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# A Study on the Force Balance of an Unbalanced Globe Valve

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**Abstract**

A pneumatic control valve is a piping element that controls the volumetric flow rate and pressure of a fluid; it is necessary to analyze the characteristics of the forces with respect to the opening of the valve in order to evaluate its operating performance. The forces occurring during operation are: resisting force and actuator force, where the load resistance is mostly affected by the fluid pressure difference of the valve. In this study, a force balance equation derived from the equilibrium relationship between the resisting force and the actuator force of an unbalanced globe valve is proposed, and the force balance equations are used to model the dynamic equations of a pneumatic unbalanced globe valve installed in nuclear power plants. A CFD analysis is also carried out to evaluate the pressure distribution and forces acting on the top and bottom planes of the valve plug. The results of this analysis have been verified through experimentation. This study has shown that the fluid pressure difference between the inlet and outlet of the valve, measured from the force balance equation of an unbalanced valve, should actually be examined with the fluid-pressure difference between the top and bottom side of the valve plug.

*Keywords:* Air-operated valve; Unbalanced globe valve; Differential pressure; Diagnosis; Force balance

## 1. Introduction

A pneumatic control valve installed at the main safety system of a nuclear power plant is a kind of valve that blocks or controls fluid flow. A pneumatic control valve can be classified according to its actuator and valve body type; a diaphragm type and a cylinder type exist by the actuator, and a globe, gate, butterfly and ball valve exist by the valve body. A pneumatic control valve is composed of complex elements such as an IP positioner, diaphragm, spring, stem, packing, yoke, etc. and each element has a factor that could reduce the valve's performance. Therefore, in order to ensure the safety of a nuclear power plant, predicting a breakdown or a drop in performance of a valve, which is one of its components, is a very important issue. Recently, nuclear power plants have developed a procedure of carrying out performance evaluation on a pneumatic control valve during periodic inspections, and are actually doing a performance tests on a nuclear power plant model. The valve's performance evaluation is an analysis of the valve's operational margin using relationship between the required force and actuator force calculated from the valve's design information and diagnostic test. (Heiko et al. 2004)

The required force of a valve is the resisting force affecting its operation, which is the differential pressure across valve and the valve's friction force. The actuator force is a force that the valve's actuator provides to operate a valve, which depends on the air pressure and spring force of the actuator. Various studies on the performance evaluation of motor-

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operated valves and on the diagnosis of pneumatic valves have been carried out lately.

Kim et al.(1999) summarized the evaluation methods of the motor-operated valves and presented the methods to make design basis differential pressure and flow during the dynamic test. Jeong et al.(1999) suggested an analytic method based on a valve factor to estimate the required stem thrust that reacts the differential pressure. Terashima(1992) analyzed the factors that produce the valve-stem- driving force, spring force, and seal-friction force using the relations of the actuator air pressure and valve travel. Kaseda et al.(1999), Cho et al.(2004) and Yang et al.(2003) described the study on diagnosis of operating characteristics of the pneumatic control valve using the stem thrust model in a process by measuring actuator pressure and valve stem displacement.

Kostin et al.(1971) described the relationships between pressure and fluid flow rate under steady-state conditions of unbalanced and balanced plug. Schuder(1971) identified the nature of forces acted on the valves's moving parts such as the plug of valve to minimize filed problems arising from fluid forces.

Since a pneumatic control valve controls the flow and pressure by adjusting the valve's opening, it is necessary to analyze the characteristics of the forces with respect to the valve travel. An unbalanced globe valve is a kind of pneumatic control valve, where the differential pressure is a critical factor that affects the resisting force occurring during the valve's operation. In this paper, a study on the effect of forces due to the differential pressure has been carried out using the equilibrium relationship between the valve's required force and actuator force with respect to its travel, through static and dynamic tests of an unbalanced globe valve.

