำถูกพิจารณาถึงความสัมพันธ์ที่มีผลต่ออัตราการไหล สามารถสรุปได้ว่า ปัจจัยเหล่านี้มีผลต่อการปรับลดหรือเพิ่มระดับอัตราการไหลเมื่อลิ้นเม็ดกลมได้ถูกปรับเปลี่ยนไปตามตำแหน่งเปิดต่าง ๆ งานออกแบบลักษณะการไหลเชิงเส้นของลิ้นเม็ดกลมจึงต้องคำนึงถึงปัจจัยเหล่านี้มาพิจารณาไว้รวมด้วย

ภาควิชาระบบการผลิตและวิศวกรรมเครื่องกล สถาบันเทคโนโลยีนานาชาติสิรินธร มหาวิทยาลัยธรรมศาสตร์ ศูนย์รังสิต ตู้ป.ป.22 ปท.ธรรมศาสตร์-รังสิต จังหวัดปทุมธานี 12121

Up to now, flow control valves have been used in a wide range of applications in fluid processes. Typically, the term "valve" applies to a variety of devices for controlling the flow of fluid. Various valves allow for on-off control, modulation of the flow rate through the system, prevention of back flow, pressure relief as a safety device. A combination of a valve and a manual/automatic actuator is usually referred as a flow control valve. In general, flow control valves can vary from simple manual on-off devices to sophisticated control equipments which act as metering instruments and deliver predetermined amounts of fluid to the system (Leephakpreeda, 2003). For normal on-off control, one of the most widely used choices is a ball valve by simply turning a spherical flow control element over an orifice in the valve body. At fully opening position, a passage through a ball valve is unrestricted which results in a low pressure loss through the valve. Although the ball valve is very compact, operates on 90° turn and creates minimum pressure loss through the valve when it is fully open, it is not recommended for flow regulation due to nonlinear flow characteristics. On the other hand, an ideal throttling valve is to exhibit a linear flow response to partial closing.

This kind of flow modulation is increasingly required in tight flow-control processes. Unlike the ball valve, for example, the needle valve might be preferred for use since its flow control characteristic curves are approximately linear. However, control implementations of the needle valve are limited owing to several turns for fully closing and low flow rate. Therefore, there are some attempts in research and in industry to modify the passage of the ball valve as shown in Figure 1. The linear flow characteristics are expected to be accomplished by the special design of the flow path through the valve. This paper presents preliminary studies in order to provide the insights of what is behind the idea of "linear" ball valve by theoretical analysis and supporting experimental results. The contribution of this paper is to be beneficial to inductively answer the questions of feasibility of "linear" ball valve.

Experiment

A setup of the flow experiment is illustrated in Figure 2. A reservoir and a pump were used to properly supply the water with the maximum flow rate and pressure required in a testing line. The

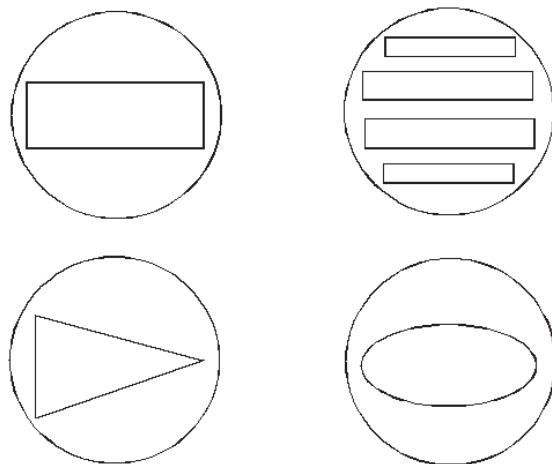


Figure 1. Modified passage of valve ball.

