Isı Bilimi ve Tekniği Dergisi, 30, 2, 103-112, 2010
J. of Thermal Science and Technology
©2010 TIBTD Printed in Turkey
ISSN 1300-3615

EFFECT OF THE FLOW CONDITIONS AND VALVE SIZE ON BUTTERFLY VALVE PERFORMANCE

Mehmet SANDALCI[1], Ebru MANÇUHAN[2], Emre ALPMAN[2], Kurtul KÜÇÜKADA[3]

[1] Gedik Casting and Valve Company, Pendik, 34 916 Istanbul, Turkey, msandalci@gedikdokum@com
[2] Marmara University, Faculty of Engineering, Mechanical Engineering Department,
Göztepe, 34 722, Istanbul, Turkey emancuhan@marmara.edu.tr
[3] Marmara University, Faculty of Engineering, Chemical Engineering Department,
Göztepe,34 722, Istanbul, Turkey kurtul.kucukada@marmara.edu.tr

(Geliş Tarihi: 21. 10. 2009, Kabul Tarihi: 03. 02. 2010)

Abstract: In the present work, two different sizes butterfly valves, DN65 and DN80, were tested according to standard testing method ANSI/ISA-75.02-1996. The tests were performed at different flow rates such as 2, 3 and 4 m/s and at different valve opening angles such as 0, 10, 20, 30 and 40°. The opening angle 0° was considered as the fully open valve. The flow area percentages, ϕ, were calculated for different valve openings as 100, 82.64, 65.80, 50 and 35.72% and pressure drops, ΔP, were recorded for different valve openings at different velocities. Using the experimental data the loss and flow coefficients, K and C_v, were calculated and correlations were proposed to give K and C_v as a function of the flow area percentage, ϕ. Uncertainty analysis was performed to show the effect of the measurement uncertainties on the performance coefficients. The proposed correlations provide an effective way to determine the performance coefficients of two different sizes of butterfly valves. This approach can be applied to other valves for determining their performance.
Keywords: Butterfly valve; Loss coefficient; Flow coefficient; Uncertainty analysis.

AKIŞ KOŞULLARI VE VANA ÇAPININ KELEBEK VANA PERFORMANS KATSAYILARINA ETKİSİ

Özet: Bu çalışmada vana sektöründe tesisatlarda çabuk açma ve kapama durumları için ideal bir tasarım olan kelebek vanalarda (DN80 ve DN65) farklı akış hızlarında 2, 3, 4 m/s (türbülanslı akış koşulunda) farklı disk açılarına (θ=0°, 10°, 20°, 30°ve 40°) karşılık gelen akış alan yüzdelerinde (ϕ =%100, %82,64, %65,80, %50 ve %35,72) basınç kaybı ölçülmüştür. Kelebek vana diski tam açık pozisyonda (θ=0°) iken borudan geçen akışkan debisi maksimumdur. Vana merkezine yataklanmış disk, θ açısı kadar döndürüldüğünde akışkan akışı sınırlanmaya başlar ve θ açısı 40^o olduğunda akışkan geçişi kısmen azalır. Ölçümler test metodu ANSI/ISA-75.02-1996'da belirtilen şartlara uyularak kurulan test düzeneğinde yapılmıştır. Bu çalışmada, iki farklı çap kelebek vanada basınç kaybı ölçüm değerleri kullanılarak hesaplanan kayıp (K) ve debi katsayılarının (Cv) disk açılarına göre değişimi gösterildi. Ölçümlerdeki belirsizliklerin performans katsayılarına (K ve Cv) etkisini görebilmek için belirsizlik analizi yapıldı. Ölçüm sonuçları kullanılarak performans katsayılarını, kelebek vanadaki disk açısına bağlı olarak kolayca hesaplayabilecek korelasyonlar önerildi. Üretici firma veya kullanıcılar bu korelasyonları kullanarak DN80 ve DN65 kelebek vanalarda farklı disk açıları için K ve Cv değerlerini kolayca hesaplayabileceklerdir.
Anahtar Kelimeler: Kelebek vana, Kayıp Katsayısı, Debi katsayısı, Belirsizlik analizi

NOMENCLATURE

A_v	valve cross section area [m^2]
A_o	valve flow area [m^2]
C_v	flow coefficient [m^3/s or gal/min]
K	loss coefficient [-]

Q	volumetric flow rate [m^3/s or gal/min]
r	valve radius [m]
Re	Reynolds number
v	velocity [m/s]
U_K	Uncertainty for loss coefficient [-]
U_{Cv}	Uncertainty for flow coefficient [m^3/s or gal/min]
$U_{\Delta P}$	Uncertainty for the pressure drop [N/m^2 or psia]
U_Q	Uncertainty for the volume flow rate [m^3/s or gal/min]

Greek Letters

ΔP	pressure drop [N/m^2 or psia]
ΔP_0	pressure drop [N/m^2 or psia]
ρ	density [kg/m^3 or lb/ft^3]
ρ_0	density of reference water [kg/m^3 or lb/ft^3]
θ	disk rotation angle [Degree or radians]
ϕ	the opening angle [Degree]

