Technical Information

Introduction to Self-operated Regulators

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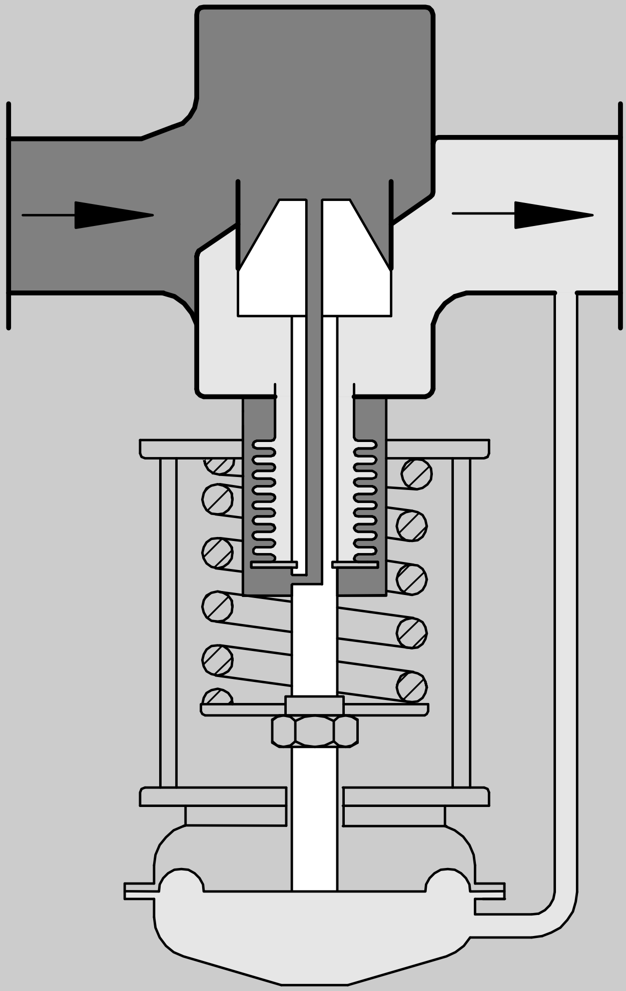

Part 2 Self-operated Regulators

Technical Information

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Part 3: Control Valves

Part 4: Communication

Part 5: Building Automation

Part 6: Process Automation

Should you have any further questions or suggestions, please do not hesitate to contact us:

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Introduction

The control of a process variable requires three basic functional units – the measuring equipment, the controller, and the final controlling equipment – as well as the knowledge of how to make proper use of the individual belonging elements. Usually, these control loop components are separate devices that must be supplied with auxiliary energy (Fig. 1; see also lit. [1] and [2]).

control with...

For simple pressure, flow, differential pressure, or temperature control tasks, such instrumentation is often too complex and, from an economic point of view, too expensive. For these applications, self-operated regulators can be used.

...or without auxiliary energy

Self-operated regulators take over all the tasks required in a control loop. They integrate measuring sensor, controller as well as control element all in one system (Fig. 2). The combination of these components results in very rugged and reasonably priced devices.