## 2. The force balance relationship of a pneumatic control valve

A pneumatic control valve operates either by air pressure or spring force according to the direction. In this study, the test valve has been used with a single acting diaphragm actuator and an unbalanced globe valve. Figure 1 is a schematic diagram of the forces acting on the valve. The force balance of the valve is derived from the relationships between the air pressure force entering the actuator, spring force and resisting force. Following is the force balance equation of the test valve.

$$F_{Air} = F_S + F_{SP} - F_{SR} - F_{DP} \pm F_P \tag{1}$$

Where, $F_{Air}$ is the air pressure force, $F_S$ the spring force, $F_{SP}$ the spring preload, $F_{SR}$ the stem rejection force, $F_{DP}$ the differential pressure force, and $F_P$ the packing friction force, respectively.

The air pressure $F_{Air}$ force entering the actuator is the product of the air pressure and the effective area of the actuator.

$$F_{Air} = P_{Air} \times A_{act} \tag{2}$$

The spring force $F_S$ is the product of the spring constant $k$ and the displacement $x$. The spring preload $F_{SP}$ is the product of the minimum bench set $BS_{min}$ obtained from a static test and the actuator's effective area. Here, the spring constant uses the value provided by the manufacturer or the value resultant of the product of the slope obtained from relationship between the valve travel and actuator pressure at the static test, and the actuator’s effective area.

$$F_S = F_{SP} + kx \tag{3}$$

$$F_{SP} = BS_{\min} \times A_{act} \tag{4}$$

The differential pressure force $F_{DP}$ is the product of the pressure difference $F_{DP}$ and the seat area $A_{seat}$. The stem rejection force $F_{SR}$ is the product of the plug's top pressure $P_{up}$ and the stem section area $A_{stem}$.

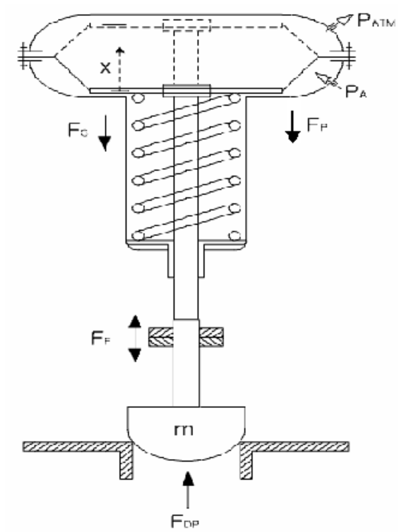



Fig. 1. Schematic diagram of unbalanced globe valve .

$$F_{DP} = P_{DP} \times A_{seat} \quad (5)$$

$$F_{SR} = P_{up} \times A_{stem} \quad (6)$$

The valve friction force comes from the actuator and the valve stem, but is mainly due to the packing friction force produced by the valve stem and packing. The packing friction force is the product of the difference between actuator pressure during the increasing and decreasing valve travel multiplied by the actuator effective area equals twice the friction. However, the packing friction force acts in opposite directions when the valve opens and closes, thus is left out of the force balance relationship.

$$F_P = (P_{AOpen} - P_{AClose})/2 \times A_{act} \quad (7)$$

## 3. Static and dynamic tests of the valve

Figure 2 shows a dynamic property testing apparatus used for the flow and pressure of a valve, with a flow rate of 100000 L/H, lifting stroke of 150 m, and with 25 mm, 50 mm, 75 mm, 100 mm pipes, which enable it to carry out dynamic tests on valves of different sizes. It is built to change the condition of flow and pressure entering the test valve by adjusting the opening of the flow control valve (Table 1) connected to the bypass pipe. Figure 3 is a schematic diagram of a valve testing apparatus, which measures the dynamic property of a valve by taking the actuator's air pressure, valve travel, pressure and flow rate values.

As a control signal is delivered to the current-to-pressure converter, a supply air pressure proportional to the control signal is provided to the actuator and the valve moves. A displacement sensor connected to the yoke measures the valve travel, the air pressure entering the actuator and a pressure sensor measures the fluid pressure of the inlet and outlet of the valve. The measured sensor signal is then transferred to a computer through an A/D converter, where the relationship between the valve travel and the actuator air pressure is analyzed.