INTRODUCTION

Selecting the proper valve for piping systems plays an important role in reducing the energy requirement and thus the operating cost. Various valves are used for on-off control, modulation of the flow rate through the system, prevention of back flow and pressure relief as safety devices. One of the most widely used valves is butterfly valve. The primary aim of butterfly valve is to regulate the flow rate. The flow characteristics inside and downstream of the butterfly valves behave differently in different angle of valve disk and different inlet velocities. Coefficients (loss and flow coefficients) defining the performance of a valve are affected by the valve opening. In addition the flow coefficient is a function of the valve diameter. The flow rate and pressure measurement together with the particle tracking flow visualization method were used to estimate the performance and flow patterns of a ball valve by (Chern et al., 2007). The correlation between the flow pattern and valve performance is discussed. They stated that the inlet velocity and ball valve opening play very important roles in the flow characteristics of ball valves and they proposed correlations to determine the loss and flow coefficients as functions of the valve opening for a ball valve of 38 mm in diameter. The research on butterfly valves concerned the investigation of valve performance for various valve and pipe configurations. The effect of the downstream of an elbow on the valve performance was investigated by (Morris and Dutton, 1991a). The effect of the valve/elbow interactions on the pressure drop and flow coefficient was investigated using air as the working fluid for a butterfly valve of 76.2 mm in diameter. They also investigated the effect of two butterfly valves mounted in series on the valve performance (Morris and Dutton, 1991b). Pressure losses were measured by (Fester et al., 2007) for 5 different sizes of diaphragm valves of diameters ranging from 40 mm to 100 mm using both Newtonian and non-Newtonian fluids for laminar, transitional and turbulent flow. Empirical correlations were derived to calculate the loss coefficients for each diaphragm valve in the fully open position. (Perry, 1997) gives loss coefficient data for butterfly valves in the nearly fully open (5°) and 10°, 20°, 40°, 60°open position. But, there is no mention of a diameter effect. The effect of the two different disk configurations such as perforated and solid disk plates on the loss coefficient was investigated by (Eom, 1998) for a butterfly valve of 100 mm in diameter for position of every 10° from 0° to 90°.

The aim of this study is to measure and observe variations of performance coefficients (loss coefficient and flow coefficient) of DN65 and DN80 butterfly valves for different flow conditions. These two different sizes being DN65 and DN80 are the most commonly used sizes in industrial applications. The flow conditions refer to 3 different Reynolds numbers for two different sizes of the valves at 5 different valve flow area percentage (100%, 82.64%, 65.80%, 50%, 35.72%) corresponding to 0°, 10°, 20°, 30°, 40°, regarding the fully open position (100% open) as 0°. The Reynolds number changes from 1.555×10^5 to 3.12×10^5 for DN80 and from 1.255×10^5 to 2.52×10^5 for DN65 sizes of valves. These values of the Reynolds number correspond to 3 different velocities such as 2, 3 and 4 m/s.

EXPERIMENTAL INVESTIGATION

Experimental Set-up

Experimental set-up was installed on the test site of Standard Pump Company according to the (ANSI/ISA-75.02-1996, 1996) and the experimental set-up was shown schematically in Fig. 1. Two different sizes of wafer style butterfly valves, DN65 and DN80, were used. The experimental set-up is a closed system with a water reservoir of a capacity of 1000 litres and the circulation of water is achieved by using a centrifugal pump (Standart Pump) with a power of 18.5 kW. The volumetric flow rate, Q, is controlled using two flow balance valves (Todr and Anderson) and a digital flowmeter (Khrone) is used to record the flow rate. The accuracy of the flowmeter is within ±0.1%. The inlet pressure is measured using a barometer (Pakkens) and the inlet pressure was kept constant at 400kPa. Valve performance or in other words, the flow coefficient and loss coefficient were computed using the experimental data. Pressure drop was measured using a U-tube manometer with probes installed 2 diameters upstream and 6 diameters downstream of the valve according to the standard test method of (ANSI/ISA-75.02-1996, 1996).

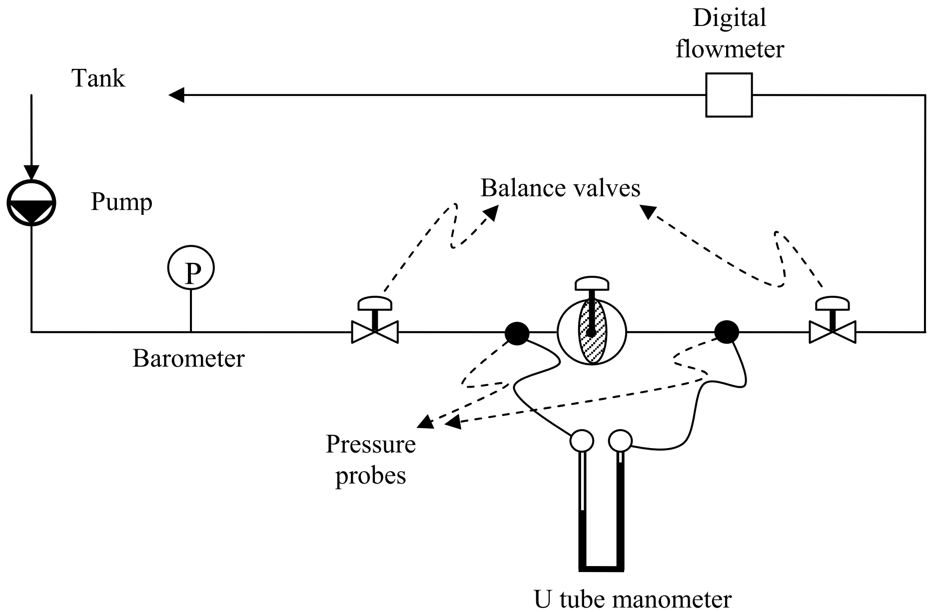

Figure 1. Schematic View of Experimental Test Set-up.

The reading accuracy of the manometer is around ±3%. The diameter of the probes to which the manometer tubes are connected is 3 mm. The diameter of the pipes connected to the valves is 65 mm (2.5 in) and 80 mm (3 in) for the butterfly valves of DN65 and DN80, respectively. The pressure drops were measured for different valve opening angles and for different Reynolds numbers corresponding to the velocities of the fluid 2, 3 and 4 m/s. Measurements were repeated three times and performance values were computed by using the arithmetic mean of the measured values in formulas.

