A small-diameter (DN150) venturi valve for constant air volume that provides safety and security in the coronavirus era

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Keywords
Room pressure control, airflow control, venturi valve, pressure independence, pandemic, countermeasures for infectious diseases, CFD, MATLAB®/Simulink®

Venturi valves for air volume and room pressure control are rated highly for their contribution to safety and comfort in chemical laboratories and medical facilities. The minimum diameter of our current product (Infilex™ VN) was DN200, but there was a need for further miniaturization and smaller airflow. Commercialization of a smaller product was long delayed due to technical difficulties in design. In the development of DN150 products, by revising materials for weight reduction, optimizing the design of sliding parts, etc., we have now achieved the same flow accuracy and pressure independence as current products.

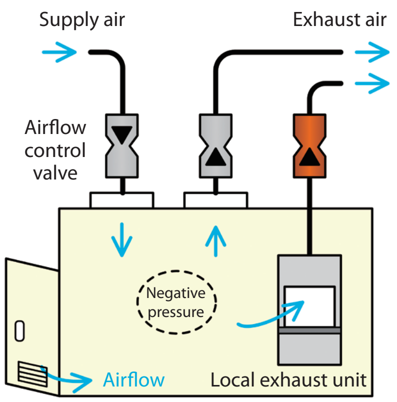
1. Introduction

The exhaust airflow from a local exhaust unit such as a fume hood or safety cabinet must be maintained. The same is true for the airflow direction between rooms and the air pressure within rooms (referred to as room pressure below) in chemical research facilities that handle hazardous chemicals or in biological research facilities that handle viruses and bacteria, in order to prevent contamination through the air. As a safety measure that can be implemented on the building/equipment level to prevent in-hospital transmission of disease, it has also become very important recently at hospitals to accurately control the supply or exhaust airflow in hospital rooms and wards to properly maintain the needed ventilation and room pressure to protect patients and staff from exposure to contaminated air.

Azbil has for a long time provided airflow control systems that achieve an indoor environment free of contamination between areas for organizations such as research facilities and hospitals. These systems use airflow control valves with high accuracy, high reliability, and high-speed response, the core product being venturi valves for air volume and room pressure control (Infilex VN series). This article describes the two main applications for an airflow control system that uses this product.

The first application is exhaust control for fume hoods or safety cabinets. It is used especially when hazardous substances are handled in a large-scale local exhaust system in a laboratory. The face velocity of a fume hood is legally defined as a safe performance indicator to protect workers from exposure to hazardous substances. Face velocity refers to the speed at which air passes through the opening of the fume hood. Although this velocity must be above a certain statutory speed in order to contain hazardous substances, if the velocity is too high, functionality decreases and energy consumption increases. Consequently, to ensure safety and energy efficiency, accurate control that maintains the appropriate airflow for the area of the opening is used. However, accurate airflow control has not been available for local exhaust units with low airflow that cover a smaller range on a desk (called arm hoods, flexible hoods, etc.) because they are not regulated and control products with suitable size and airflow were not available. This results in both poor usability and safety concerns.

The second application is the provision of accurate intake airflow and exhaust airflow in rooms where the room pressure must be maintained. At laboratories that handle hazardous chemicals, negative pressure is used to prevent chemicals from escaping outside of controlled areas. Alternatively, airflow is controlled so that rooms have a positive pressure in order to prevent hazardous chemicals from entering from outside. An example of the former is a laboratory where a local exhaust unit is installed (Fig. 1). An example of the latter is a hallway or office adjacent to the laboratory. Since the same principles apply in the case of pathogens like bacteria and viruses, the airflow control system is applied to prevent in-hospital infection, as mentioned above. An infectious disease room has negative pressure to prevent pathogens from escaping, whereas an operating room or intensive care unit has positive pressure to prevent pathogens from entering from outside. However, airflow control valves are often not installed in smaller spaces such as changing rooms, restrooms, or air locks due to limited installation space. This is problematic in terms of safety.



Exhaust volume is about 10 % larger than intake volume, creating negative pressure in the room.

Fig. 1. Example of airflow control in a chemical laboratory

To address these safety issues, we began developing a small-diameter airflow control valve. By significantly reducing the size and weight of the existing product while maintaining its high airflow accuracy and pressure-independence function, we have made it possible to apply airflow control in places that were often excluded from the use of this kind of valve. Below, we give some details about this valve. For reference, valves fall into the following two categories: constant air volume valves, which always allow a fixed volume of air to pass, and variable air volume valves, which automatically change the volume of air according to operating conditions. This product is a constant air volume valve, which is the prerequisite for the future commercialization of a variable air volume valve.

