Development of Control Valve for Flow Measurement and Flow Control

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Summary:

This paper reports on the development of a product that incorporates flow measurement functions in the heating and cooling water control valves used mainly in building air-condition systems. This product can be used to obtain the energy usage efficiency in detail for each air-conditioning unit. It also allows flow rate control operation (previously, opening control operations) to reduce excessive flow rates for contributing to energy savings. In addition, the required flow rate is maintained without being affected by flow rate changes in order air-conditioning units for allowing improved comfort in living spaces.

1. Introduction

In recent years, there has been an growing realization of the urgent need to bring about a low carbon society, and demand for energy management and energy efficiency in buildings and factories is growing rapidly, as can be seen by the revision of the Energy Saving Act. The Energy Saving Act obliges business operators to, for example, set energy management criteria, periodically report energy management conditions to the government, and prepare and submit a mid- to long-term (3 to 5 years) plan for achieving their goals for rationalization of energy use.  

To review measures for saving energy used in air conditioning and to verify the effectiveness of these measures, it is important to measure the heat treatment quantity in each air-conditioning apparatus. It is also important, from the perspective of energy conservation, to prevent not only waste in energy transfer resulting from excessive flow of chilled/hot water in the air-conditioning apparatus, but also a drop in the operating efficiency of the heat source equipment.

It is possible to solve the above problems by adding flow and temperature measurement functions to the chilled/hot water control valve, without adding a flow meter or a calorimeter.

The ACTIVAL Intelligent Component series motorized two-way valve with flanged-end connection, model FVY51 (hereinafter referred to as “FVY51”), which this paper introduces, consists of a conventional product (ACTIVAL Intelligent Component series motorized two-way valve, model VY51: hereinafter referred to as “VY51”) as a base and the addition of flow measurement and control functions and other functions.

Figure 1 shows the exterior of the product, and Figure 2 shows its configuration.
Information on the flow rate, pressure, and temperature measured by the valve is transmitted to the controller by SAnet Communication(2). As optional accessories, a panel for displaying information such as flow rate and pressure and a temperature sensor for measuring the temperatures at air-conditioning apparatus inlets and outlets in conjunction with the temperature measurement function of the valve are available.

2. Product lineup and main specifications
FVY51 series products and their main specifications are as follows.

2.1 Product lineup
There are 6 valve sizes with calibers ranging from 15 A to 80 A, and 10 Cv values ranging from 1.0 to 125.

2.2 Main specifications

2.2.1 Specifications common to FVY51 and VY51
- Valve body material: FC200 (gray cast iron)
- Pressure rating: JIS 10K
- Face-to-face dimension: JIS B 2002 series 6
- Power supply voltage: 24 V ac
- Opening and closing operation time: 63 s (50 Hz)
- Communication: SAnet (voltage transmission)

2.2.2 Additional specifications
- Flow measurement
  (accuracy: ±5% rdg, 10 to 100% of maximum setting flow rate, differential pressure range: 30 kPa to 300 kPa)
- Fluid temperature measurement
  (accuracy: ±1 °C in 0–80 °C range)
- Fluid pressure measurement
  (reference accuracy: ±0.5% FS, 0 to 1 MPa)
- Flow control operation
- Calculation of cumulative flow

By making the basic specifications of the valve the same as those of the VY51, valves can be selected in the same manner as before. This makes it possible to replace a conventional product used in existing equipment with this product without any piping work, so that the cost of adopting the valve is reduced.

3. Technical elements for flow measurement
Unlike flow measurement using an ordinary flow meter, in valve flow measurement, the flow velocity and pressure distribution inside the valve vary greatly depending on the valve opening. Also, in many cases, a sufficient length of straight pipe cannot be secured because of an elbow (bent piping), reducer, or hand valve installed immediately before the valve. Under these conditions, the flow measurement accuracy of ±5% of the reading must be achieved across wide ranges of valve travel, differential pressure, and flow rate. The technical elements developed to achieve the above requirements are described below.