In order to analyze the force balance of a pneumatic control valve, static and dynamic tests were carried out for a 50 mm unbalanced globe valve(Table 2). The change in the dynamic property of an unbalanced globe valve is greater than that of a balanced globe valve, due to the differential pressure across valve. Fluid does not enter into the pipe in a static test whereas it does in a dynamic test; the valve's force

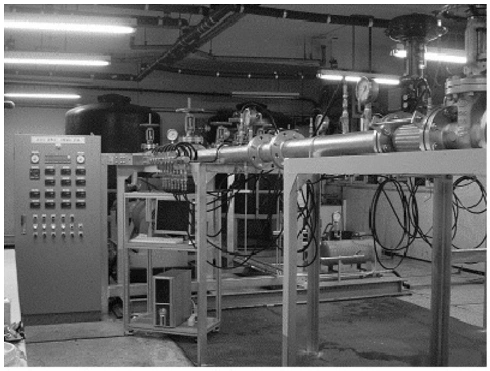


Fig. 2. Dynamic test equipment.

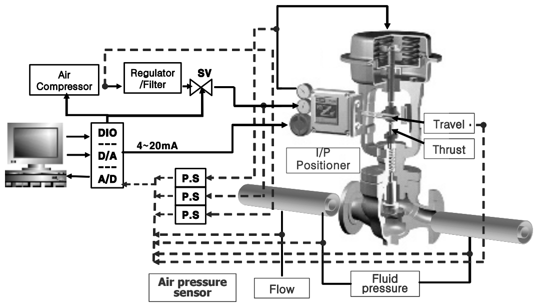



Fig. 3. Schematic diagram of diagnostic system

Table 1. The valve travel and flow varying control signal of control valve installed in bypass pipe.

| Test NO | Control signal(mA) | Valve travel(mm) | Flow(L/h) |
|---|---|---|---|
| 1 | 4 | 39.92 | 106,700 |
| 2 | 9 | 27.89 | 101,700 |
| 3 | 11 | 23.09 | 85,500 |
| 4 | 13 | 18.09 | 66,100 |
| 5 | 15 | 13.19 | 43,200 |

Table 2. A list of the components and specifications of test valve.

| Component | Specification |
|---|---|
| Control valve | Type : unbalanced disk<br>Size : 50.8mm<br>Actual travel : 28mm<br>Packing type : graphite |
| Actuator | Type : diaphragm<br>Effective area : 677 $cm^2$<br>Air acting : reverse |
| Pressure transducer | Input range : 3, 7, 10 kgf/ $cm^2$<br>Output range : 4~20 mA |
| Position sensor | Type : wire<br>Input range : 0~500 mm<br>Output range : 0~10 Vdc |

balance relationship due to the test valve's pressure differential across the valve is analyzed by adjusting the opening of the flow control valve connected to the bypass pipe and further changing the flow entering the test valve. Table 1 shows the relationship between the valve travel and flow with respect to the control signal of the control valve connected to the bypass pipe.

Figure 4 is the dynamic test results and shows the change in flow with respect to the test valve's travel. A study on the force balance relationship due to the pressure differential between the inlet and outlet of the test valve was enabled by adjusting the opening of the flow control valve connected to the bypass pipe in 5 stages and further changing the condition of flow entering the test valve. Figure 5 shows the change in pressure difference between the inlet and outlet of the valve with respect to the test valve's travel. Depending on the flow rate entering the valve, the differential pressure across the valve went up to 16.6 $kg_f/cm^2$, and it is seen that the pressure differential increases as the flow rate increase.

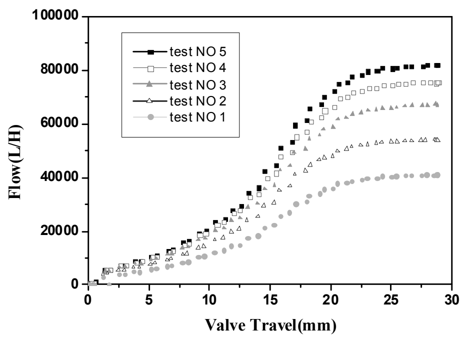



Fig. 4. Flow of unbalanced globe valve.

