Improving mass flow controller usability

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Key words
micro-flow sensor, mass flow controller, flow control, F4Q, usability improvement, MEMS

Due to a decrease in the number of skilled workers and stricter quality requirements in the mechanical, electrical, semiconductor, and other markets, automation of control involving mass flow controllers is progressing apace. Since an increasing number of measuring instruments are being managed by a limited number of operators, there is a growing demand for a quick means of ascertaining their status and for easy-to-use operating methods. By redesigning the user interface and providing better adaptability to various operating conditions, we are able to offer a mass flow controller that satisfies market demands and provides optimal control for more applications than existing products.

1. Introduction

Mass flow controllers have been used mainly for flow control of process gases in the front-end process (wafer generation) in the semiconductor industry. In recent years, the market has been expanding in general industries such as the automotive, machinery, electrical, and electronic industries, and market demand is also becoming increasingly diverse. Although the functionality of mass flow controllers has been expanded in response to market demand [1], usability requirements related to status tracking and device settings, or compatibility with operating conditions, including the piping direction and pressure conditions [2], had not been met.

Azbil sells various mass flow controllers (such as models MQV_ _ _, F4H, MPC_ _ _), each of which combines Azbil's micro-flow sensor (a thermal mass flow rate sensor utilizing microelectromechanical systems (MEMS) technology) and a proportional valve. Since these products use displays with a 7-segment LED and LED indicators, the amount of information displayed was limited and only limited operability was offered. In addition, due to the characteristics of the sensor, there were some problems with compatibility with operating conditions, such as measurements not being taken accurately when the sensor orientation changed, which put limitations on the orientation of the piping.

In response, we developed the model F4Q mass flow controller (fig. 1), which has a completely new user interface and new functions. Details on its development are reported in this paper.

Fig. 1. Examples of model F4Q.

2. Overview of mass flow controller products

Azbil's products that preceded the newly developed F4Q are models MQV, MPC, and F4H. As an example of the new product, the main specifications of the F4Q0002 digital mass flow controller are shown in table 1. This section gives an overview of these mass flow controllers from Azbil.

Table 1. Main specifications of a mass flow controller

Model No.	F4Q0002
Display	Full-dot 96 × 96 pixel LCD
Valve type	Proportional solenoid valve (normally closed)
Control range	0.02 to 2.00 L/min (1 to 100 %)
Compatible gas type	Air/nitrogen, oxygen, argon, carbon dioxide, fuel gas 13A, propane, methane, butane
Responsiveness	0.3 s (typ.) to the setting ±2 % FS
Accuracy (Q: flow rate)	±1 % SP (15 ≤ Q ≤ 100 % FS) ±0.15 % FS (1 ≤ Q ≤ 15 % FS)
Repeatability (Q: flow rate)	±0.25 % SP (15 ≤ Q ≤ 100 % FS) ±0.0375 % FS (1 ≤ Q ≤ 15 % FS)
Operating differential pressure range	50 to 300 kPa
Pressure resistance	1 MPa (gauge)
Operating temperature range	−10 to +60 °C
Communication	USB 2.0, RS-485
Power supply	24 V DC, current consumption: 300 mA max.
Mounting orientation	Horizontal or vertical
Weight	About 1.2 kg

2.1 Measurement principle

The structure of the sensor used in our products is shown in figure 2. The temperature distribution on the surface of the sensor is measured by heating the atmospheric gas with the heater and using the temperature sensors on the upstream and downstream sides of it. When the fluid moves over the sensor, the temperature distribution changes as shown in figure 3, which is reflected in the sensor signal. The flow rate is measured by converting the sensor signal into a flow rate signal [3]. As shown in figure 2, by using a small chip and thermally insulated diaphragm, transient entrance and exit of heat is suppressed and fast response is achieved.