3.1 Flow measurement method
The various methods of flow measurement include electromagnetic, ultrasonic wave, vortex, and differential pressure. In devices like valves, in which the internal flow is asymmetric and the flow conditions vary greatly depending on the degree of valve opening, the differential pressure flow measurement method using the differential pressure generated at the restriction mechanism (valve plug) inside the valve is the most suitable. Figure 3 shows the pressure distribution of a flow passing through a valve.

$$C_v = 11.57 \times \frac{\rho}{\rho_w} \sqrt{\frac{Q}{\Delta P}} \quad \text{(1)}$$

Q: Volumetric flow rate of fluid (m$^3$/h)
$C_v$: Flow coefficient
$\Delta P$: Differential pressure between front and back of valve (kPa)
$\rho$: Fluid density (kg/m$^3$)
$\rho_w$: Water density (kg/m$^3$)

In general, the relation represented by Equation (1) below holds between the front-back differential pressure of a valve installed in a piping and the flow rate running through the valve.(3)

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Figure 3. Pressure distribution of flow passing through valve

![Pressure distribution of flow passing through valve](image)

Figure 4. Characteristic of $C_v$ value

![Characteristic of $C_v$ value](image)
The differential pressure $\Delta P$ in Equation (1) is defined as the difference between the primary side pressure at the 2D distance from the valve and the secondary side pressure at the 6D distance from the valve (see Figure 5).

Figure 5. Flow coefficient measurement test conditions

The pressure distribution at a location near the valve inlet when an elbow is installed before the valve is calculated by using CFD (computational fluid dynamics) analysis. The result shows that asymmetrical pressure distribution (a pressure difference of around 4 kPa at maximum) occurs in this area (see Figure 7). The pressure difference of 4 kPa can be converted into a flow rate accuracy of about 6.5%, which means that installation of an elbow has a large effect.

In Figure (7), (a) is the target area of calculation, (b) shows equipressure contours, and (c) shows equipressure contours near the valve inlet. The equipressure contours show that the pressure distribution is asymmetrical with respect to the right and left sides of the inlet diagram.

Figure 7. Result of CFD analysis near the valve inlet

Based on the above algorithm, flow is measured with the following procedure.

1) Measure the pressures inside the valve to obtain the differential pressure.
2) Measure the valve opening.
3) Determine the $C_{v,v}$ (see section 3.4) from the valve opening and the differential pressure.
4) Plug the determined $C_{v,v}$ and differential pressure in Equation (1) to calculate the flow rate.

3.2 Pressure measurement

To enhance the accuracy of flow rate measurement, it is important to measure stable differential pressure in a limited space without changing the face-to-face dimension of the valve and to measure the differential pressure when it is high.
The effects of this structure were examined in actual flow rate tests, both for the case where there is straight piping before the valve and for the case where there is an elbow. The result shows that this structure sufficiently reduces the impact of the elbow installed before the valve (see Figure 10).

### 3.2.2 Measurement of secondary side pressure

The condition of the flow inside the valve varies greatly depending on the valve opening. Figure 11 (a) shows a velocity contour diagram and Figure 11 (b) shows a pressure contour diagram. As shown in Figure 3, the pressure inside the valve rapidly drops immediately after the flow passes the valve plug, and immediately after the drop, the pressure slowly begins to recover. Under these circumstances, the requirements for measurement of primary side pressure are as follows.

1) Measure at a position not subject to dynamic pressure.
2) Measure at a position where there is no difference in pressure distribution.

1) and 2) above must be achieved for the entire range of valve travel.

### Table 1: Impact of upstream piping on flow rate accuracy

<table>
<thead>
<tr>
<th>Opening %</th>
<th>Piping upstream of valve</th>
<th>Differential pressure kPa</th>
<th>Accuracy difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>54</td>
<td>Straight</td>
<td>33</td>
<td>-0.1%</td>
</tr>
<tr>
<td></td>
<td>Elbow</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>79</td>
<td>Straight</td>
<td>30</td>
<td>-0.3%</td>
</tr>
<tr>
<td></td>
<td>Elbow</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>Straight</td>
<td>100</td>
<td>-0.1%</td>
</tr>
<tr>
<td></td>
<td>Elbow</td>
<td>104</td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>Straight</td>
<td>107</td>
<td>0.7%</td>
</tr>
<tr>
<td></td>
<td>Elbow</td>
<td>106</td>
<td></td>
</tr>
<tr>
<td>79</td>
<td>Straight</td>
<td>105</td>
<td>-0.6%</td>
</tr>
<tr>
<td></td>
<td>Elbow</td>
<td>101</td>
<td></td>
</tr>
</tbody>
</table>