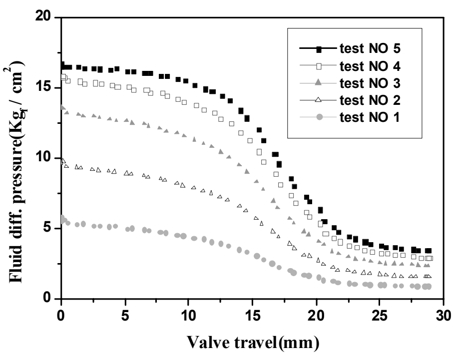
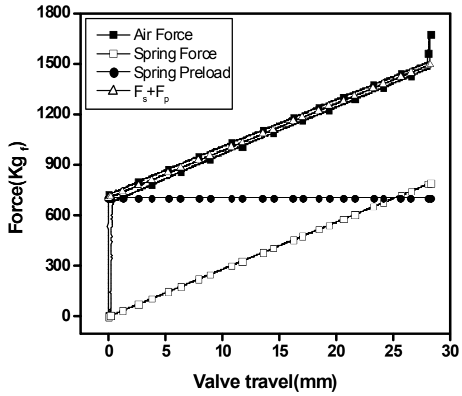
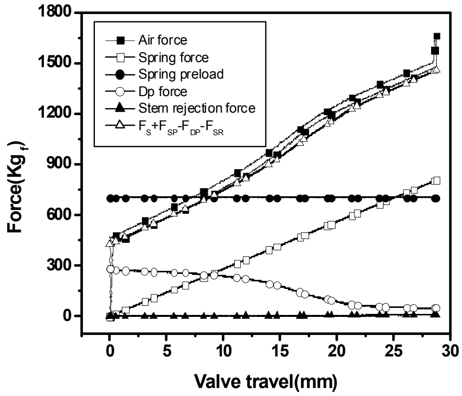



Fig. 5. Differential pressure of unbalanced globe valve.

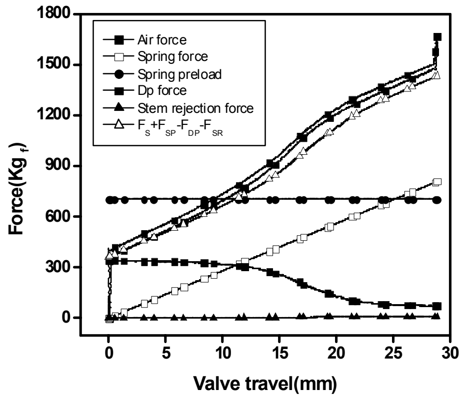
Figure 6 shows the force balance relationship by applying the pressure differential between the inlet and outlet of the valve measured in static and dynamic tests. Figure 6 (a) is the result of the static test, where there is no pressure difference, showing the relationship between the air pressure force acting on the actuator with respect to the valve travel and




(a) Static test




(b) Dynamic test(NO 3)




(c) Dynamic test(NO 5)

Fig. 6. Force balance results of unbalanced globe valve.

the spring force, which is a resisting force. With no pressure difference, it is seen that the spring and resisting force maintains the mean value of the actuator's air pressure at opened and closed states. This is a result of not taking into account the packing friction force; and the packing friction force need not be considered in the force balance analysis since packing friction force acts in opposite directions as the valve opens and closes. Though, in the case of a dynamic test where the pressure difference between the inlet and outlet of the valve is taken into account [Figs. 6(b) and 6(c)], the spring and resisting force cannot make the mean value of the actuator air pressure force. Unlike a static test, the fluid enters into the valve in a dynamic test and this presumably affects the pressure differential of the valve. Also, it is seen that the margin of error in the force balance increases as the differential pressure across the valve gets greater. Therefore, in order to solve this kind of force balance issue, it is necessary to study what influence the pressure difference acting on the valve plug has on the force balance. It is seen that it is actually not the pressure difference between the inlet and outlet of the valve measured in the dynamic test, but the influence of the force due to the pressure differential between the top and bottom of the valve plug that directly affects the dynamic property of a valve. As it is difficult to measure the pressure at the top and bottom of a valve plug, engineering flow analysis software was used to calculate the fluid pressure at the top and bottom of the plug.