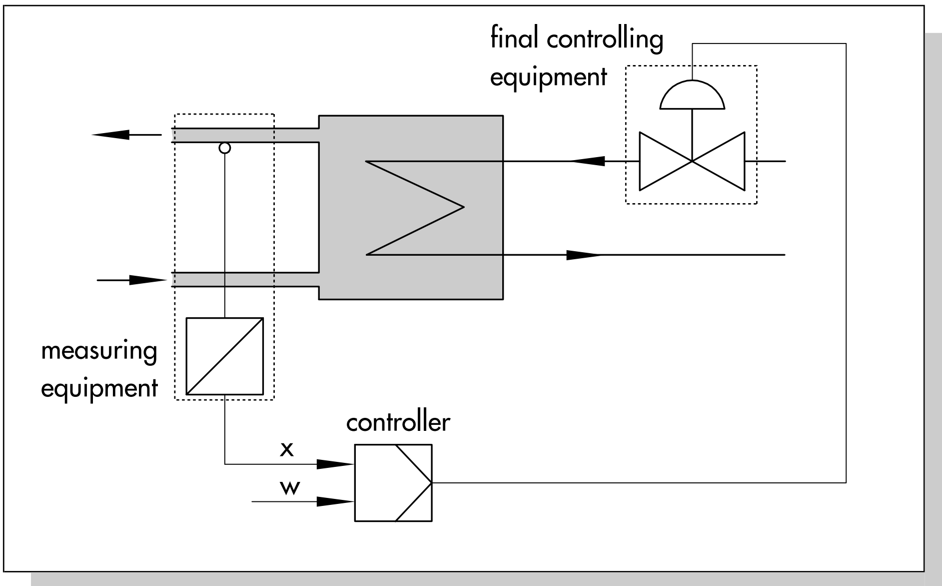


Fig. 1: Control loop with conventional instrumentation

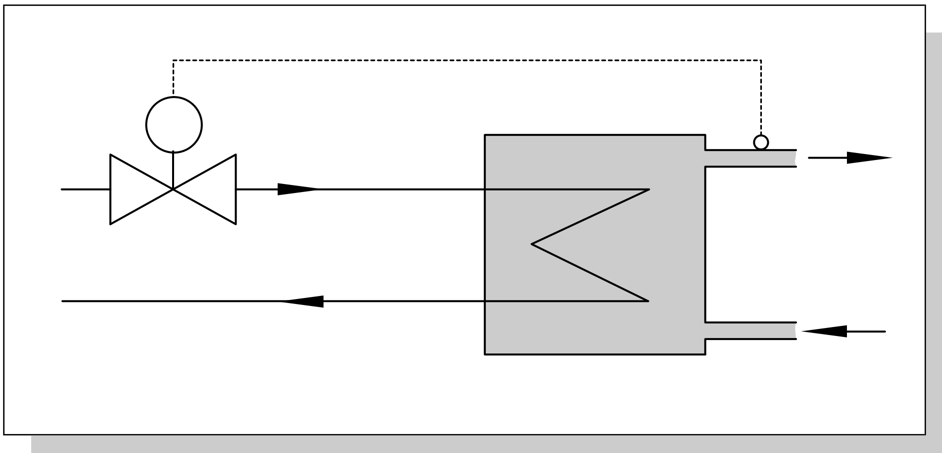


Fig. 2: Control loop with self-operated regulator

Since self-operated regulators – as the name indicates – do not require auxiliary energy from external supply sources, the cost of installation is significantly lower than for conventional instrumentation.

Fields of Application

Self-operated regulators are available for temperature, pressure, flow, and differential pressure control. They are suitable for all those applications where deviations of the controlled variable from the adjusted set point are acceptable and the set point remains constant over a long time – often during the entire useful life.

constant set point – fixed set point control

Self-operated regulators are especially suitable for applications that would otherwise require high investment due to the auxiliary energy supply system additionally required by other equipment. Therefore, self-operated regulators are frequently used in the wide-ranging networks of gas, water and heat suppliers.

easy to install

Since self-operated regulators are very reliable in fulfilling their switching and control functions, even or especially when the energy supply fails, they are ideally suited as safety equipment. Typetested devices designed according to the applicable regulations can be used in many fields of application and, at the same time, they have a good price/performance ratio compared to other solutions.