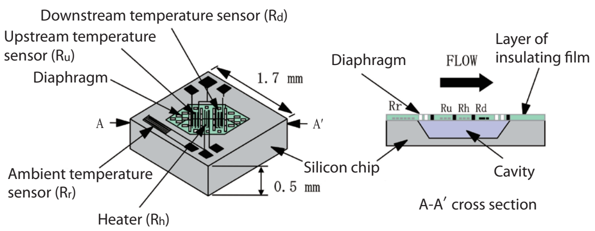


Fig. 2. Micro-flow sensor structure

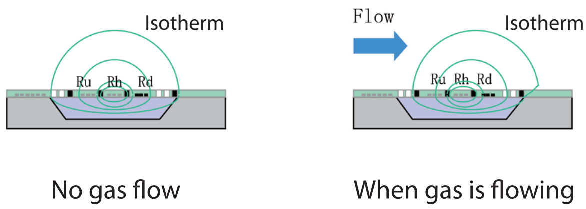


Fig. 3. Temperature distribution on the micro-flow sensor

2.2 System configuration

Figure 4 shows the structure of our mass flow controllers. A rectifying wire mesh, the aforementioned micro-flow sensor, and a normally closed proportional solenoid valve are used.

Each product has a user interface with display and operation panel, I/O, RS-485 communication, and more. The interface configuration differs depending on the product concept.

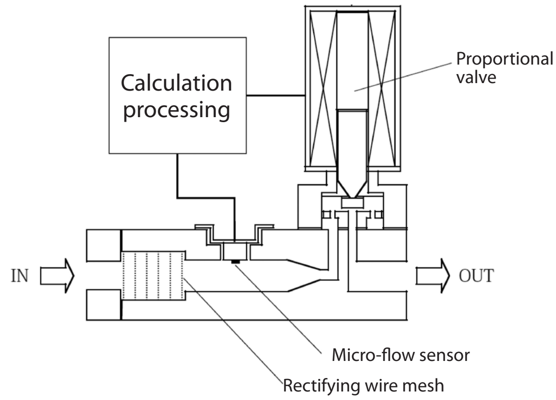


Fig. 4. Mass flow controller system configuration

2.3 Features

Features of our mass flow controllers include high-speed control, low differential pressure operation, and single power supply operation.

2.3.1 High-speed control

For the control-related sensor and valve, a micro-flow sensor and solenoid valve with fast response are used. Calculation for PID control is executed on a cycle of 5 ms or less (5 ms for MQV, MPC, and F4H; and 1.5 ms for F4Q) for high-speed control. This can reduce the time required for the flow rate to settle to the set amount when control is started from a fully closed state, when the flow rate is changed during control, or when a flow rate change occurs due to a disturbance such as a change in pressure.

2.3.2 Low differential pressure operation

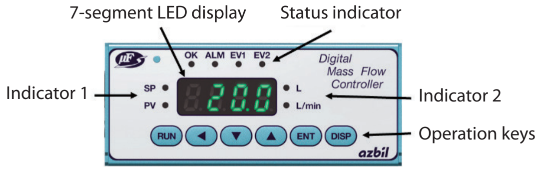
Since the measurement principle described in 2.1 is applied, almost no pressure loss occurs in flow rate measurement. Instead, the dominant pressure loss is caused by the coupling and flow rectification. By taking advantage of this characteristic, we have created a model with a low gas supply pressure that can be used for applications such as burners.

2.3.3 Single power supply operation

All models are designed for a single 24 V DC power supply, so inexpensive general-purpose power supplies can be used, and it is possible to share the power supply with other devices. In addition, all models other than the MPC have a power supply jack to which an AC adapter can be connected. Therefore, they are easy to use for simple applications such as experiments, since there is no need for power supply wiring.

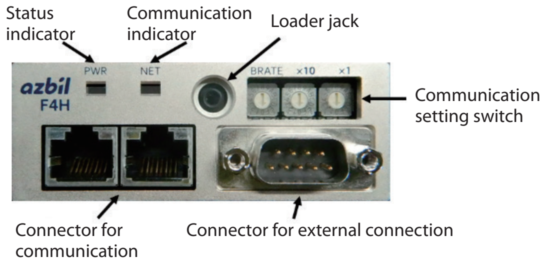
3. User interface design

The new UI is designed to enable early detection and quick handling of abnormalities to facilitate stable operation and quality management. The new UI and the UIs of earlier products are shown in figure 5. In this section, the features and purposes of the new UI are explained.