## 4. Computational fluid dynamics analysis

It is difficult to directly measure the fluid pressure at the top and bottom of the plug, which is inside a valve. Thus, engineering flow analysis software was used to calculate the fluid pressure at the top and bottom of the plug; and this kind of analytical method proved the results to be valid by calculating the differential pressure between the inlet and outlet of the valve simultaneously and comparing it to the fluid pressure from the dynamic test. Figure 7 shows the locations using an engineering flow analysis software where the fluid pressures at the inlet and outlet of the valve, and at the plug's top and bottom are calculated; $P_{mi}$ and $P_{mo}$ are locations where the fluid pressure at the inlet and outlet of the valve, equal to the fluid pressure differential measured in the dynamic test, is calculated; $P_{ri}$ and $P_{ro}$ are locations where the fluid pressure at the top and bottom of the plug is calculated.

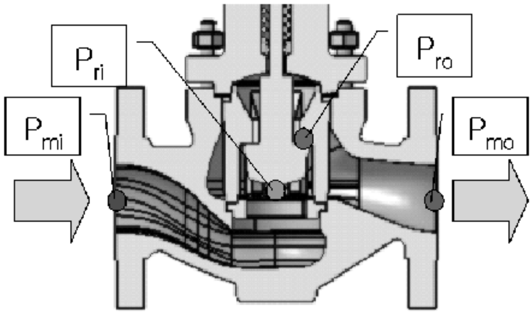



Fig. 7. Pressure positions applied in experiment and analysis.

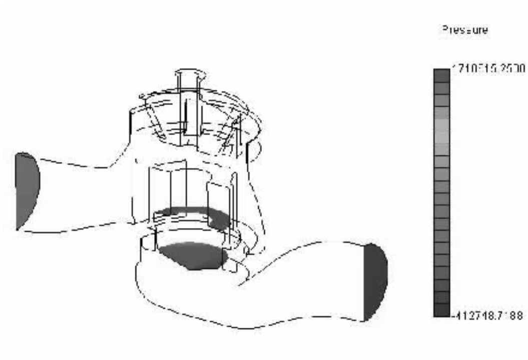


Fig. 8. Pressure distribution of numerical analysis

Figure 8 shows the calculated fluid pressure distribution at the actual measuring locations and at the plug's top and bottom using the engineering flow analysis software. The SC/Tetra software was used to calculate the 3-dimensional flow field inside the valve; the flow space inside the valve is dispersed into 2 million unstructured volumetric grids for a low-opening rate and into 1million for a high-opening rate. The turbulent model uses a k-$\varepsilon$ model, with a y+ value of less than 1000 in order to properly use logarithmic wall-functions.

Figure 9 shows the discrepancy between the test results of the experimental pressure differential and the results from computational analysis. From this, it is seen that the magnitude of error in the resultant fluid pressure differential between the actual measuring locations and the plug's top and bottom is small at low valve-opening rate but farther increases as the opening rate increases. The computational fluid dynamics analysis results show that a significant pressure difference of 4 $kg_f /cm^2$ occurred at some particular location.

Figure 10 shows the results of the pressure difference measured at the inlet and outlet of the valve, and the results of the force balance assessment

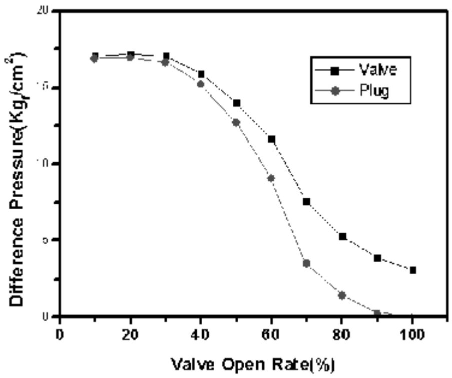



Fig. 9. Comparison of differential pressure

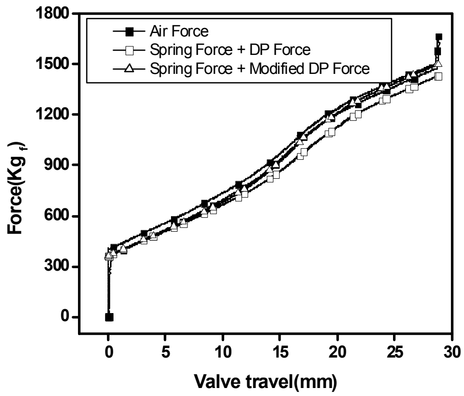



Fig. 10. Results using force balance equations with differential pressure of experiment and analysis.

