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Flow control system design without flow meter sensor

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ABSTRACT

This paper proposes a flow control system using only pressure meters and the flow coefficients of the valves. To obtain the flow coefficient of a control valve, flow rates for various opening and closing valve angles were first measured and an equation to approximate these values was derived. A valve disk control system was designed to improve the control function by analyzing the characteristics of mechanical friction caused by the movements of the disk. The functionality of the proposed control system was verified by comparing the measured flow rates with predicted flow rates of the proposed method.

1. Introduction

A variety of apparatus and materials are used by plumbing systems in plant engineering. Within those systems, valves are critical components controlling the flows of working fluids. Valves are classified as globe valves, butterfly valves, gate valves, etc., by disk type and driving method, and into control valves and manual valves, by operation method [1,2]. Control valves are further subdivided into pneumatic valves, hydraulic valves and motor valves, depending on their actuator type. However, regardless of the type of actuators, the flow rates and fluid pressures can be controlled by the opening and closing the disk of valve angles [3,4]. To control fluids in this way, the dynamic equation between flow rate and the valve opening degree should be estimated, which will be the basis of the design of the control system regulating the working fluids flowing through pipelines. However, the flow capacity of the valves can vary by the manufacturer of the valves even when they have the same shape. Hence, a variable determining valve capacity should be chosen for use in designing a plumbing system [5,6]. Flow coefficients are widely used as parameter among the various capacity variables [6,7].

To control flow rate in a plumbing system, the feedback control system of the control valve should be designed. The various flow control systems in process control loop have been studied in [8–10]. These approaches designed the flow control system with flow signal. However, contact type flow meters create pressure drops, which require more energy for pumping [11,12]. To address this, non-contact flow meters have been developed. However, the costs of non-contact type flow meters are comparatively more expensive than conventional flow meters [13]. In response to this, flow sensorless control system was proposed by [11,14], these approaches were based on the neural network algorithm. In general, the neural network algorithm is difficult to apply to the industrial field. Therefore, the novel flow rate control method is proposed in this paper. The proposed control system is used as the flow coefficient instead of the flow meter. In the control system, the main controller for the degree of valve disk is used by the sliding mode controller, and LuGre friction model was applied to improve the control performance of the valve system [9,15,16]. The performance of the proposed control method was verified by comparing the measured flow rates with the predicted flow rates of the proposed method.

This paper is divided into 5 sections. Section 2 explains how the flow coefficient of a valve is experimentally estimated. Section 3 shows the analysis of the mechanical friction characteristics. Section 4 explains how a position control system for the valve disk is designed and a flow control experiment is conducted for analysis, based on the mechanical friction and flow characteristics of the valve analyzed experimentally. Lastly, Section 5 presents the conclusions.

2. Estimation of the valve flow coefficient

When a valve opens, volume of fluid that passes into the valve is called capacity of valve. It is fixed and it depends on the type of valve and port size. Even if the same size and same kind of valve is used, the capacity is different according to vendors. And it is changed by various factors such as the kind of fluid, differential

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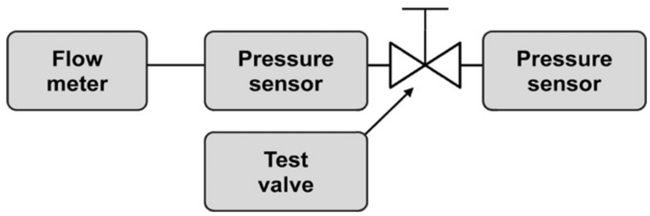

Fig. 1. Schematic diagram for experiment of flow coefficient.

pressure, temperature, viscosity, specific gravity, pressure, port design and dimensions. Furthermore, even the same size valves have both big pressure loss and small pressure loss which also depends on the kind of valve. These fluid conditions are called coefficient capacity, it can be selected kind of valve and size easily. There is a C_v factor for coefficient capacity. C_v is used generally and it is a represented factor for fluid at 5–40 °C that flows into valve by 1 gal/min (3.785 l/min). In a situation of special travel and differential pressure 1 lbf/in.^{2} (0.07 kg/cm^2), the formula equation for C_v is represented by

$$C_v = Q\sqrt{\frac{G}{\Delta p}} \tag{1}$$

where Q is flow rate, G is specific gravity and Δp is differential pressure.

The flow coefficient measuring methods indicated in international standards IEC 534-1 and IEC 534-2-3 were used to determine the flow coefficient, C_v. To analyze the relationship between the opening and closing angles of a valve and its flow coefficient, the valve was opened in 10% increments and the flow coefficient was calculated for each increment. The estimation equation was derived from the flow coefficients calculated experimentally and a nonlinear curve fitting algorithm. Fig. 1 shows the schematic diagram of the flow coefficient experiment. A 100 mm diameter butterfly valve was used for the experiment. The pressure meter used was a PSHF 0500RCBJ model from Sensys and the flow meter used was an MC 308C from Euromag.