(a) UI of model MQV

(b) UI of model MPC



(c) UI of model F4H

Fig. 5. User interface of earlier products

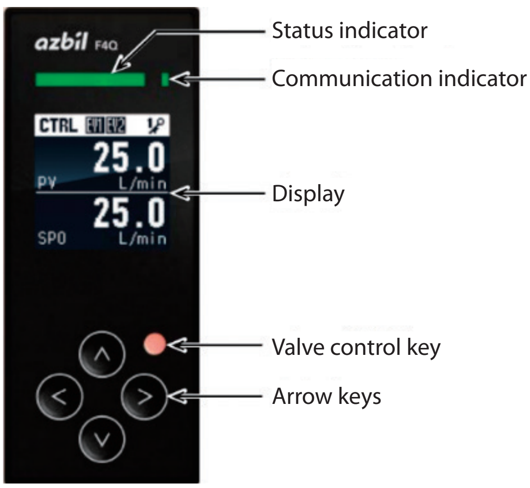


Fig. 6. UI of model F4Q

3.1 Operability

In order to improve operability, a full-dot LCD and buttons arranged in a diamond pattern are used in the UI.

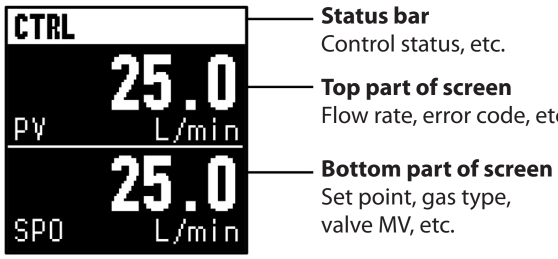
By using a full-dot LCD for the display, screen transitions have been significantly improved from those of the existing UI, radically improving the amount of information provided to the user. Examples of the content displayed by the LCD are shown in figure 7.

On the main screen during normal operation, the display area is divided into three sections: the status bar, top part of the screen, and bottom part of the screen.

The status bar displays information such as the status of control and of events. It is always displayed, so the user can see changes in device status even while changing the settings. This allows the user to check the status of control at a glance, which was not possible with the previous UI. If something abnormal happens and there is a change in the control status, the user can respond quickly.

The top and bottom part of the screen each show a number of parameters. The top part of the screen shows information such as flow rate and error codes. The bottom part of the screen shows set points, gas type setting, valve MV, etc. The bottom part of the screen can be set by the user, so any parameter can be checked there at the same time as the flow rate on the top part of the screen. Device operation can be adjusted to suit the user's application by, for example, displaying a parameter that is checked often to reduce man-hours, or displaying the valve MV or flow rate setting to make it easy for the user to notice pressure changes in the supply source or abnormalities such as foreign matter caught in the valve.

■ Main screen



■ Example of screen transitions

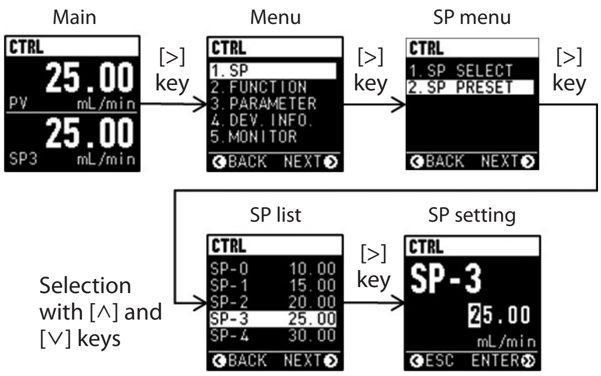


Fig. 7. Displayable content

For display areas other than the status bar, the user can use the arrow keys to change screens. As an example, figure 7 shows how the screen changes when set point 3 is being set. An operation guide for the keys is displayed at the bottom of the screen. It changes depending on the operation, making it easy for new users to change the settings.

As shown in figure 6, on the operation panel there are four arrow keys arranged in a diamond pattern and a valve control key, which is highlighted by a different color.

The arrow keys provide a UI that can be intuitively operated when making the aforementioned screen transitions.

The frequently used key for changing the valve operation mode (corresponding to the RUN key of previous products) is separate from the arrow keys and is made to stand out by its different color. Pressing this key opens the window shown in figure 8. The operation mode can be changed simply by selecting any desired mode.

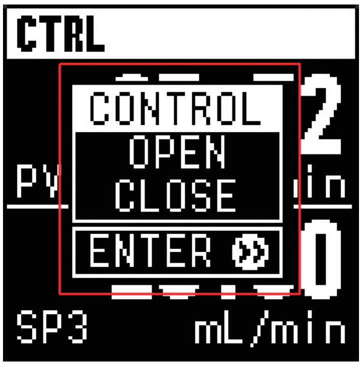


Fig. 8. Pop-up menu when valve control key is pressed

In previous products, the 7-segment LED and LED indicators required some learning before the device could be operated. The new UI clearly displays abundant information for the user and has significantly improved status tracking and operability in the field through the combination of a full-dot LCD and operation keys.