Fig. 2. A small-diameter (DN150) constant air volume venturi valve

2. Product overview

2.1 Features of the valve for air volume and room pressure control

The main feature of our venturi valves for air volume and room pressure control is the pressure-independence function. Generally, supply and exhaust ducts branch out like an ant nest. Airflow control devices like valves and dampers are installed along the way or at the ends, and are connected to a room or local exhaust unit. Because the whole system is connected through the ductwork, changes to the amount of air supply and exhaust, that is, the ventilation frequency, in each room and operations such as turning a local exhaust unit on or off affects the whole system. Therefore, in general, the pressure is constantly fluctuating inside the ducts, and the area of the airflow pathway must be adjusted according to the fluctuation in pressure so that the airflow control devices can accurately maintain the desired airflow. Pressure independence, then, refers to the accurate maintaining of the airflow without effects from the pressure fluctuations inside the duct.

Generally, the airflow that passes through airflow control devices is constantly measured and the mechanism that adjusts the flow path area is controlled using an electrical circuit to maintain the set airflow. However, this method requires a power supply, is not optimally responsive due to control that uses a fluctuating moving average of air speed, and has disadvantages such as concerns about component lifespan, failure of the adjustment mechanism, and the possible necessity for periodic sensor calibration or cleaning, depending on the method of airflow measurement.

In our venturi valve, whose shape enables it to reduce the airflow (Fig. 2), we installed a spring that lengthens and compresses according to the pressure. As a result, the structure of the venturi valve allows it to autonomously keep the passing airflow constant and provides considerable pressure independence without the need for a sensor to measure airflow or an electrical control mechanism. The movable part that surrounds the spring has an very simple structure and provides stable operation for a long time without the need for maintenance.

A differential pressure across the valve within a certain range is required for pressure independence to function properly. If the performance of the AHU or exhaust fan drops or stops for some reason and the correct airflow is not maintained, contamination with hazardous substances could occur in a worst-case scenario. Therefore, all of our valves have a sensor to detect insufficient differential pressure across the valve. The sensor can be connected not only to our system, but also to a third-party system for remote monitoring as needed.

Each valve is calibrated at the factory to the airflow specified in the order before it is shipped. This facilitates installation, since it is not necessary to adjust the airflow on the site. However, it may be necessary to change the supply or exhaust airflow later if there is a change such as the addition or removal of equipment or a change of operations. Therefore, the valves have a mechanism for onsite changing of the airflow setting. They also provide a method (an airflow feedback function) for properly adjusting the setting even in an environment without airflow calibration equipment.

2.2 Specifications of the small-diameter valve

The following table lists the main specifications of the small-diameter constant air volume valve that we developed.

Table 1. Main specifications

Item	Specifications
Size	DN150 (6-inch)
Total length of valve	420 mm
Weight	● 1.9 kg (slip-in model) ● 2.2 kg (flange model)
Flow range*	50–600 m^3/h
Airflow accuracy	±10 m^3/h (50–100 m^3/h) ±10 % rdg (100–600 m^3/h)
Differential pressure across valve**	150–750 Pa
Duct connection	● Slip-in model ● Flange model
Mounting position	● Horizontal ● Vertical (bottom-up airflow)
Anti-corrosive coating	● None (for room supply/exhaust) ● Coating for exhaust mainly of organic solvents ● Coating for exhaust of highly corrosive gas
Insulation to prevent condensation	● None (for exhaust) ● Provided (for supply)
Airflow feedback function	● Not provided ● Provided
Power	Not required

* Supported airflow range. The range can be specified in intervals of 5 m^3/h.
** When the valve is used within this range, pressure independence is guaranteed.

3. Product structure

3.1 Pressure-independent mechanism

This product has a flow path that is doughnut-shaped in cross-section, consisting of a cone and the valve body, as shown in figure 3. The cone is designed to instantaneously change position according to the balance between the force of the flow in the duct, which pushes the cone from right to left in the figure (received pressure), and the force of the nonlinear spring inside the cone (spring force), which pushes the cone back from left to right against that force.

In general, when the pressure increases on the inlet side of the valve, the differential pressure across the valve also increases, and as a result the airflow from the valve increases. However, when the cone of this product is pressed toward the downstream side as the differential pressure increases, the flow path area is reduced, as shown in figures 4 and 5. Therefore, the product can keep a constant airflow even if the differential pressure across the valve changes.