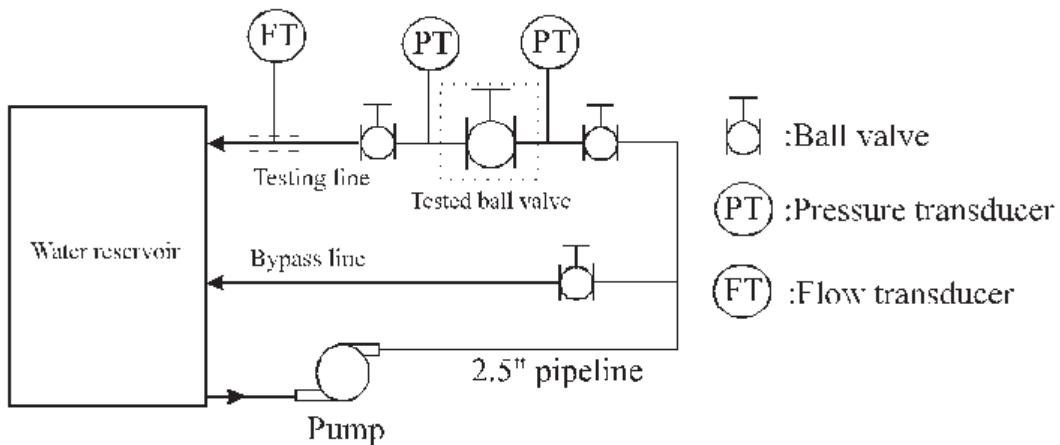


Figure 2. Diagram of Flow experiment.

excess water can be circulated out of the testing line through a bypass line. A tested ball valve (large symbol) is placed between two pressure transducers for determining the pressure drop across the ball valve. The pressure range of transducers was 0 bar -6 bar with accuracy $\pm 0.2\%$ of full scale. In experiment, the pressure drops can be obtained by adjusting the tested ball valve and other ball valves (small symbols) in testing line and bypass line respectively. An ultrasonic flow transducer is used to measure the flow rate of the water flowing through the tested ball valve. The flow-speed range of the transducer was 0.02 m/s -

8 m/s with accuracy $\pm 1\%$ of full scale. The 2.5-inch diameter of circular pipe and the size of all ball valves were chosen according to the minimum pipe-size requirement of the ultrasonic flow transducer.

Theoretical Background

The theoretical background for the flow characteristics of valve (Skousen, 1998) is reviewed as follows. For fluids, the flow rate of fluid passing through the flow-control valve can be determined as:

$$Q = \eta C_v P Y \sqrt{\frac{x}{\gamma T Z}} \quad (1)$$

with the ratio of pressure drop to the upstream pressure,

$$x = \frac{\Delta P}{P} \quad (2)$$

where Q is the flow rate, η is the numerical multiplier for compatible units, C_v is the valve coefficient, P is the upstream pressure, Y is the expansion factor, γ is the specific gravity, T is the upstream temperature, Z is the compressibility factor and the ΔP is the pressure drop across the control-flow valve.

The expansion factor can be determined by:

$$Y = 1 - \frac{x}{3F_k x_T} \quad (3)$$

where F_k is the ratio of specific heat factor and x_T is the terminal pressure-drop ratio.

The ratio of specific heat factor is defined as:

$$F_k = \frac{k}{1.4} \quad (4)$$

with the specific heat ratio k , expressed as:

$$k = \frac{c_p}{c_v} \quad (5)$$

where c_p is the specific heat at constant pressure and c_v is the specific heat at constant volume.

The compressibility ratio Z is determined by the pressure and temperature normalized with respect to the critical pressure and temperature. The normalized pressure and temperature are called the reduced pressure P_r and the reduced temperature T_r , respectively. The value of Z can be expressed as non-linear function:

$$Z = f(P_r, T_r) \quad (6)$$

with

$$P_r = \frac{P}{P_c} \quad (7)$$

and

$$T_r = \frac{T}{T_c} \quad (8)$$

where P_c is the critical pressure and T_c is the critical temperature.

According to Eqs. (1)-(8), it can be obviously seen that the flow characteristics of fluid flowing through the valve are dependent upon the properties of both the fluid and the valve itself. Conclusively, those are the pressure drop ΔP , the upstream pressure P , the upstream temperature T , and the valve coefficient C_v .