Butterfly Valves Features and Simulation of Valve Flow Area

The butterfly valve consists of three main components such as the body, the shaft and the valve disk. It is generally set up into the system to control the flow of the process. The principal advantages of this type of valve are their simplicity, their low cost, their speed of closing and the weak pressure drop which they produce when they are completely open. They give little resistance to fluid flow hence allow smooth flow.

As it is known, butterfly valves are fittings operated by a circle profiled flap or disk in central or eccentric bearing rotated in a tube. Besides, flow rate is adjusted by rotating the disk between 0° and 90°. The relation between working principle of a butterfly valve, rotation angle of the disk and valve opening are simply shown in Fig. 2.

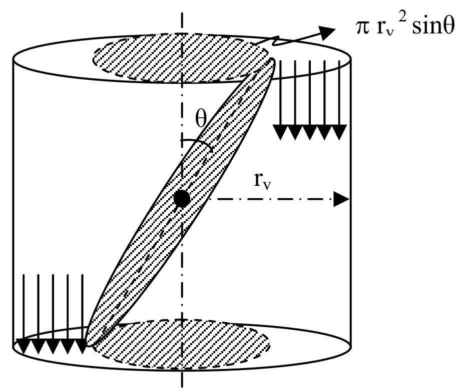

Figure 2. Geometrical Diagram for Simulation of Turning of Disk in a Butterfly Valve.

Cross section area of the fully open valve, in which the fluid flows, is calculated using the following equation:

$$A_v = \pi\, r_v^2 \tag{1}$$

Valve flow area, A_o, and the opening angles, ϕ, are calculated for the disk rotation angle, θ, using the following equations:

$$A_o = \pi\, r_v^2 - \pi\, r_v^2 \sin\theta = \pi\, r_v^2 \left(1 - \sin\theta\right) \tag{2}$$

$$\phi = \frac{A_o}{A_v} x100 \tag{3}$$

Equations 2 and 3 were used to calculate flow area percentages, ϕ, for different angles of valve openings. Valve flow area or flow area percentages for 5 different positions (0°, 10°, 20°, 30°, 40°) of the disk rotation angle, θ, from fully open, θ=0°, to partially open, θ=40° for DN80 and DN65 butterfly valves, are given in Table 1. Fig. 3 shows the variation of butterfly valve flow areas and flow area percentage versus the disk rotation angle starting from fully open to fully closed positions by using Eqs. (1)-(3).

Table 1. Valve Flow Area and Flow Area Percentages Corresponding to Different Disk Rotation Angle of DN80 and DN65 Valves

Rotation angle, θ (Degrees)	0	10	20	30	40
Rotation angle, θ (Radians)	0	$\pi/18$	$\pi/9$	$\pi/6$	$2\pi/9$
Valve flow area for DN80 (m^2)	0.00478	0.00395	0.00314	0.00239	0.00171
Valve flow area for DN65 (m^2)	0.00312	0.002576	0.00205	0.00156	0.00112
Flow area percentage (%)	100	82.64	65.80	50	35.72

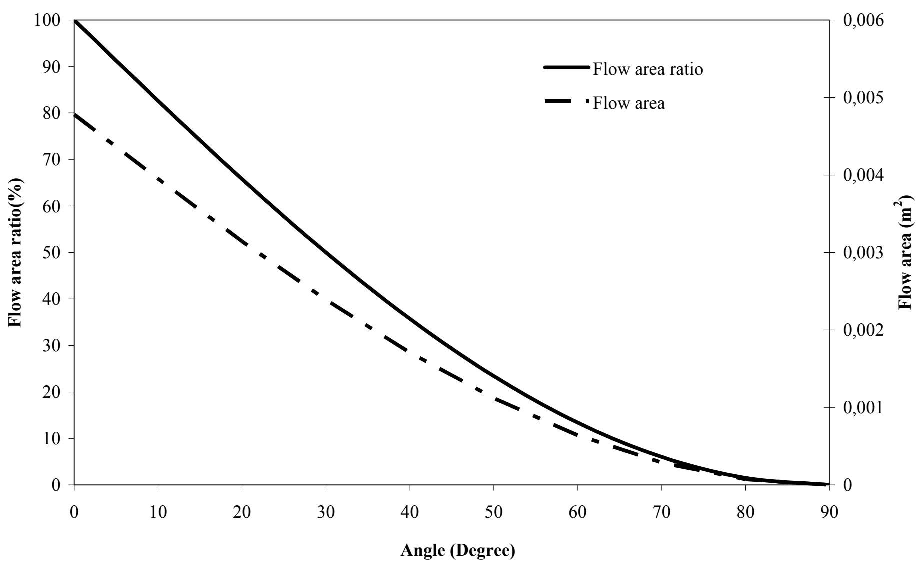

Figure 3. Variation of Butterfly Valve Flow Area and Flow Area Percentages Versus the Disk Rotation Angles (DN80).

Uncertainty Analysis

In the calculation of the performance coefficients such as the flow and loss coefficients there are uncertainties due to the uncertainties in the pressure drop and flow rate measurements. The reading accuracy of the manometer and the flowmeter is around ±3% and ±0.1%, respectively. Therefore, the uncertainty in the pressure drop is ±3% while the uncertainty in the flow rate ±0.1%. Using these values the uncertainties in the flow and loss coefficients were calculated and given in Table 2. The uncertainty analysis was performed using the method described by (Taylor et al, 1999). The procedure for calculating the uncertainties in the loss and flow coefficients was explained in detail in the Appendix A. The percent relative uncertainties for K and C_v values are the ratio of the uncertainties at different angles to the values of K and C_v, such as U_K /K and U_{Cv} /C_v, respectively. Then the percent relative uncertainty in the loss coefficient is ±3.0 % for two different sizes of valves. However, the percent relative uncertainty in the flow coefficient is ±1.50 % for DN80 while it was found to be ±3.35 % for DN65 size of valve.