also suitable as safety equipment

Functional Principle

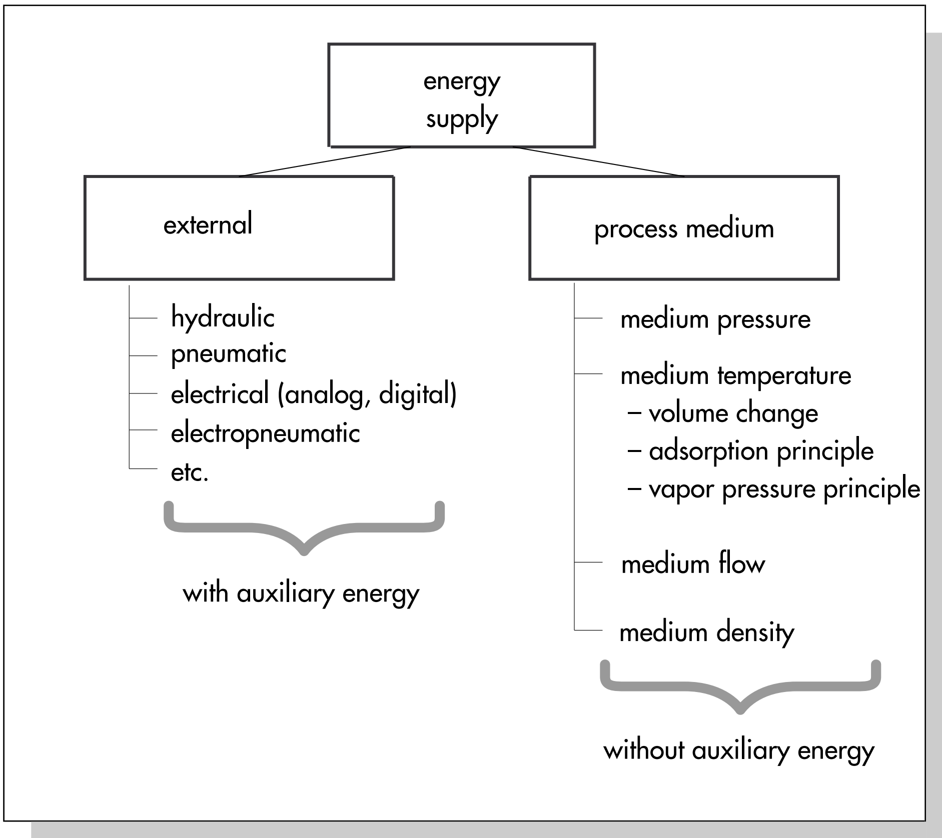


Fig. 3: Energy supply of control equipment

the medium supplies the energy

The performance of work requires energy. Self-operated regulators withdraw this energy from the medium to be controlled.

Using the medium pressure or the thermal properties of the medium (see Fig. 3), the sensor unit of the self-operated regulator builds up a pressure which creates the required positioning forces on an actuator diaphragm or a so-called operating element.

Example: pressure reducing valve

In the pressure regulator, the medium pressure p_2 acts directly or, if required, via equalizing tank on the rolling diaphragm of the actuator.

Proportional to the diaphragm area A_M, a force F_M is created which is opposed by the force of a spring F_F as well as the flow-related plug force F_K (Fig. 4):

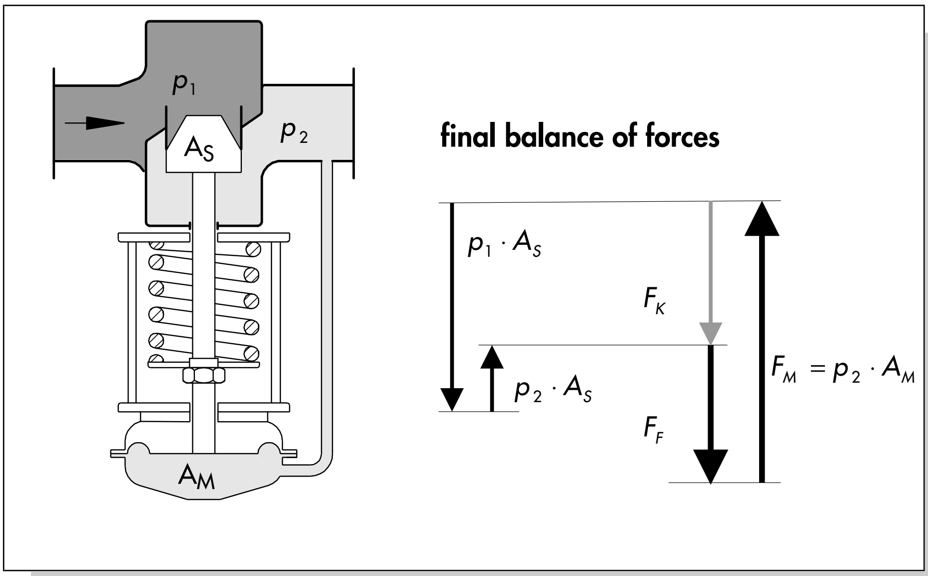
$$F_M = p_2 \cdot A_M = F_K + F_F$$

F_K is created due to the pressure difference $\Delta p = p_1 - p_2$ between the upstream and downstream pressure acting on the surface of the plug:

$$F_K = \Delta p \cdot A_S \qquad A_S\text{: seat area}$$

The spring creates reset forces in proportion to the spring range x and enables the adjustment of the set point or operating point through preloading:

$$F_F = c_F \cdot x \qquad c_F\text{: spring rate}$$



A_S: seat area
F_K: force acting on the plug
F_F: spring force
F_M: force acting on the diaphragm