Now, the valve coefficient can be determined by:

$$C_v = \frac{Q}{\eta P Y} \sqrt{\frac{\gamma T Z}{x}} \quad (9)$$

In Eq. (9), it should be noticed that the valve coefficient depends upon not only the physical properties of the fluid but also the opening degree of the valve because, for a given condition of fluid, the variation in the opening degree of valve causes the change in the flow rate of fluid. Physically, the opening degree of valve explicitly means the amount of the cross-sectional opening area of the valve. Therefore, the valve coefficient of valve is a function of the cross-sectional opening area of the valve (α). Consequently, the idea of the valve designer is that the modification of the cross-sectional opening area is an alternative to adjust the function of the valve coefficient. In turn, the flow characteristics of the fluid can be changed accordingly. For a sake of convenience in further discussion, the flow characteristics for a incompressible liquid in Eq. (1) is considered in this work as:

$$Q = C(\alpha) \sqrt{\Delta P} \quad (10)$$

where C is the valve constant which is dependent upon the cross-sectional opening area of the valve.

It should be noted here that there might be other implicit factors on the change in flow rate in Eq. (9) when the opening degree of valve changes. More details will be discussed in the Result and Discussion Section below.

Simulation of cross-sectional opening area of ball valve

In this section, the cross-sectional opening area α is to be simulated by a mathematical model

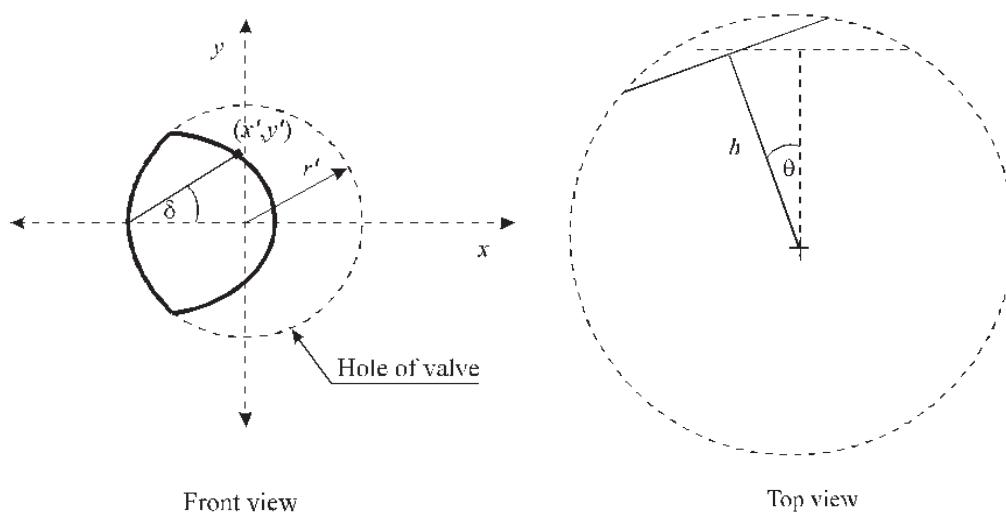


Figure 3. Geometric diagram for simulation of turning valve ball.

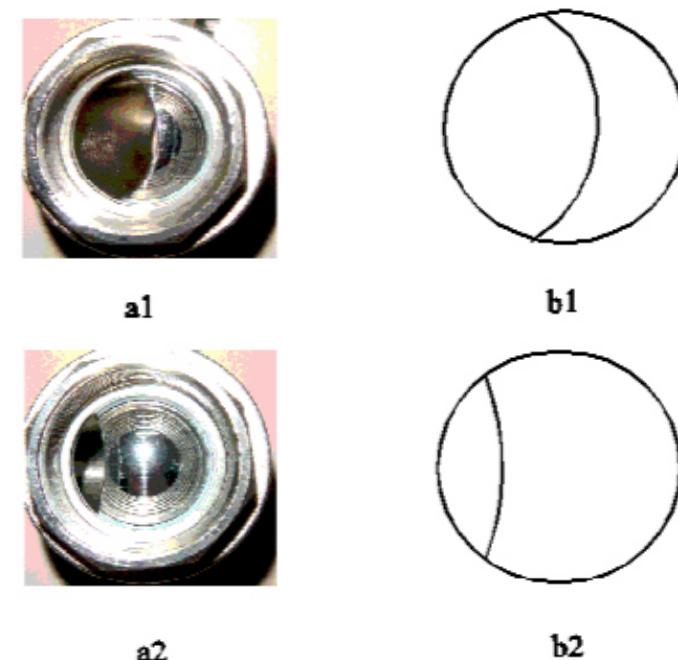


Figure 4. Comparison of cross-sectional opening areas between actual ones: a1, a2 and simulated ones: b1, b2 respectively.