Table 2. Uncertainties in the Loss and Flow Coefficients for Two Different Valve Sizes.

Opening angles(deg.)	θ	0	10	20	30	40
Flow area percentage(%)	ϕ	100.0	82.64	65.80	50.00	35.72
DN80	$K \pm U_K$	1.15±0.035	1.65±0.050	2.36±0.071	5.38±0.16	15.2±0.46
	$C_V \pm U_{CV}$	291.2±3.94	243.1±3.29	203.5±2.75	134.7±1.82	80.08±1.08
DN65	$K \pm U_K$	1.51±0.045	1.65±0.050	2.33±0.070	4.95±0.15	16.7±0.50
	$C_V \pm U_{CV}$	149.5±5.01	142.8±4.79	120.2±4.03	82.47±2.77	44.96±1.51

PERFORMANCE COEFFICIENTS

In general, a valve is evaluated using the loss coefficient K, and, the flow coefficient C_v. In this work, K and C_v coefficients were calculated by using the pressure drop and volume flow rate measurements. The pressure drop measurements, ΔP, were recorded for five different valve the flow area percentages (100%, 82.64%, 65.80%, 50%, 35.72%) corresponding to 0°, 10°, 20°, 30°, 40° at different inlet velocities. The values of inlet velocity for experiments are 2, 3 and 4 m/s. The Reynolds numbers corresponding to three different velocities are 1.56×10^5, 2.33×10^5 and 3.12×10^5 for DN80 valve. Similarly, the Reynolds numbers are calculated to be 1.26×10^5, 1.89×10^5 and 2.52×10^5 for DN65 valve at three different velocities.

The Loss Coefficient

The loss coefficient is unique to each type of valve and it is a dimensionless parameter giving the ratio of the pressure drop to the kinetic energy of the fluid. The loss can be given as follows for any valve geometry:

$$K = \frac{\Delta P}{\frac{1}{2}\rho v^2} = \frac{1}{v^2}\frac{2\,\Delta P}{\rho} \tag{4}$$

In Eq. (4), v is the inlet velocity, ρ is the density of the fluid and ΔP is the pressure drop measured between 2 diameters in front of the valve and 6 diameters behind the valve.

The Flow Coefficient

The flow coefficient is defined as the flow capacity of a valve at a standard temperature between 5 and 40°C corresponding to a unit pressure drop, ΔP_0, at an opening position. The value of ΔP_0 is 1 psia, or 1 N/m^2 depending on the units of Q being U.S. gal/min or m^3/s. In the below equation, ρ_0 represents the density of the reference fluid which is water and it is taken as 62.4 lb/ft^3 or 1000 kg/m^3 depending on the units of Q.

$$C_V = Q\left(\frac{\Delta P_0}{\Delta P}\frac{\rho}{\rho_0}\right)^{1/2} \tag{5}$$

The flow coefficient is generally given in U.S. gal/min in the literature and it is given for a reference temperature of 60°F and for a reference pressure loss, ΔP_0, of one pound per square inch at a specific opening position. When ΔP_0 and ρ/ρ_0 are taken as unity the above equation reduces to:

$$C_V = Q\left(\frac{1}{\Delta P}\right)^{1/2} \tag{6}$$

In the above equation when the volume flow rate, Q, and the pressure drop are used in units of U. S. gal/min and psia, the flow coefficient, C_v, is obtained in U.S. gal/min, (Perry, 1997) and (Zappe, 1999).

RESULTS AND DISCUSSION

The pressure drop measurements for five different valve openings and for three different velocities were used to calculate the flow and loss coefficients. The calculations were done for two different sizes of butterfly valves being DN65 and DN80. In the following sections, the loss and flow coefficients obtained using experimental measurements will be presented.

The Loss Coefficient

The variation of the loss coefficient with the opening angles at three different velocities was shown in Fig. 4. As it can be seen the dependence of the loss coefficient on the velocity is negligible and it is a strong function of the opening angles. Fig. 4 shows that the loss coefficient is independent of the Reynolds number in turbulent flow.

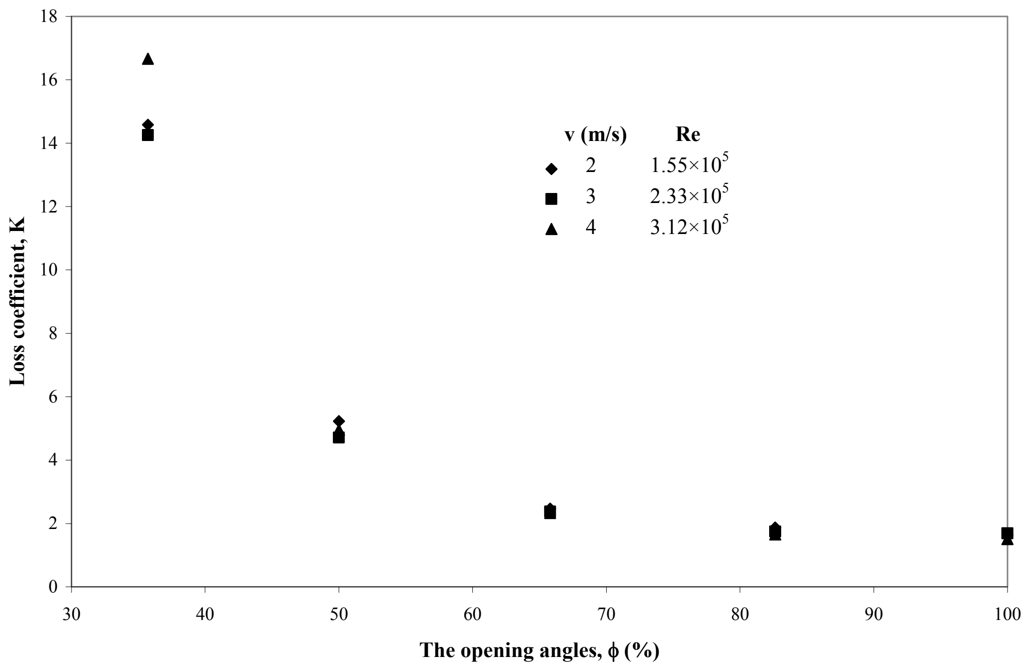

Figure 4. Loss Coefficient for DN65 Versus the Opening Angles at Three Different Velocities.