Fig. 4: Balance of forces in a pressure reducing valve

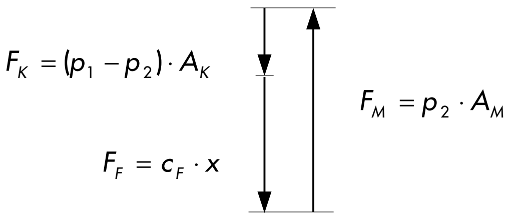
Assuming an initial state of equilibrium, as illustrated in Fig. 4, any change of pressure results in a changed balance of forces, thus causing adjustments of travel.

This can be clearly seen in the control cycle described in Fig. 5 (next page).

control cycle

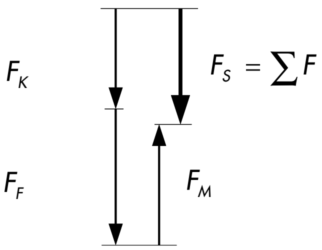
- If the operating point is in a state of equilibrium, the spring force F_F and the force F_K acting on the plug are compensated for by the diaphragm force F_M (phase 1).
- If the consumption increases, the pressure drop across the valve increases so that the downstream pressure p_2 decreases (phase 2).
- The spring opens the valve against the decreasing diaphragm pressure until a balance of forces is reached again with a wider open valve (phase 3).
- In the new valve position (phase 4), the spring force as well as the pressure p_2 to be controlled are reduced. A steady-state error (offset) remains with a value that depends on the proportional-action coefficient of the regulator.

1. Balance of forces in the operating point



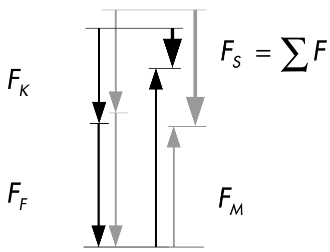
- Downstream pressure p_2 is constant
- Valve remains at steady state

2. Consumption increases (disturbance variable)



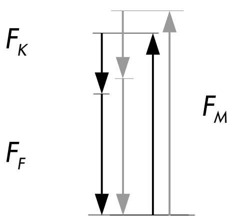
- Downstream pressure p_2 is falling
- Diaphragm force F_M is decreasing and F_K increasing
- Result: positioning force F_S
- Valve opens

3. Valve opens



- Spring is relieved: spring force F_F is decreasing
- p_2 rises: F_M is increasing while F_K is decreasing
- Result: F_S is decreasing
- Approximation of a new state of equilibrium

4. Equilibrium with changed valve position



Changes compared to phase 1:

- Higher flow rate: valve is open wider
- Spring is further relieved $\Rightarrow$ p_2 is lower than at the operating point
- Result: stead-state errror signal (offset)

Fig. 5 Control cycle in self-operated pressure reducing valves

Adjusting the operating point of a pressure reducing valve

parallel displacement of spring characteristic

The operating point of the regulator is adjusted via spring preloading. Fig. 6 shows the spring forces in travel positions T_{closed}, T_x and T_{open}, including the resultant spring characteristic. Preloading the spring causes a parallel displacement of the spring characteristic so that at travel position T_{open}, preloading $F_{PL} = F_{open}$ is already effective.