In order to satisfy the above requirements, we designed the interior of the valve body using CFD analysis, and successfully created a space between the valve plug and the valve body where it is possible to reliably measure the secondary pressure for all degrees of valve opening. The above problems were solved by providing secondary side pressure ports at this position (patent pending). Figure 12 (a) shows a contour diagram and a vector diagram of the flow rate near the secondary pressure measuring section and (b) shows equipressure contour lines.
3.3 Pressure sensor

To be suitable for FVY51, a sensor must have the capability to measure pressure, temperature and differential pressure in a limited space.

As it is difficult for commercially available sensors to satisfy these requirements, we have developed a novel pressure sensor. In brief, it is a hybrid sensor consisting of two pressure sensors and one temperature sensor packed in an engineering plastic case (patent pending). The differential pressure is obtained by calculation using the primary side and secondary side pressures. The sensor element is in a stainless steel diaphragm structure that does not require oil sealing, with the aim of downsizing (see Figure 13).

![Figure 13. Exterior of pressure sensor](image)

3.4 Valve opening measurement

The degree of valve opening is measured using a potentiometer attached to the actuator output shaft. Figure 14 shows its structure. In order to measure valve travel with a high level of accuracy, a highly linear potentiometer is used and, through improvement of the assembly method, the backlash generated between the gear of the potentiometer and the gear section of the actuator output shaft is reduced. Furthermore, to eliminate the impact of the positional displacement in the valve rotation direction that occurs during assembly of the valve body and the actuator, adjustment is made after assembly of the valve actuator in order to correct the potentiometer output (patent pending).

![Figure 14. Valve travel measuring structure](image)

3.5 Flow coefficient $C_{vv}$

Generally, the $C_v$ obtained in the test conditions as shown in Figure 5 will not be affected by the differential pressure. Therefore, it is determined unambiguously by the degree of valve opening. However, through testing of the relationship between the differential pressure inside the valve and the flow coefficient as verified by this product, it was found that this relationship has a certain tendency to change depending on the differential pressure, because the secondary pressure was measured while the pressure was recovering (see Figure 15). To differentiate from the test conditions in Figure 5, the flow coefficient obtained from the differential pressure inside the valve is defined as $C_{vv}$, and the differential pressure inside the valve as $\Delta P_v$. For the relative flow coefficient in this figure, the value at the differential pressure of $\Delta P_v = 100$ kPa is used as a reference. The flow coefficient $C_{vv}$ drops greatly especially in the differential pressure range of 100 kPa or less. Therefore, to conduct flow measurement over a wide differential pressure range, the flow coefficient $C_{vv}$ must be treated as a function of valve opening and differential pressure inside the valve.

For FVY51, the $C_{vv}$ for a given valve opening and differential pressure is determined using a table of $C_{vv}$ values (Figure 16) that have been obtained experimentally (patent pending).

![Figure 15. Relationship between differential pressure inside valve and flow coefficient $C_{vv}$](image)

![Figure 16. $C_{vv}$ values](image)

3.6 Measures to improve flow measurement accuracy

The technical elements for flow measurement inside valves have been discussed. In actual flow measurement, accuracy will be affected by variations such as differences in the individual parts of different valves and differences in part combination and product assembly work. Among these, differences between individual valve plugs (see Figure 17) and variations in the physical valve openings, which determine the characteristic of the $C_{vv}$ value, have an especially large effect on flow rate accuracy.

The port section of the valve plug that determines the characteristic of $C_{vv}$ value takes a complex three-
dimensional shape so as to obtain necessary flow characteristics. FVY51 is manufactured by lost wax casting in consideration of dimensional accuracy, but this method produces more dimensional variation than machining. Furthermore, since the number of parts related to the valve opening is great, it is difficult to completely eliminate the opening displacement.

To ensure reliable and high-flow measurement accuracy of FVY51, correction of the amount of valve opening against flow rate is made through actual flow tests.

Figure 17. Valve plug

3.6.1 Correction method for flow rate calculation

Specifically, correction is performed in the following procedure.

1) Measure the actual flow rates for multiple valve travel values using a reference flow meter and then obtain the \( C_{vv}' \) value.