Variation of the loss coefficient which is calculated using measurements is compared by obtained data from products of (Hybvalve, 2008) manufacturer in figures 5 and 6. It was observed that the loss coefficient is not affected by the flow rate of the working fluid, but the opening angles of butterfly valve. The value of K decreases as the disk angle moves form partially closed position, θ=40°, to fully open position, θ=0°.

The relations can be given to relate the loss coefficient to the opening angles, ϕ. The loss coefficients for a velocity of 4 m/s, and for DN80 and DN65 butterfly valves are $K = 1.074 \times 10^5 \phi^{-2.514} \pm 3\%$ and $K = 0.244 \times 10^5 \phi^{-2.269} \pm 3\%$, respectively and they are shown in figures 5 and 6.

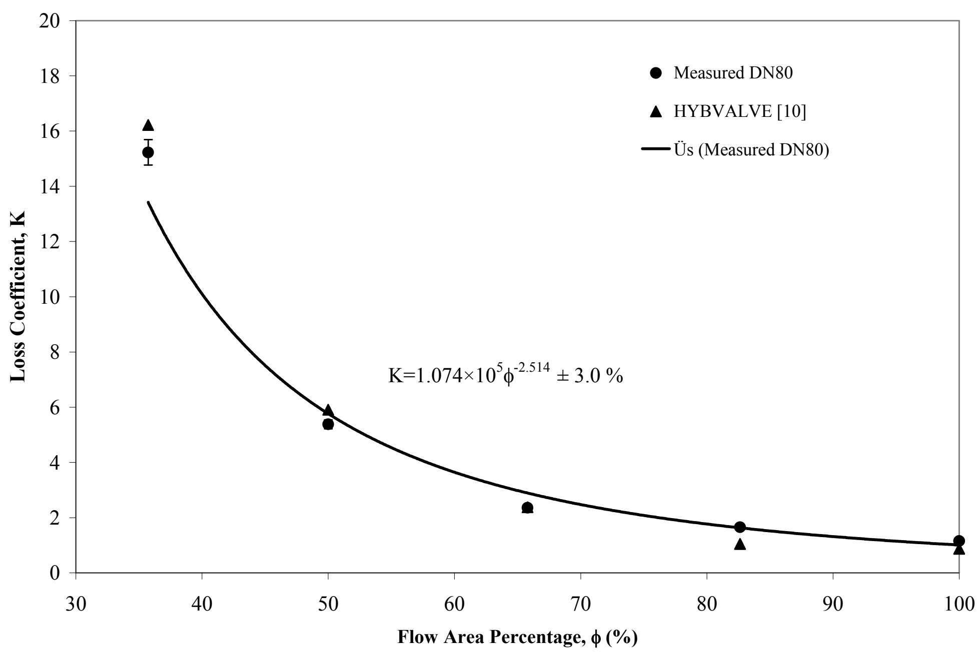

Figure 5. Comparison of Calculated K Values at 3.12×10^5 Reynolds number with the Other Literature Data (DN80).

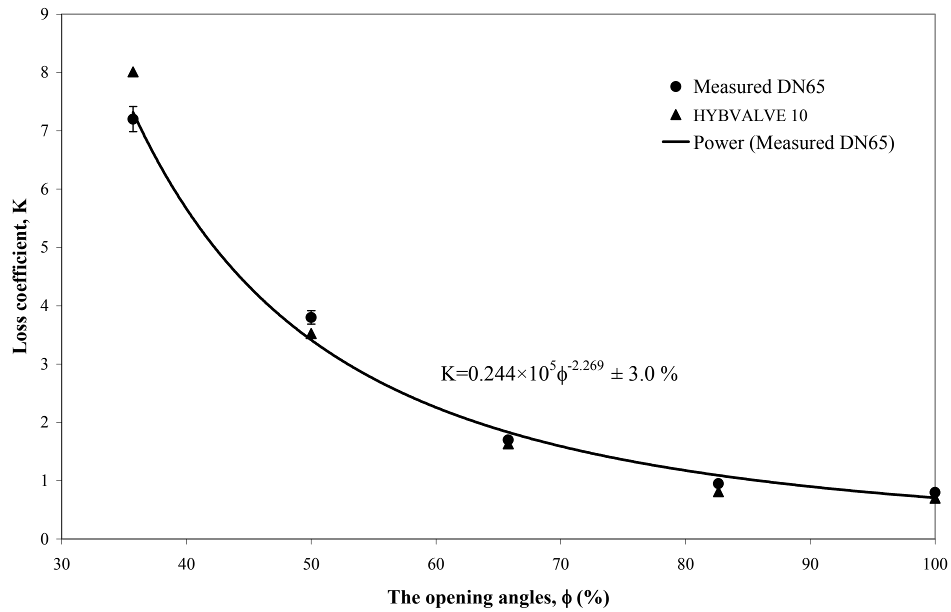

Figure 6. Comparison of Calculated K Values at 2.52×10^5 Reynolds number with the Other Literature Data (DN65).

The Flow Coefficient

Variation of flow coefficient, C_v, is the indicator of the flow rate at a certain pressure drop as a function of the valve opening. The computed values of the flow coefficient with respect to the opening angles at different velocities for DN65 valve size were given in Fig. 7.