3.2 Visibility

The new UI provides high visibility regardless of the orientation of the pipe by having a large status indicator at the top, a full-dot LCD, and redesigned arrow keys.

The status indicator (fig. 6), which notifies the user of an abnormal status or other valve control status, is a large rectangle so that the user can see the state of the device even from a distance. As seen in table 2, the status indicator turns red if an abnormality that affects fluid control occurs, contributing to the early detection of problems.

The display can be rotated in 90° increments by changing the setting. Since the display is square, the same information can be shown regardless of the device's orientation, as shown in figure 9. The operation panel is designed so that values are assigned to the arrow keys according to the orientation of the screen. This makes it possible to offer high visibility and good operability also in vertical installations.

This UI takes into consideration separable models, the display unit of which can be installed in a control panel located at a distance from the mass flow controller main unit, and the changeable UI direction can improve flexibility in control panel design.

Table 2. Status indicator and communication indicator details

Name	Display details
Status indicator	• Off: Power OFF • Green: Normal (control) • Green, slow blink: Normal (fully closed or fully open) • Green, fast blink: Warning • Red, fast blink: Alarm • Red: Error • Orange: Fallback operation
Communication indicator	• Off: Communication standby • Green, blinking: Communicating

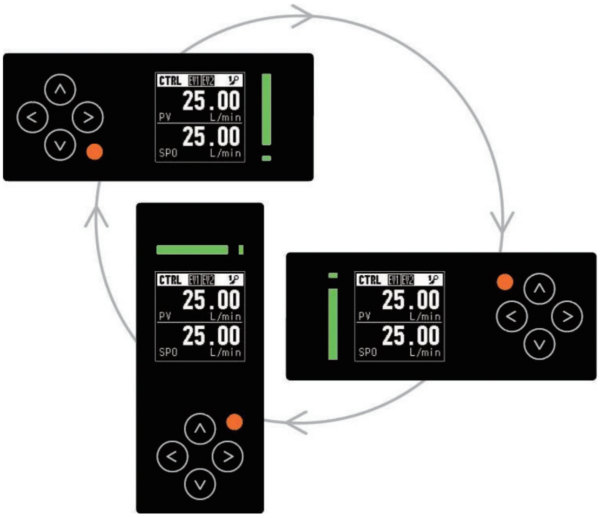


Fig. 9. UI orientation changes

In earlier products, indicator LEDs were used to signal an error, so there was a possibility that they could be overlooked at a distance. Also, to change the orientation of the display (if it could be changed at all), it was necessary to remove the UI unit from the main unit and rotate it, and the rotation was limited to 180°. For this reason, the display and operation panel were sideways if the unit was mounted on a vertical pipe, which impaired visibility and operability. With the new UI, device status can be checked from a distance on the large status indicator, and the display and operation panel can be rotated by 90° simply by changing the setting, ensuring high visibility at all times.

4. Functions that improve suitability for operating conditions

Flow controllers operate under many different conditions depending on the application and the industry. We have added and improved functions with the aim of developing a product that can contribute to stable quality by providing excellent control even for applications under different operating conditions. As examples of added or improved functions, in this section we will report on vertical installation compensation, user-set PID, and high-speed control.

4.1 Vertical installation compensation

We have implemented a device orientation and pressure compensation function to reduce the effect of vertical installation on control accuracy.

When the sensor is oriented vertically, the change in the density of the fluid that is heated by the heater results in the temperature distribution shown in figure 10. No natural convection occurs [4].