2) Obtain the \( C_{vv} \) value for each valve travel value from the flow coefficient table for the specific product.

3) Obtain the error between the \( C_{vv} \) value and the \( C_{vv}' \) value for each amount of valve opening, and then add an offset to the values for openings in the flow coefficient table so that the error distribution width is minimized. Figure 18 shows a conceptual diagram.

Figure 18. Correction for \( C_{vv} \) table

3.6.2 Inspection of flow measurement accuracy

For FVY51, flow is measured at 10 valve opening points in the shipping inspection process, and the offset value for the \( C_{vv} \) table is determined and then stored in the product’s microcomputer. Flow rate accuracy is then checked for 5 combinations of valve opening and differential pressure, and a judgment is made on the result. By means of the above inspection process, the flow rate accuracy of the product is guaranteed. Figure 19 shows the overview of the inspection equipment installed next to the product assembly line.

Figure 19. Overview of inspection equipment

3.7 Flow rate accuracy

Thanks to the technical elements discussed so far, this product has achieved a flow rate accuracy of ±5% rdg at 10 to 100% of the maximum flow rate setting and in a front-back differential pressure range of 30 kPa to 300 kPa at the valve plug (see Figure 20). Accuracy is ±1% FS in the low flow rate range.

Figure 20. Flow measurement accuracy specification

4. Contribution to energy conservation

Thus far we have focused mainly on the flow measurement function, which provides important information for energy management. This section discusses the contribution of the flow control action to energy conservation, which is another distinctive feature of this product.
4.1 Flow control action

FVY51 has a flow control action and not a conventional valve opening control action. Conventional chilled/hot water control valves open or close (opening-control action) until they reach the valve opening corresponding to the output value from the controller. For example, when a setting of 100% is output from the controller, the valve operates up to the 100% opening. The flow rate at this point is substantially higher than the design flow rate of an ordinary air-conditioning apparatus. The reason for this is that, for both the valve and the pump that sends chilled/hot water supply, products with a specification equal to or higher than the design value tend to be selected in order to prevent shortage of air-conditioning capability resulting from a shortage of flow rate. On the other hand, the heat exchange quantity in the air-conditioning apparatus does not increase greatly even when the flow rate is higher than the design flow rate. Therefore, when the valve opening is 100%, the flow of chilled/hot water is greater than the design flow rate of the air-conditioning apparatus, but the time required to reach the setting temperature differs little from the time in the case with the design flow rate. This means that waste from energy transfer occurs as a result of excessive flow of chilled/hot water.

With FVY51, due to its flow measurement function, the flow control action can be made so that the valve opens and closes to adjust to the flow rate corresponding to the output value from the controller. By adjusting the maximum flow rate setting of the valve to the design flow rate of the air-conditioning apparatus through this flow control, the valve can be made to open and close so that the flow rate of 80 l/min or more is kept within the design flow rate, thereby preventing excessive flow.

4.2 Energy-saving effect due to flow control action

We have installed about one hundred FVY51 valves in the air-conditioning chilled/hot water supply system of a seven-story office building in our Fujisawa Technology Center to collect data for evaluating the difference in air-conditioning related energy between flow control action and opening control action.

Among the days when the air conditioning system was operated with flow control action and the days when it was operated with opening control action, we have selected days with almost identical thermal loads, weather and temperature, and compared the quantities of chilled/hot water transfer energy consumed on those days. The result of the comparison shows an energy-saving effect of approximately 7%.

Figure 21 shows the air-conditioning data for the day of the evaluation. In the case of opening control action, the flow rate is larger than the design flow rate of the air-conditioning apparatus during its start-up in the morning. By contrast, in the case of flow control action, the flow rate is kept within the design flow rate, greatly contributing to energy conservation.

5. Conclusion

FVY51, leveraging the flow measurement technology introduced in this paper, and using flow control action based on flow rate information, will contribute to energy management and energy efficiency, which will play an increasingly important role in bringing about a low-carbon society.

The valve models equipped with a flow measurement function make up only a part of the whole ACTIVAL series. We intend to expand the product portfolio by adding models with the flow measurement function one after another. We hope to address every aspect of building air-conditioning in order to make a contribution to the realization of a low-carbon society.

Reference material

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