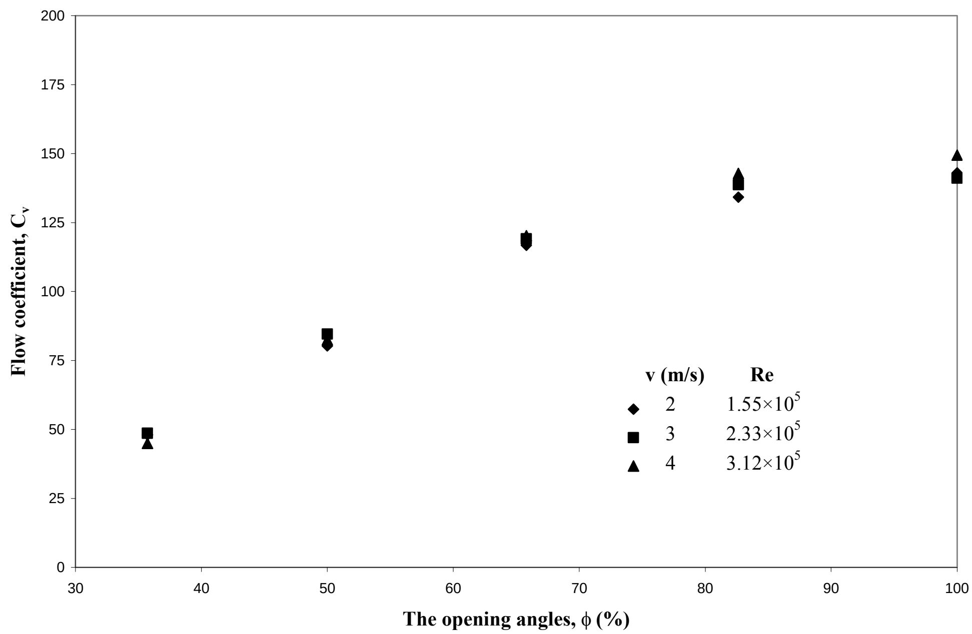

Figure 7. Flow Coefficients for DN65 Versus the Opening Angles at Three Different Velocities.

It was observed that the flow coefficient increases as the flow area of the valve increases. However, the effect of the velocity is negligible. Variation of the flow coefficient with the opening angle is not linear but an exponential function as shown in figures 8 and 9. For two different sizes of butterfly valves such as DN80 and DN65 the flow coefficients are $C_V = 42.431 \exp\left(0.0195\,\phi\right) \pm 1.50$ and $C_V = 34.334 \exp\left(0.018\,\phi\right) \pm 3.35$, respectively. The results were compared to obtained data from (Valmate, 2008) and (Crtec, 2008) manufacturers.

Differences between the computed results from experimental data and the results given in the literature were observed at higher the opening angles.

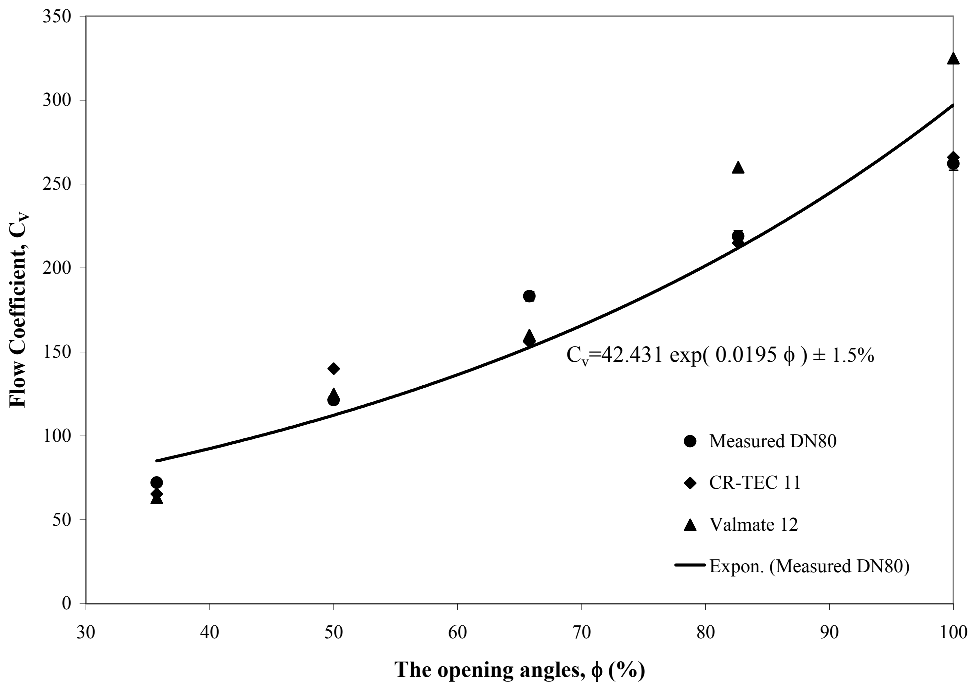

Figure 8. Comparison of Calculated C_v Values with the Other Literature Data for $3.12x10^5$ Reynolds number (DN80).