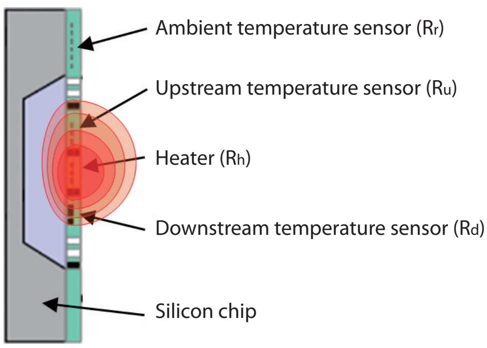


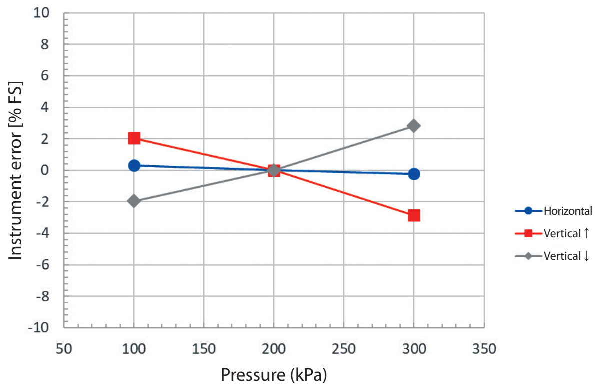
Fig. 10. Conceptual diagram of temperature distribution on vertical pipe

This causes a deviation in the temperature distribution in the vertical direction, which results in an output that is different from the output when the sensor is horizontal. This temperature distribution is affected by the density, so the effect changes according to the pressure conditions of the gas. In addition, since the effect also changes depending on the flow rate, it is necessary to adjust the flow rate by the function shown in formula (1).

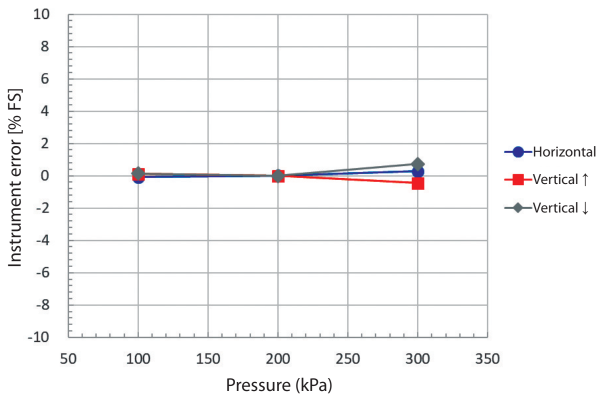
$$Q = Q_n \times f(v,p) \qquad \text{Formula (1)}$$

Where: Q= flow rate, Q_n= flow rate before correction, v= flow speed, p= pressure

We verified the amount of the effect by evaluating actual devices in order to arrive at formula (1). Figure 11 compares measurement results with and without compensation. The graphs show the results of evaluation at the 100 % FS point of the 5 L model. We confirmed that instrument error in the case of vertical installation has been significantly reduced, allowing additional installation orientations.



(a) Effect of pressure before correction (SP = 100 %)



(b) Effect of pressure after correction (SP = 100 %)

Fig. 11. Pressure characteristics before and after correction

4.2 User-set PID

Control that is suited to a wide variety of applications is enabled by allowing users to set the PID parameters.

In models MQV, F4H, and F4Q, users can choose standard PID parameters or parameters that prioritize either fast response or stability, so control can be improved according to the user's application. These PID parameter selections are tuned under three types of conditions determined by Azbil, but do not offer optimal control if the operating conditions (such as pressure, straight pipe length, or pipe diameter) are different or if the control results prioritized by the user are different.

Therefore, we have allowed the PID parameters to be modified by users in order to enable control according to the user application.

4.3 High-speed control

In order to further improve controllability, the interface-related processing and measurement and control–related processing are performed on different CPUs to make the control cycle faster.