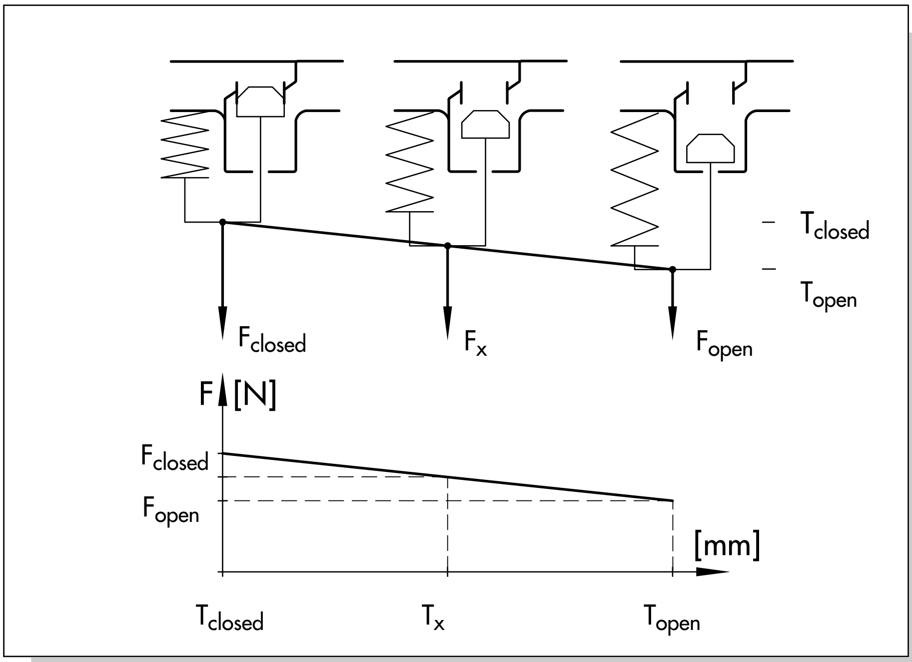


Fig. 6: Spring forces and characteristic

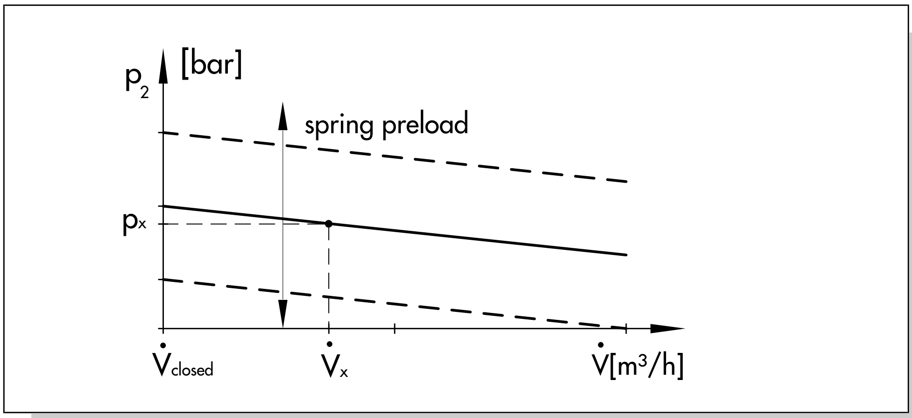


Fig. 7: Ideal characteristic of a pressure reducing valve

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While the operating point is adjusted, the spring preloading is increased until the process variable to be controlled reaches the required set point value. The spring force adjusted in this manner results from the balance of forces as illustrated in Fig. 4:

adjusting the operating point

$$F_F = F_M - F_K = c_F \cdot x = p_2 \cdot A_M - \Delta p \cdot A_S$$

With a small A_S seat area and low differential pressures, only small F_K plug forces are created. Under these conditions, the spring range x which is equivalent to the valve travel changes in proportion to the pressure p_2. The resultant manipulated reaction therefore directly depends on the spring characteristic (see also Fig. 7):

valve travel changes in proportion to the pressure

$$p_2 = \frac{c_F}{A_M} \cdot x = \frac{c_F}{A_M} \cdot \left(travel + x_{open}\right) = \frac{c_F}{A_M} \cdot travel + \frac{c_F}{A_M} \cdot x_{open}$$

X_{open}: preload

The equation as well as the control characteristic exhibit the proportional-action component of this self-operated regulator:

- The factor c_F/A_M represents the gradient of the characteristic or the proportional-action coefficient of the regulator.
- The second summand of the equation ($c_F \cdot x_{open}/A_M$) describes the parallel displacement of the characteristic. If high set points are to be adjusted, this term must increase. For this, either a version with a stiff spring (high c_F) and a small actuator area A_M must be chosen, or the spring must be of great length so that it can be sufficiently compressed (x_{open} will increase accordingly).

displacement of the characteristic into the operating point

As previously mentioned, these correlations are only applicable in cases where the plug force F_K can be neglected. If the seat diameter is large and/or the differential pressures are high, this method is only permissible when the valves are equipped with a so-called pressure balancing system. With self-operated regulators, such balancing systems are already suited alone due to the improved control behavior.