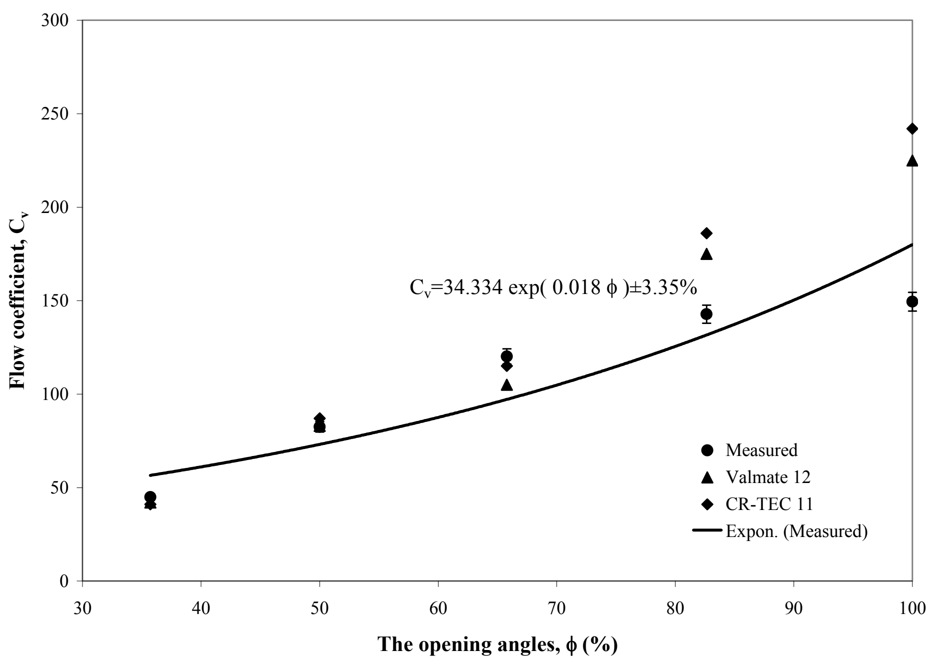

Figure 9. Comparison of Calculated C_v Values with the Other Literature Data for $2.52x10^5$ Reynolds number (DN65).

Comparison of the Loss and Flow Coefficients for Two Different Sizes of the Valves

The variation of the loss coefficient, K, and the flow coefficient, C_v, with respect to the opening angles, ϕ, for both valves, DN80 and DN65, were shown in figures 10 and 11. It was observed that the flow coefficient is a function of the valve size but the variation of the loss coefficient is different. Although the loss coefficient is independent of the valve size at the higher opening angles it is dependent of the valve size at the lower opening angles.

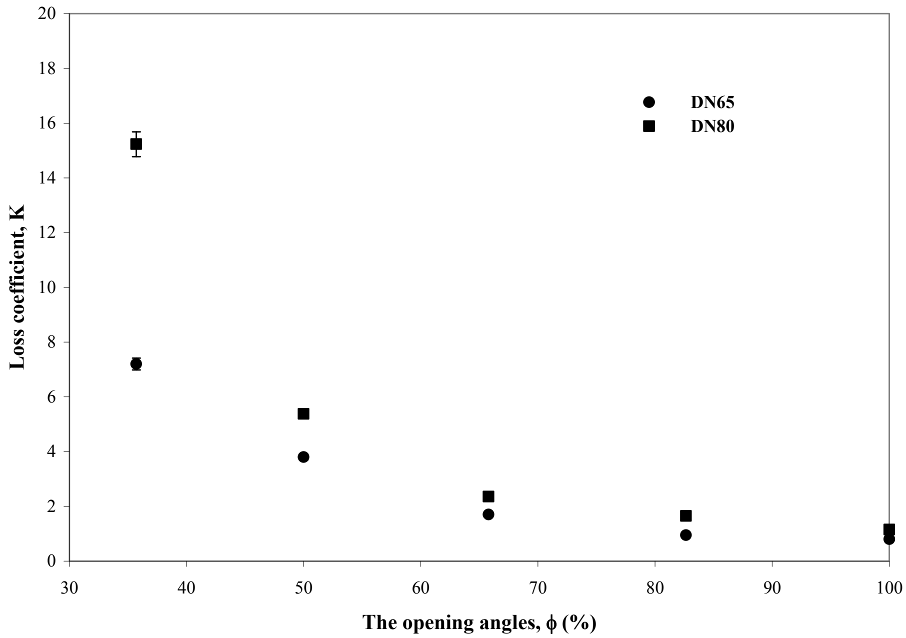

Figure 10. The Change of *K* Values Versus the Opening Angles for DN65 and DN80 at the 4 m/s Velocity.

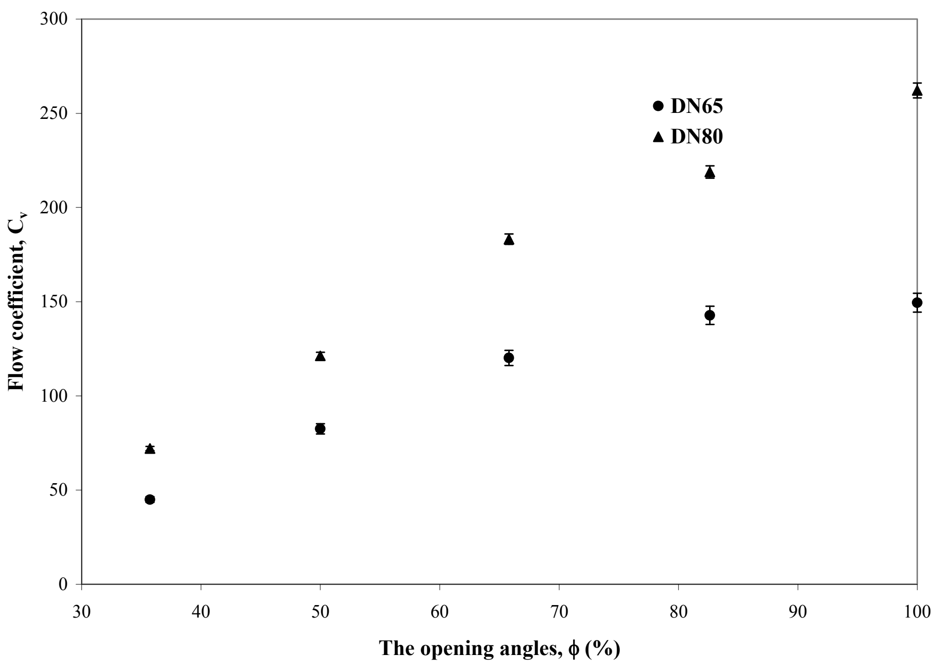

Figure 11.The Change of C_v Values Versus the Opening Angles for DN65 and DN80 at the 4 m/s Velocity.