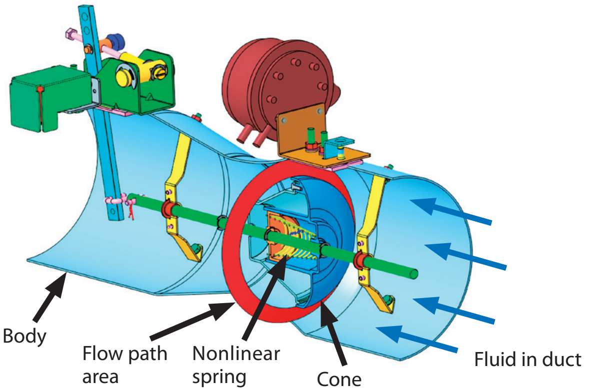


Fig. 3. Conceptual diagram of a pressure-independence mechanism

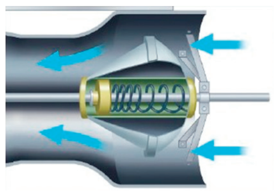


Fig. 4. Low differential pressure across a valve

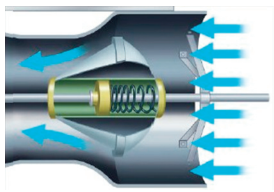


Fig. 5. High differential pressure across a valve

3.2 Airflow setting mechanism

The set airflow of this product can be specified in intervals of 5 m³/h by changing the position of the pivot arm shown in figure 6 in order to adjust the initial position of the cone connected to the shaft (i.e., the cone position when the differential pressure is 0 Pa).

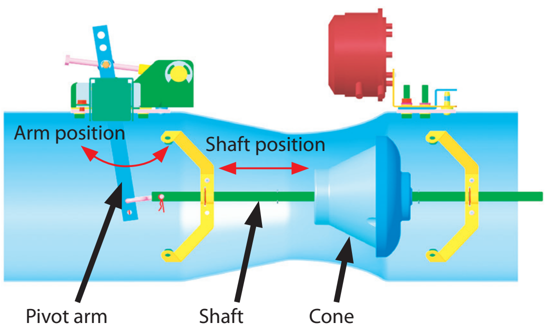


Fig. 6. Conceptual diagram of an airflow setting mechanism

4. Design of the pressure-independence function

The recent change to our product lineup was the addition of a small-diameter model. As the valve diameter gets smaller, the force received from the fluid (received pressure) decreases and the cone becomes more difficult to move, lowering responsiveness and airflow accuracy. To solve these problems, the biggest challenges were reducing the weight of the cone and making it slide more freely. Therefore, we prioritized the design of the cone and spring using the following motion equation.

$$m\ddot{x}+c\dot{x}+f_{spring}\mp\mu mg=f_{air}$$

m	:	Cone mass [kg]
x	:	Cone displacement [m]
c	:	Cone air damping coefficient [N/(m/s)]
f_{spring}	:	Spring force during cone displacement [N]
μ	:	Friction coefficient on the sliding surface [–]
g	:	Gravitational acceleration [m/s²]
f_{air}	:	Pressure received from the fluid [N]

We used general-purpose numerical analysis software applications, MATLAB® and Simulink®, to calculate the cone's position. A model of the forces applied to the cone, the configuration of the cone, and a Simulink® model are shown in figures 7 to 9.

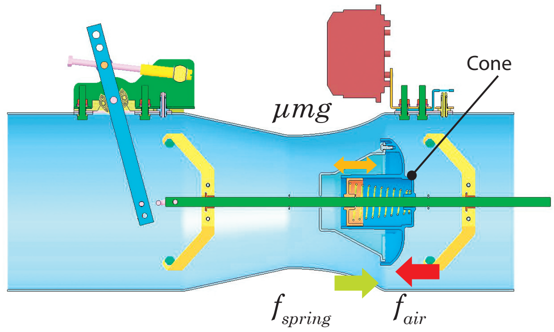


Fig. 7. Model diagram of forces on the cone

4.1 Cone weight reduction

The weight of the cone directly affects the sliding resistance, which determines the difference between the position of the cone when pressure increases and its position when the pressure decreases. This difference, in turn, affects the accuracy of the airflow. We therefore reduced the weight of the existing product by making the cone out of resin instead of aluminum.