for a given ball valve. At fully opening position, the inlet/outlet hole of the ball valve exactly matches the hole of the valve ball in general. As long as the ball in the valve body is turned in order to restrict the flow of the fluid more and more, the elliptical

part of the valve ball appears increasingly. The cross-sectional opening area can be determined from the area within the solid line as shown in Figure 3. It is straightforward to use a geometric approach to find the coordinates of x' and y'

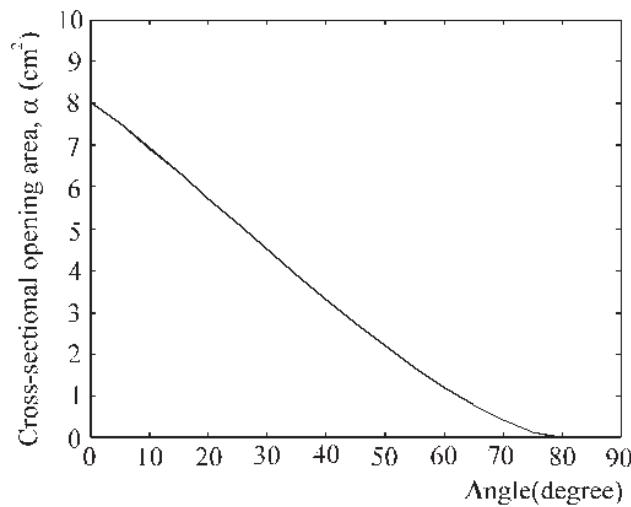


Figure 5. Plot cross-sectional opening area against turning angle.

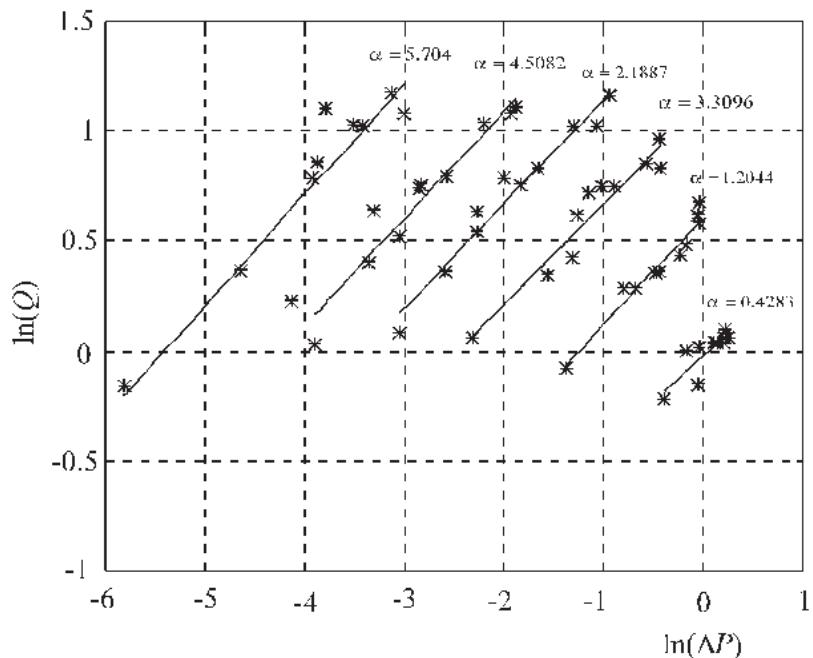


Figure 6. Logarithmic plots between flow rate and pressure drop at various cross-sectional opening area.

indicating the path of the solid line which satisfy the governing equations in Eqs. (11)-(13).

$$x' = r'(2\cos^2(2\delta) - 1)\cos(\theta) - h\sin(\theta) \quad (11)$$

$$y' = r'\sin(2\delta) \quad (12)$$

$$(x')^2 + (y')^2 \leq (r')^2 \quad (13)$$

where θ is the turning angle of ball valve from fully opening position, r' is the radius of the circular hole, h is the normal height measured from the center of the valve ball to the surface of hole and $\delta \in [-\pi/2, \pi/2]$.