CONCLUSIONS

The valve performance can be determined by using the loss coefficient *K*, and the flow coefficient C_v, using the pressure loss and volume flow rate information from the experimental data.

- The loss coefficient is independent of the inlet velocity and it is dependent on the valve size at the lower opening angles. But, each one of the proposed correlations, $K = 1.074 \times 10^5 \phi^{-2.514} \pm 3\%$ or $K = 0.244 \times 10^5 \phi^{-2.269} \pm 3\%$, can be used for two different sizes of butterfly valve at the higher opening angles.

- Flow coefficient is independent of the inlet velocity but it is dependent on the valve size. The proposed correlations giving the flow coefficients as functions of the opening angle are $C_V = 49.053 \exp(0.0195\phi) \pm 1.5$ and $C_V = 34.334 \exp(0.018\,\phi) \pm 3.35$ for DN80 and DN65 butterfly valves, respectively.
- Proposed correlations for K and C_v which are given above are appropriate for practical use. Manufacturer or designer of butterfly valves can find easily the corresponding K and C_v values for a given valve opening angles.

APPENDIX A

The Procedure for Calculating the Uncertainties in the Loss and Flow Coefficients

The set of input parameters are directly related to the measured variables in uncertainty analysis. The computed performance coefficients are obtained using the experimental measurements. Uncertainties in the performance coefficients such as K and C_v, are determined using the uncertainties in the flow rate Q, and pressure drop ΔP.

The loss coefficient K, and flow coefficient C_v can be calculated for any valve by using the below given equations:

$$K = \frac{1}{V^2}\frac{2\Delta P}{\rho} = \frac{\pi^2 D^4}{8\,Q^2}\frac{\Delta P}{\rho} \tag{A.1}$$

$$C_V = Q\left(\frac{1}{\Delta P}\right)^{0.5} = \frac{Q}{\sqrt{\Delta P}} \tag{A.2}$$

The uncertainty in the pressure drop $U_{\Delta P}$ and the uncertainty in volume flow rate, U_Q are used to be ±3% and ±0.1%, respectively.

The partial derivatives of K with respect to measured Q and measured ΔP are called the sensitivity coefficients and they are given as:

$$\frac{\partial K}{\partial Q} = -\frac{\pi^2 D^4}{4Q^3}\frac{\Delta P}{\rho} \qquad \frac{\partial K}{\partial \Delta P} = \frac{\pi^2 D^4}{8Q^2\,\rho} \tag{A.3}$$

Similarly, the sensitivity coefficients for C_V can be written as:

$$\frac{\partial C_V}{\partial Q} = \frac{1}{\sqrt{\Delta P}} \qquad \frac{\partial C_V}{\partial \Delta P} = -\frac{Q}{2(\Delta P)^{3/2}} \tag{A.4}$$

The uncertainty in the loss coefficient in terms of the uncertainties and sensitivity coefficients is given as:

$$U_K = \left[\left(\frac{\partial K}{\partial Q}U_Q\right)^2 + \left(\frac{\partial K}{\partial \Delta P}U_{\Delta P}\right)^2\right]^{1/2} \tag{A.5}$$

Similarly the uncertainty in the flow coefficient due to uncertainties in the pressure drop and volume flow rate:

$$U_{C_V} = \left[\left(\frac{\partial C_v}{\partial Q}U_Q\right)^2 + \left(\frac{\partial C_v}{\partial \Delta P}U_{\Delta P}\right)^2\right]^{1/2} \tag{A.6}$$

REFERENCES

Chern, M. J., Wang, C. C., and Ma, C. H., Performance Test and flow Visualization of Ball Valve, Exp Therm. and Fluid Sci. 31, 505-512, 2007.

Morris, M. J. and Dutton, J., C., An Experimental Investigation of Butterfly Valve Performance Downstream of an Elbow, J. of Fluids Eng. 113, 81-85, 1991a.

Morris, M. J. and Dutton, J. C., The Performance of Two Butterfly Valves Mounted in Series, J. of Fluids Eng. 113, 419-423, 1991b.

Fester, V. G., Kazadi, D. M., Mbiya, B. M. and Slatter, P. T., Loss Coefficients for Flow of Newtonian and Non-Newtonian Fluids Through Diaphragm Valves, Chem. Eng. Res. and Des. 85, 1314-1324, 2007.

Perry, R., H., Perry's Chemical Engineering Handbook (7th Ed.), McGraw-Hill Companies, U.S.A., 1997.

Eom, K., Performance of Butterfly Valves as a Flow Controller, J. of Fluids Eng. 110, 16-19, 1998.

ANSI/ISA-75.02-1996, Control Valve Capacity Test Procedures, American National Standards Institute, 1996.

Taylor, R., P., Hodge, B., K., and James, C., A., Estimating Uncertainty in Thermal Systems Analysis and Design, Appl.Therm. Eng. 19, 51-73, 1999.

Zappe, R., W., Valve Selection Handbook (4th Ed.), Gulf Professional Publishes, Burlington, MA, U.S.A., 1999.

Hybvalve Loss Calculations, Available from: <http://www. hybvalve.com>, 2008.

Valmate Industrial Corporation. Available from: <http://www. valmate.com.tw>, 2008.

Crtec Flow Calculations. Available from: <http://www. crtec.com>, 2008.