To estimate the flow coefficient according to the opened valve angle, flow coefficients at different percentages of valve openings were obtained through experiments as shown in Fig. 2. Based on the experiment results, the estimated flow coefficient is fitted by nonlinear curve fitting method. Fig. 3 shows the fitted and

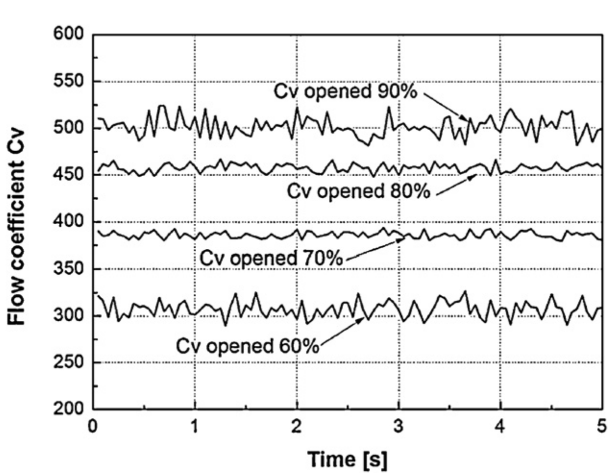

Fig. 2. Flow coefficient in accordance with percentage of opened valve.

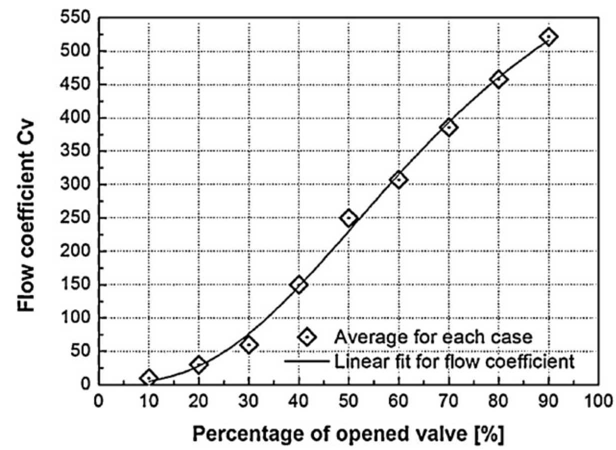

Fig. 3. Estimated flow coefficient.

experiment results. The fitted result is evaluated by R^2 which is calculated based on Eq. (3). The result of R^2 is 0.99953.

$$\hat{C}_v = 767.25 - \frac{766.38}{1+(x/68.75)^{2.67}} \tag{2}$$

where $\hat{C}_v$ is approximated flow coefficient and x is percentage of opened valve.

$$R^2 \equiv 1 - \frac{\sum (C_v - \hat{C}_v)^2}{\sum (C_v - \bar{C}_v)^2} \tag{3}$$

where $\bar{C}_v = (1/n)\sum C_v$, n is number of experiment data.

Using Eqs. (1) and (2), the estimated flow rate can be induced as follows:

$$\hat{Q} = \hat{C}_v\sqrt{\frac{\Delta p}{G}} \tag{4}$$

3. Analysis of valve friction characteristics

To design a control system for the angle of valve disk, not only did the characteristics of the valve disk movement have to be analyzed, but the friction caused by mechanical contact should also be properly compensated. Accordingly, this paper analyzes the friction characteristics of the butterfly valve and suggests a friction compensation control system based on it. First, to analyze the friction characteristics of the butterfly valve, an experimental apparatus for torque measurement was set up, as in Fig. 4. The torque sensor used in the experiment was an SBS-100K from Sensortech. The signals recorded by the torque sensor were measured by an NI USB-6221 DAQ (Data Acquisition) board from NI (National Instruments).

In general, there are two types of friction – static friction (such as viscous friction and Coulomb friction) and dynamic friction (such as the Streibeck effect, stick-slip and hysteresis) [15]. In order to represent these friction phenomena, LuGre model which is widely used to mathematically describe the characteristics of static and dynamic frictions is applied. LuGre model is represented in Eqs. (5)–(7).

$$f_{\text{LuGre}} = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 v \tag{5}$$

$$\dot{z} = \dot{\theta} - \frac{|\dot{\theta}|}{g(\dot{\theta})} z \tag{6}$$

$$g(\dot{\theta}) = \frac{1}{\sigma_0}[F_c + (F_s - F_c)e^{-(\dot{\theta}/v_s)^2}]. \tag{7}$$

where σ_0, σ_1 and σ_2 are positive constant, F_c and F_s are Coulomb and static friction, v_s is Streibeck velocity.