using a numerical analysis method. When the measured pressure difference is applied, the force balance relationship of the valve cannot be established, whereas the calculations from the numerical analysis results show a force balance relationship due to the air pressure force entering the actuator and the load resistance. By applying the results from the numerical analysis method and the measured pressure difference, it is shown that; while using the numerical analysis results, the force calculated from the force balance relationship is inferior by approximately 8% to the pressure difference measured from the dynamic test.

After applying the numerical analysis results and the measured results to the force balance analysis, it is shown that the pressure differences between the inlet and outlet of the valve; and between the plug's top and bottom are relatively large. This is because the plug and the plug sheet, which constitute a boundary of pressure distribution, move farther away from each other as the valve opening increases and the flow occurring from a complicated flow path affects the plug's top where the top pressure becomes even larger. Thus, the differential pressure across the valve becomes smaller than that between the plug's top and bottom. So far, while carrying out valve performance tests, the differential pressure across the valve was applied to analyze the influence of the pressure difference on the valve's dynamic behavior. However, it is shown that it is actually the pressure difference between the plug's top and bottom that affects the dynamic behavior.

## 5. Conclusion

A pneumatic control valve used in the nuclear power plant is a pipe element that controls the flow and pressure of a fluid, and it is necessary to evaluate its performance with respect to the valve travel. Generally the pressure in the inlet and the outlet is measured in order to analyze a valve system because it is impossible to measure the pressure around the plug and in the valve. However, the pressure in the valve should be considered in order to analyze the exact valve mechanism. This study, analyzing the force balance relationship, which uses the air pressure force entering the actuator and the load resistance. This result is used for evaluating these valves exactly and understanding the acting mechanism of a valve. Therefore, it is possible to predict the exact performance of valves.

(1) In a static test where there is no differential pressure across the valve, the force balance relationship of the valve is linear and the resisting force, which occurs at the opening and closing of the valve, has a mean value of the actuator force.

(2) In a dynamic test where the differential pressure is taken into account; it is shown through a force balance analysis that the load resistance of the valve does not equal the mean value of the actuator force. The unachieved force balance relationship of a valve in a dynamic test is due to the differential pressure acting on the plug's top and bottom rather than the fluid pressure measured between the inlet and outlet of the valve.

(3) It is shown that in the case of applying the numerical analysis results to the force balance equation, the force decreases by 8% compared to the case where the measured pressure difference is applied.

(4) Therefore, from the results of this study, it is shown that; while examining the force balance of a

valve, the actual difference between the fluid pressures at the top and bottom of the plug should be taken into account for the pressure difference between the inlet and outlet valve with respect to the measured fluid pressure.

## Nomenclature

| | | |
|---|---|---|
| $F_{Air}$ | : | Actuator air force(N) |
| $F_{DP}$ | : | Differential pressure force(N) |
| $F_P$ | : | Packing friction force(N) |
| $F_S$ | : | Spring force(N) |
| $F_{SP}$ | : | Spring preload(N) |
| $F_{SR}$ | : | Stem rejection force(N) |
| $P_A$ | : | Air pressure of actuator($kg_f/cm^2$) |
| $P_{AOpen}$ | : | Open air pressure of actuator($kg_f/cm^2$) |
| $P_{AClose}$ | : | Close air pressure of actuator($kg_f/cm^2$) |
| $A_{act}$ | : | Effective area of actuator($cm^2$) |
| $A_{stem}$ | : | Stem section area($cm^2$) |
| $A_{seat}$ | : | Seat area($cm^2$) |
| $k$ | : | Spring coefficient($cm^2$) |
| $x$ | : | Spring displacement(mm) |
| $BS_{min}$ | : | Minimum benchset($kg_f/cm^2$) |
| $P_{up}$ | : | Plug upper pressure($kg_f/cm^2$) |
| $P_{DP}$ | : | Difference pressure($kg_f/cm^2$) |

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