Figure 4 shows the comparison of the cross-sectional opening areas between the actual valves in Figure 4.a1, 4.a2 and the simulated valves in Figure 4.b1, 4.b2 respectively for a certain opening degree. It can be seen that the mathematical model in Eqs(11)-(13) can be applied to simulate the cross-sectional opening areas similar to the actual ones. In next section, it is used to determine the cross-sectional opening area of the tested valves.

Results and Discussion

In experiments, the determination of the valve constant C at the various cross-sectional opening areas was performed for a given ball valve as mentioned in Experiment Section. Corresponding to the ball valve tested in experiment with 3.81-cm diameter of ball and with 3.2-cm diameter of hole, Figure 5 shows the plots of the cross-sectional opening areas against the turning angle starting from fully opening to fully closing from simulation of Eqs. (11)-(13). The cross-sectional opening area is inversely proportional to the turning angle of the valve ball except for the end section ($\sim 70^\circ$ - 90°). Referring to Figure 1, the pressure drops across the tested ball valve were varied by adjusting all the ball valves and then the

flow rates were measured at given cross-sectional opening areas. In Figure 6, the star-signed plots show the experimental results of flow characteristics for given cross-sectional opening areas. The plots were obtained by Eq. (14) which taking a logarithmic function to Eq. (10).

$$\ln(Q) = \ln(C(\alpha)) + \frac{1}{2} \ln(\Delta P) \quad (14)$$

According to Eq. (14), the value of the slope is equal to 0.5 and the value of the interception at vertical axis is equal to the logarithmic value of the valve constant. The solid lines are well fitted by a linear function in Eq. (14) to experimental results. Table 1 lists the value of the slope and the valve of C corresponding to the cross-sectional opening areas. It can be seen that the slopes in all cases are nearly close to the theoretical value 0.5 while the values of C decrease as the values of α decrease as expected. Explicitly, the less the cross-sectional opening area, the less the value of the valve constant as shown in Figure 7. It was observed that the pressure drop across the ball valve at fully opening position is significantly small at operating condition in this experiment. This small magnitude including signal noise from measurement lessens the accuracy when the valve constant is determined by Eq. (14). The deter-

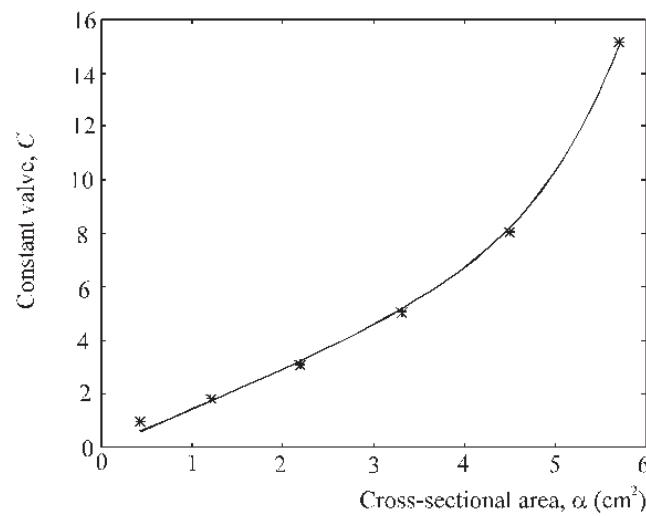


Figure 7. Plots of valve constant against cross-sectional opening area.