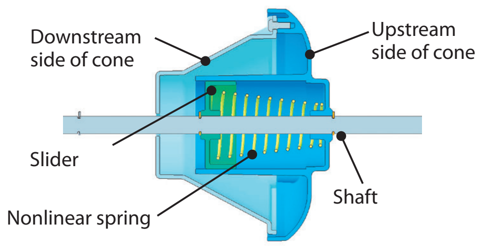


Fig. 8. Configuration of DN150 cone

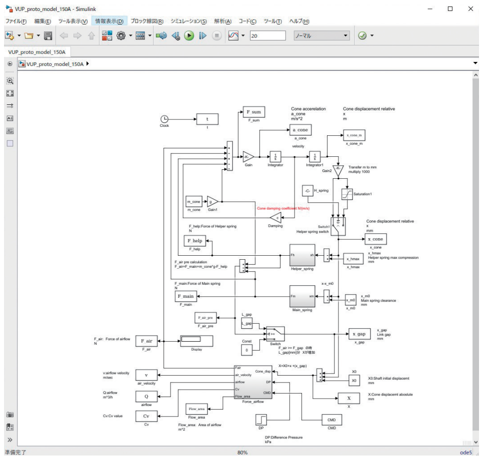


Fig. 9. Simulink® model for the cone

4.2 Air damper

An air damper is required for stable cone operation when the flow changes in the duct. If the force of the air damper is insufficient, the cone's movement will be unstable, resulting in a fluctuating airflow. The air damper operates when the volume of air upstream from the cone and the portion of air inside the slider that houses the spring changes. When the internal air volume decreases (when the spring is compressed), air flows out of the gap in the air damper section. If the air volume increases, air flows into the gap. This achieves the damping effect.

This product must have a high-speed response (1 second max.) to changes in differential pressure. Increasing the damping coefficient increases the stability in the event of flow disturbance but worsens the responsiveness to changes in differential pressure. In other words, the two are in a mutually exclusive relationship. Figure 10 shows the result of a responsiveness test (a step response test). In light of the above, we achieved high airflow accuracy by using the sliding property and nonlinear spring of the cone assembly (Fig. 17) and we achieved stability with respect to airflow and high-speed responsiveness by creating a proper air damper.

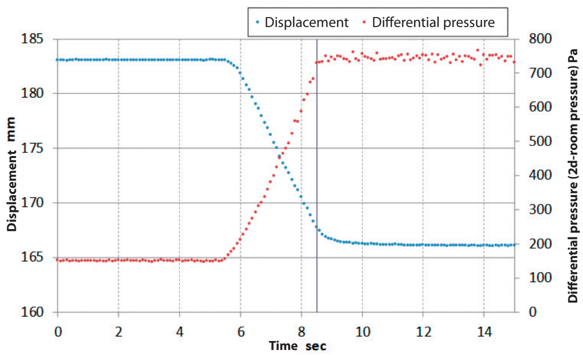


Fig. 10. Step response test result

5. Flow path design around the cone

5.1 Effect of the flow path shape

Figure 11 shows two proposed shapes. In figure 12, cross-section diagrams of their shapes inside the valve are superimposed. Since shape 1 is convex, the flow gently increases from the constriction toward the downstream side, as shown in figure 12. On the other hand, shape 2 has a thinner cone in the vertical direction, which causes the flow to sharply increase from the constriction. We conducted computational fluid dynamics (CFD) analysis and an airflow test to confirm the airflow accuracy of these two shapes. The details are described below.

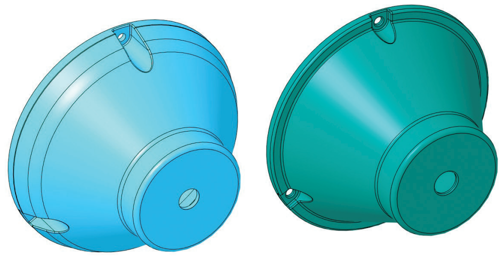


Fig. 11. Comparison of shape 1 (left) and shape 2 (right)

To create a more attractive product, the maximum airflow should be as large as possible (and the minimum airflow should be as small as possible). If the flow path after the constricted section gently expands, which results in a smooth flow, the airflow tends to be large.

In fact, we succeeded in increasing the maximum airflow while maintaining the area of the flow path constriction by adding a convex part as in shape 1. This is ideal because the minimum airflow remains small.