Pressure balance

differential pressure acts as disturbance variable

The plug force F_K depends on the differential pressure and, therefore, acts as a disturbance variable in the control loop. A high upstream pressure and large seat diameters create considerable plug forces which the actuator must overcome, as indicated in the following example:

$$\Delta p = 10\,bar;\;\; \text{seat}\,\varnothing = 125\,mm \qquad F_K = 12\,722\,N$$

By applying special structural measures, this disturbance variable can be almost entirely compensated for.

plug balanced by a bellows

Fig. 8 shows the version of a valve with a plug balanced by a bellows. The upstream and downstream pressures additionally act on the plug stem via

A_S: seat area
A_B: bellows area
F_F: spring forces (incl. bellows)
F_M: force acting on the diaphragm

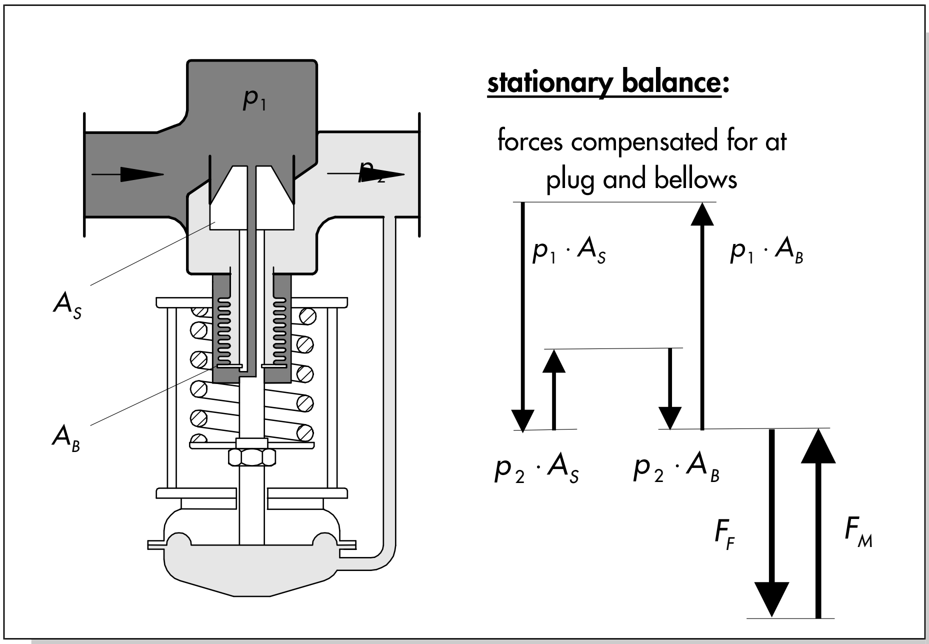

Fig. 8: Balance of forces in a pressure reducing valve with plug balanced by a bellows

the bellows area A_B, thus creating forces that oppose F_K. If the effective area sizes of A_S and A_B are identical, and if the cross-sectional area of the plug stem is neglected, F_K is compensated for by the forces acting on the bellows.

spring reset force

Pressure balanced valves require clearly smaller actuator forces than unbalanced valves (compare Figs. 4 and 8). When calculating the spring reset force F_F that must be overcome, the elasticity of the bellows must be additionally accounted for:

$$F_F = F_M = (c_F + c_{bellows}) \cdot travel + F_{open} \qquad F_{open}\text{: spring preloading}$$

Valves with balanced plugs are used for applications requiring that the control process be as accurate as possible. Balancing systems are always required when high differential pressures are created across the valve, especially with large nominal sizes, which then also necessitates high positioning forces. These cannot be issued by the actuator anymore without much bigger diaphragms.