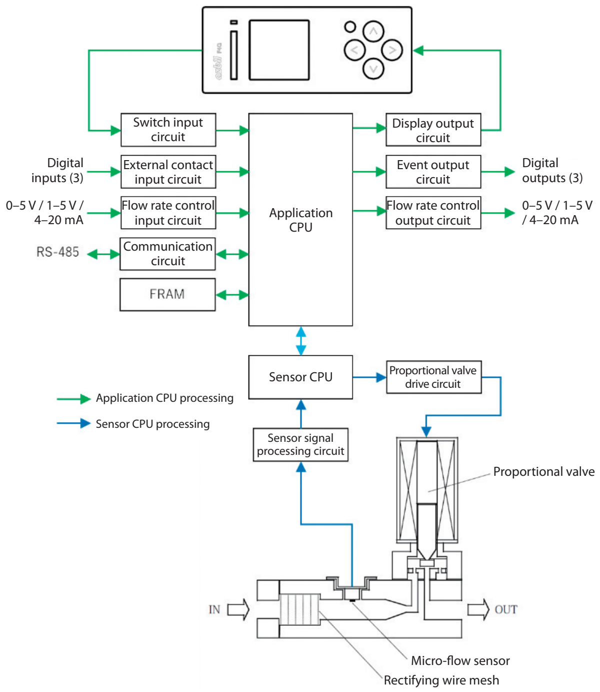


Fig. 12. Model F4Q system configuration

The control cycle was shortened to 1.5 ms from 5 ms, the cycle time of previous products, by configuring the system as shown in figure 12 and by using the sensor CPU solely for measurement and control, while other processing is done by the application CPU. Thus, we successfully increased the responsiveness of the micro-flow sensor.

To confirm controllability, we compared the pressure fluctuation characteristics of the newly developed product with an earlier product. Controllability was measured for flow control by the products shown in the evaluation system of figure 13.

The pressure fluctuation characteristics were obtained by recording the control results for the devices being evaluated when the primary pressure was changed during control. The control results obtained were the flow rate values output by the devices in the form of analog signals. The results are seen in figure 14. Compared to the response of the earlier model MQV0002, the response of the F4Q0002 has smaller peak values and shorter settling times.

These results indicate that shortening the control cycle has improved controllability. Therefore, the newly developed product can make a greater contribution to stable quality than earlier products, even in applications where pressure fluctuations occur or in systems where the flow rate is frequently changed.

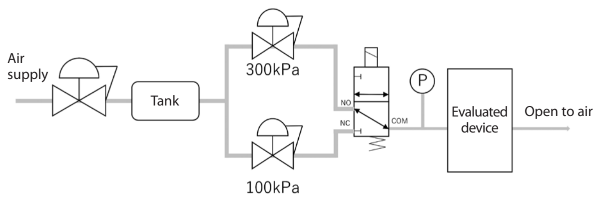


Fig. 13. System for evaluating pressure fluctuation characteristics

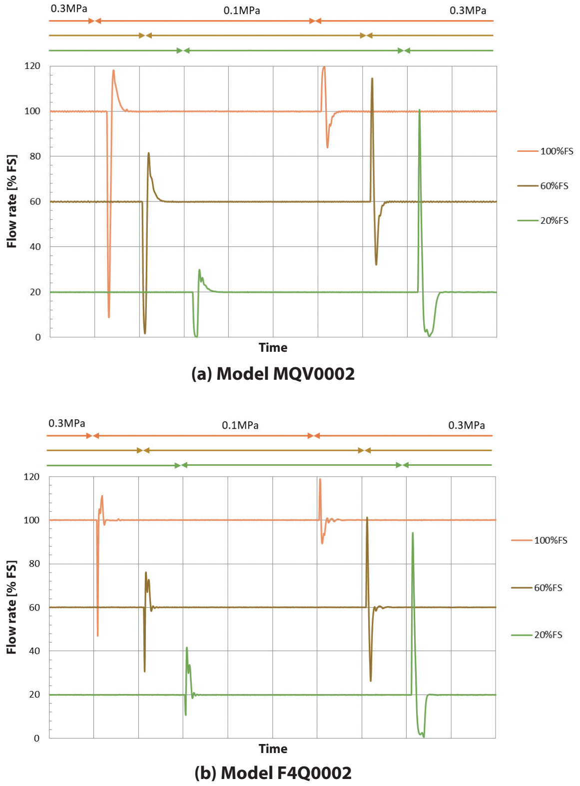


Fig. 14. Pressure fluctuation characteristics

5. Conclusion

In the development of this product, we were able to expand the operating conditions in a way that significantly improves operability and visibility and enables superior control through redesign of the UI and the addition and improvement of functions. We believe that this newly developed product will meet the increasing requirements of the market and contribute to stable operation and quality control at manufacturing sites.

The newly developed model F4Q was recognized for its design by receiving the iF Design Award 2022 and Good Design Award 2021. For the Good Design Award, the product was particularly recognized for the 90° rotation of the display and assignment of the arrow keys according to the rotation, which ensures high visibility at all times.

Through our development efforts, we have improved usability. In terms of the functionality of products to be developed in the future, we plan to provide support for tuning the PID parameters set by the user and higher control accuracy for gases other than air and nitrogen. We aim to apply the design of the product to other products to promote standardized operability of our flowmeter products for factory automation.

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