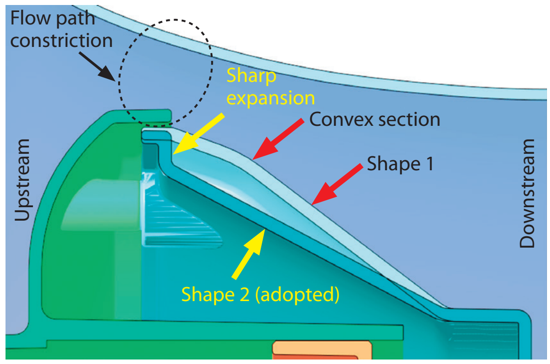


Fig. 12. Comparison of shape 1 and shape 2

However, shape 1 caused the two airflow characteristics shown in figure 13. No regularity was observed regarding which characteristic occurred and the difference in airflow reached 5 % or more, especially in areas with low differential pressure.

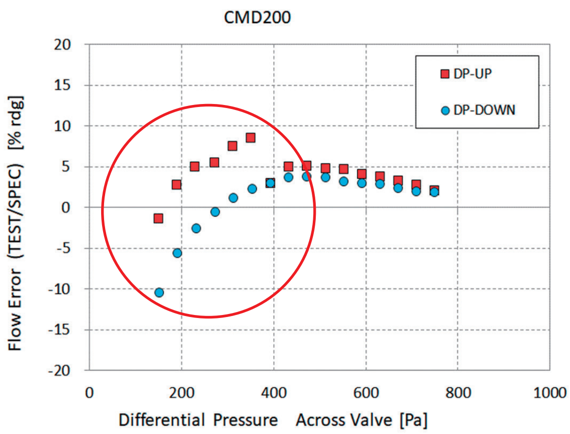


Fig. 13. Differential pressure across valve and airflow error (shape 1)

CMD200: valve airflow setting of 200 m^3/h

DP-UP: airflow measured after differential pressure was increased
DP-DOWN: airflow measured after differential pressure was reduced

Although the airflow differs greatly within the red circle in figure 13, it can be seen that the difference is not caused by a difference in differential pressure. However, whether the difference in flow path area caused this could not be determined. Therefore, for confirmation we created another plot using the valve flow coefficient

Cv,*1 which measures capacity and shows how easily fluid flows through the valve at a certain differential pressure, and also the flow path area,*2 as shown in figure 14.

Figure 14 shows that the difference in flow path area did not cause a large variation in the *Cv* value (here, *Cv* in unit area) in the red circle. This shows that neither the differential pressure nor the flow path area caused the large airflow variation.

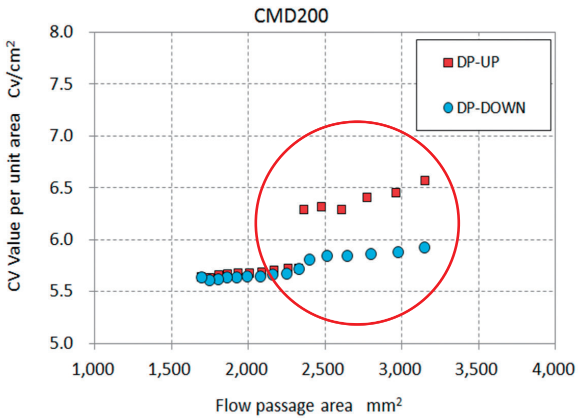


Fig. 14. Cv per unit area and flow path area (shape 1)

5.2 Analysis of flow instability

We conducted a nonstationary CFD analysis of shape 1. The flow along and behind the body in the area indicated by the dotted line in figure 15 was highly nonstationary and unstable. In addition, the flow rate was higher in some parts, but the position at which the flow rate was high constantly changed.

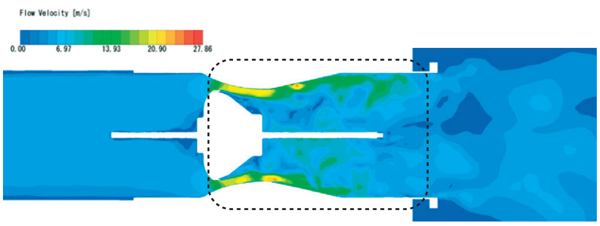


Fig. 15. Fluid contour diagram created from CFD analysis (shape 1)

Figure 16 is an enlarged view. The flow, which decreased because of the upstream side of the cone and the valve body, becomes a jet flow (indicated by red arrows) and passes through the flow path constriction (point A). After passing through the flow path constriction, the jet flow entrains the surrounding fluid and increases its mass. However, when the convex part of the downstream side of the cone obstructs the fluid flow, the Coandă effect occurs and drags the jet flow toward the wall. Then, the jet flow reaches the minimum constriction of the body (point B) without diffusing or decelerating. As a result, the entraining force of the fluid also increases at point B, the flow is drawn to the wall due to the Coandă effect, and it moves along the wall even after point B in some cases. The flow along the wall moves more smoothly than flow away from the wall because pressure loss due to detachment does not occur. This means that the airflow is higher along the wall.