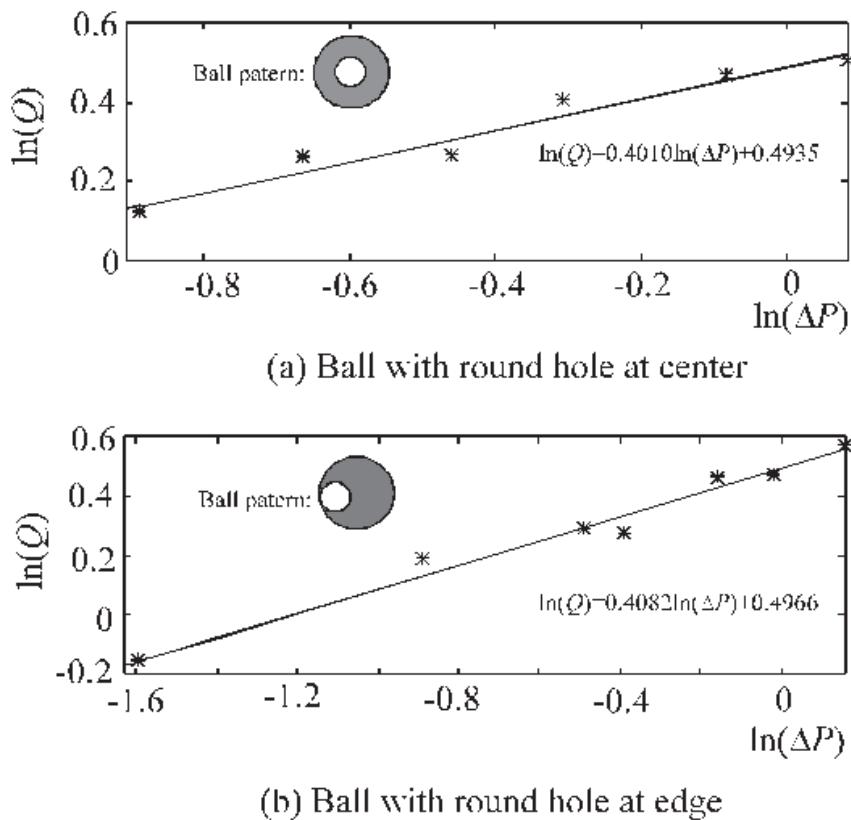


Figure 8. Modification of original holes with smaller holes at different locations.

Table 1. Values of the slope and C corresponding to the cross-sectional opening areas.

Angle (degree)	α	C	Slope
70	5.704	15.1667	0.5023
60	4.5082	8.0559	0.4928
50	3.3096	5.0764	0.4766
40	2.1887	3.1133	0.4602
30	1.2044	1.8480	0.4915
20	0.4283	0.9800	0.4106

mination of the valve constant at fully opening position is omitted in this study. However, it should be noted that the modification of experiment at different operating conditions can be made such that the pressure drop across the ball valve constant at fully opening position is sufficiently large if needed.

Table 2. Comparison of Values at different patterns of hole.

Pattern	C
Round hole at center	1.6380
Round hole at edge	1.6431
Elliptical hole at edge (in Figure 4.a2)	1.9523

It might be of interest whether other factors such as shape and location of the cross-sectional opening area result in the variation of the valve constant. To see this, the modification of the original ball valve was made as follows. The original round hole was filled with a piece of a cylindrical stainless-steel rod that is drilled for a smaller area of 1.33 cm^2 at different locations: (a) at the center and (b) at the edge as illustrated

in Figure 8. Again, the pressure drops across the tested ball valve were varied and the flow rates were measured as shown in Figure 8. Table 2 presents the values of the valve constants for each case with the equal cross-sectional areas. Comparatively, it can be seen that, at the same shape (round \leftrightarrow round) with the different location (center \leftrightarrow edge), the valve constants are slightly different while they are significantly different when the shapes of the hole passage (round \leftrightarrow elliptical) are different at same location (around the edge). The elliptical hole allows the higher mean velocity since the elliptical passage is narrower than the circular passage. These results can be simply explained by Eq. (15)

$$Q = \alpha v \quad (15)$$

where v is the mean velocity of velocity profile at the cross-sectional opening area.

From Eq. (15), not only the cross-sectional opening area but also the mean velocity of the flow is dependent to the flow rate. Therefore, modification of the hole passage makes the flow characteristics different more or less. Consequently, design of hole passage in different shape than the conventional one is to take these intricate factors into account.

Conclusion

From theoretical analysis, the physical properties of fluid and the ball valve influence on the flow characteristics of fluid flowing through the flow-control ball valve. The physical property of the ball valve is dictated by the valve coefficient, which modulate the flow rate of fluid when the cross-sectional opening area is varied. Experimental results confirmed that the valve coefficient is dependent upon the cross-sectional opening area, the shape, and the location of the hole passage through the valve ball. With modification of these factors, the flow characteristics of fluid may be adjusted to be linear for the ball valve.

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