Control Properties

Self-operated regulators are usually designed as proportional controllers. The control behavior of a P controller is essentially determined by the proportional-action coefficient (former term: proportional band) as well as by the adjusted operating point.

example of pressure reducing valve

To describe the correlations as application oriented and clear as possible, the following explanation is based on the example of the pressure reducing valve, as in the chapters above. With respect to control engineering, these statements are applicable to any other self-operated regulator with proportional control action.

proportional-action coefficient

The fundamentals of control engineering (see lit. [2], for instance) teach us that if steady-state errors are to be kept as small as possible, a proportional-action coefficient as high as possible (or a small proportional band) is required. In the vicinity of an operating point, K_P is calculated from the manipulated variable y and the error e:

$$K_P = \frac{y}{e}; \qquad \text{for pressure reducing valves: } K_P = \frac{\Delta K_v}{\Delta p_2}$$

In pressure reducing valves, it must therefore be achieved that small pressure changes create great travel adjustments which in turn create great K_v value changes:

- Large travel adjustments are created if the spring stiffness c_F is as small as possible and the actuator diaphragm area A_M is large.
- The change of the K_V value is related to the contour of the plug and the K_{VS} value. At the same travel, if the gradient of the control characteristic is high and/or the K_{VS} value is high, the K_V value changes are bigger than with a flat characteristic and/or small K_{VS} value.

If the valve is sized for a high proportional-action coefficient, i.e. small system deviation, the following equipment is required:

- soft spring, large actuator area, and high K_{VS} value, i.e. oversized in this case, or combinations of these. Proportional-action coefficients that are too high, especially in combination with an oversized K_{VS} value, increase the control loop's tendency to oscillate.

requirements for small system deviation

With respect to spring and actuator these requirements are best met by a self-operated regulator with the lowest set point range.

Example: For a set point of 1.0 bar, therefore, a set point range of 0.2 to 1.2 bar must be selected, and not the version ranging from 0.8 to 2.5 bar.

Note: As described on page 13, the following equipment is required to reach high set point values:

- stiff spring or small actuator area or long spring ranges and combinations of these.

requirements for high set point values

If the required device shall exhibit high set point values/positioning forces while system deviations are to remain small, contradictory requirements must be fulfilled in the sizing of spring and actuator area. There are only these solutions to this problem:

- Realization of small system deviations via high K_{VS} values.
- Compensation for high positioning forces via soft, though sufficiently long springs.
- Using large actuator areas.

small system deviation and high set point values

All possibilities are restricted in their application. While extremely long springs result in complex and expensive units with large dimensions, the use of an oversized K_{VS} value is restricted due to physical limitations: during positioning, the actuator must overcome the static and the sliding friction which is created along the guide and seal of the plug and actuator stem. If these frictional forces as well as the additional forces required to close the valve are taken into consideration, the result is the actual manipulated reaction as illustrated in Fig. 9, and not the ideal characteristic shown in Fig. 7.