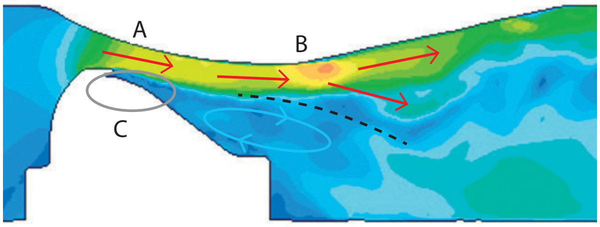


Fig. 16. Enlarged fluid contour diagram from CFD analysis (shape 1)

On the other hand, the flow near the cone (indicated by light blue arrows) moves away after the flow path constriction and causes a backflow on the downstream side. The boundary between the jet flow (indicated by red arrows) and the backflow (indicated by light blue arrows) is a discontinuous surface (indicated by the black dotted line). This discontinuous surface is unstable as vortices there break up and constantly fluctuate. As a result, the flow also becomes unstable at point B.

Thus, we concluded that flow instability due to the discontinuous surface around point B and downstream from it caused a flow along the wall due to the Coandă effect and a flow moving away from the wall, which creates instability with shape 1.

5.3 Characteristics of airflow with the adopted cone shape

Figure 17 shows the airflow characteristics of shape 2. With this shape, the flow does not become unstable as with shape 1, and repeatability was also good in the airflow test. We believe that this is because shape 2 sharply expands in size vertically from the flow path constriction and then becomes linear as shown in figure 12, reliably diffusing and decelerating the jet flow and ensuring that it moves away from the wall.

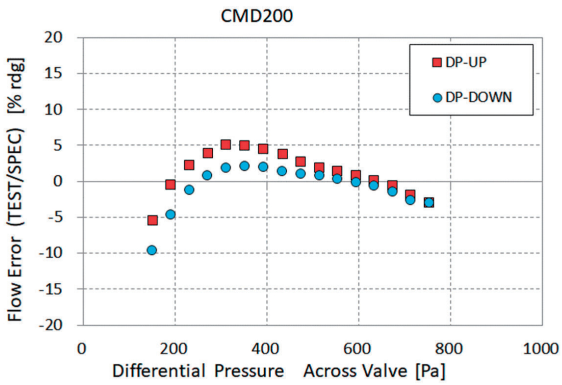


Fig. 17. Differential pressure across valve and airflow error (shape 2)

6. Future enhancements

We developed a constant air volume valve for operation with a predetermined airflow. To further enhance our product lineup we would also like in the near future to meet the need for a variable air volume valve whose airflow setting can be changed. To achieve this goal, we hope to solve challenges such as designing a control mechanism with a size suitable for small valves and minimizing the cost.

7. Conclusions

The novel coronavirus pandemic which has been ongoing since last year has brought about the need for modifications to buildings to prevent in-hospital infection, such as opening outpatient departments specialized for patients with a fever and the creation of

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*1. *Cv* is calculated from the airflow *Q* and differential pressure *ΔP* using the following equation. The flow coefficient generally depends on the flow path shape according to FCI 62-1. The *Cv* is larger with a shape that enables smoother flow.

$$Q = \text{a constant} \times Cv \times \sqrt{\Delta P \times (P_1+P_2)}$$

Q: airflow. *Cv*: valve flow coefficient. *ΔP*: differential pressure across the valve as calculated from upstream pressure P_1 and downstream pressure P_2.

2. The flow path area was calculated from the cone position measured with a laser displacement meter and 3D CAD data.

zones for possibly infected patients. Countermeasures for airborne infection have received an especially large amount of attention. To prevent airborne infection, it is necessary to have sufficient ventilation and a unidirectional airflow into rooms and wards where patients are accommodated to prevent contaminated air from escaping. Our company continues to offer hospitals a pandemic-ready airflow control system that uses airflow control valves, and we are strengthening this business in preparation for a future that may include the coronavirus and new epidemics. With the addition of this small, lightweight, high-performance product, we can offer safe spaces with room pressure control not only to medical institutions designated for infectious disease care, but also to small and medium-sized general hospitals. It is our hope that this will help to ensure the safety of health-care professionals and visitors, prevent the spread of infection, and make a significant contribution to society.

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