X_w: system deviation

X_p: proportional band

X_h: hysteresis

X_S: closing pressure

p_2: downstream pressure

$\dot{V}$: flow rate

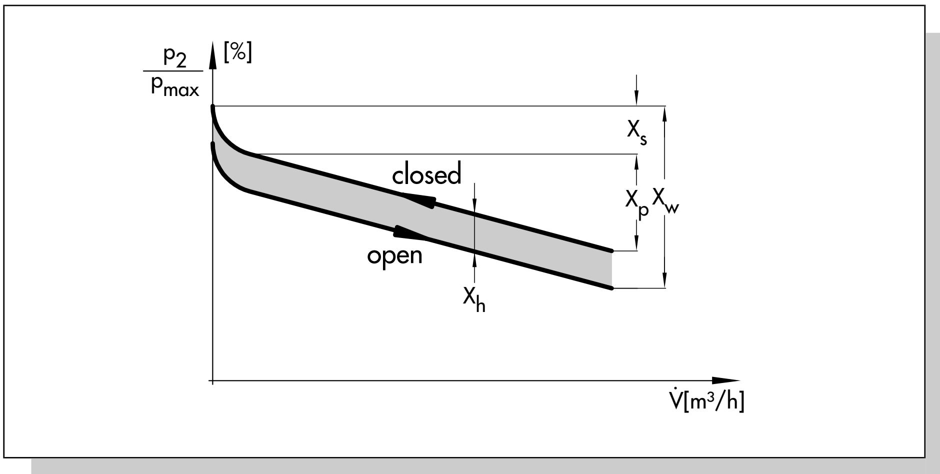

Fig. 9: Characteristic of a pressure reducing valve

hysteresis limits the control accuracy

The hysteresis X_h created by the static friction limits the control accuracy that can be reached. This error cannot be compensated for by using a higher K_{VS} value to increase K_P. Although this would reduce the stationary system deviation X_w, the hysteresis in the control characteristic will remain (Fig. 10).

Therefore, an oversized K_{VS} value involves the risk that the system begins to oscillate: on the one hand, the accurate adjustment of the K_v value will beco-

X_{w1}: system deviation with K_{P1}
X_{w2}: system deviation with K_{P2}

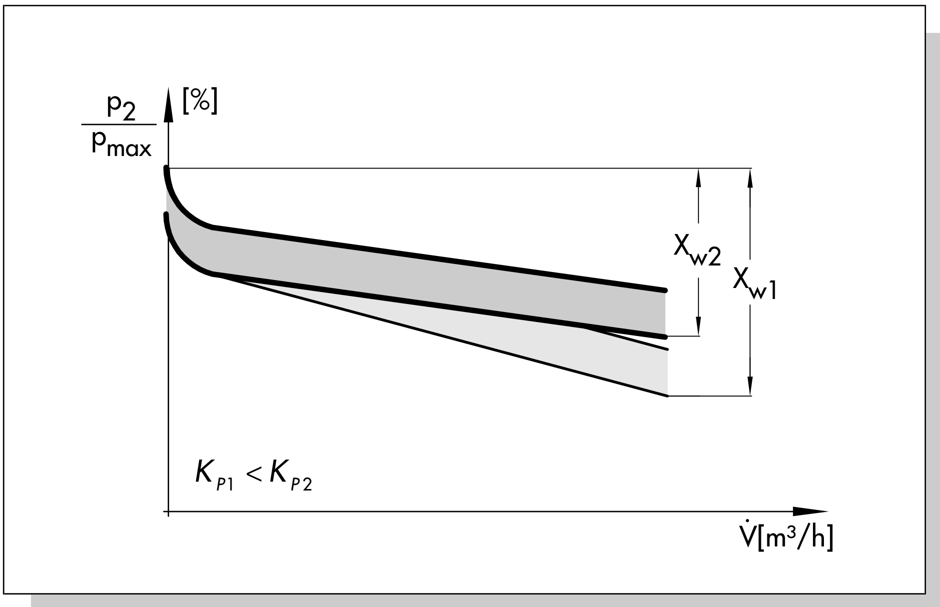

Fig. 10: System deviation with different proportional-action coefficients

me more difficult due to the hysteresis; on the other hand, already small system deviations will then result in extremely big K_V value changes.

reduction of positioning forces

Due to the described correlations and when control demands are high, it will always be desirable to reduce the effects of varying Δp values at the plug as much as possible, especially in the case of large nominal sizes, by using pressure balancing systems and, at the same time, selecting the version with the smallest set point range.

By following these sizing principles – balancing bellows, soft springs, large actuator diaphragm and, if required, high K_{VS} values – the system deviation in self-operated regulators can be kept to a minimum. However, proportional-action coefficients that are too high, especially when realized in combination with oversized K_{VS} values, involve the risk that the control loop starts to oscillate. The damping of the measured pressure signal through restrictions in the control lines to the diaphragm actuator also has its limits.

The described correlations clearly show that the system deviation in self-operated regulators strongly depends on the respective design. The system deviation in self-operated regulators can therefore be significantly reduced by the appropriate measures.

Appendix A1: Additional Literature

[1] Terminology and Symbols in Control Engineering
Technical Information L101 EN; SAMSON AG

[2] Controllers and Controlled Systems
Technical Information L102 EN; SAMSON AG

[3] Temperature Regulators
Technical Information L205 EN; SAMSON AG

[4] Regelungstechnik in der Versorgungstechnik
Verlag C.F. Müller GmbH, Karlsruhe

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NOTES

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