Technical Information

Temperature Regulators

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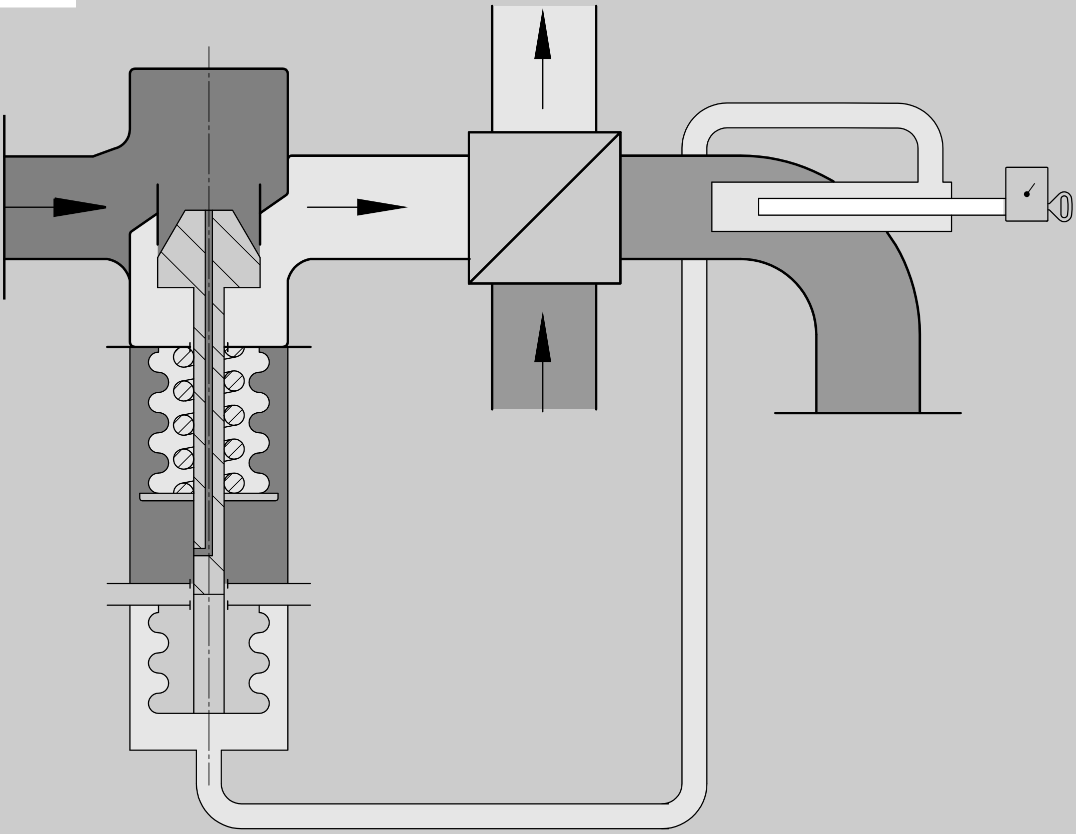

Part 2 Self-operated Regulators

Technical Information

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

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Temperature Regulators

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Temperature regulators

The characteristic feature of self-operated temperature regulators is their compact design, including a sensor, a valve and a capillary tube. Their simple operating principle is based on fundamental mechanical, physical and thermodynamic laws.

temperature control loop

A temperature control loop with a heat exchanger is shown in Fig. 1. When the water has left the heat exchanger and circulates in the domestic hot water loop, its temperature must be kept constant. In the heating loop, a heat transfer medium, e.g. hot water, circulates through the heat exchanger and transfers part of its heat to the domestic hot water loop. If we assume that the temperature of the hot water remains constant, the transferred heat quantity depends on the flow rate. The flow of hot water is adjusted by the self-operated regulator.

The sensor measures the temperature of the variable to be controlled and converts the measured value into a travel signal which is used as output variable. The sensor output signal is transmitted via the capillary tube to the valve where the signal changes the position of the plug as required. Temperature regulators obtain their actuating power from the medium to be controlled, so they do not need supply lines or auxiliary devices. This is the most important benefit of self-operated regulators. They keep costs low, while exhibiting high operational reliability.

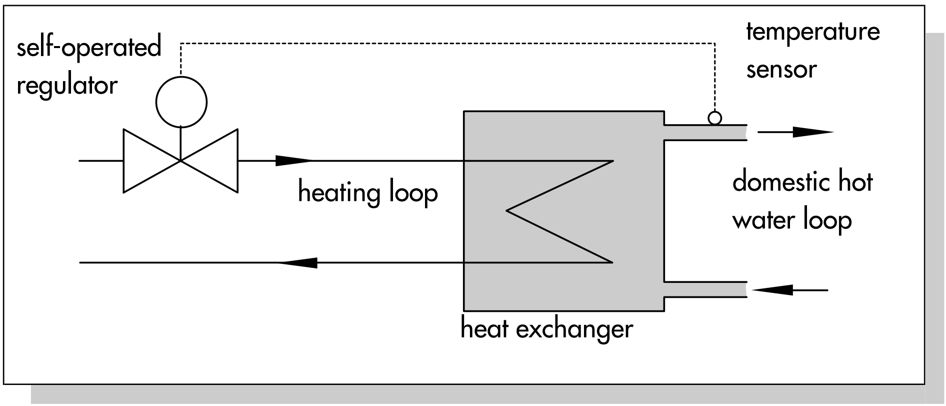

Fig. 1: Temperature control loop with heat exchanger

Sensors

measurement is based on three methods

Sensors are used to measure the temperature of the medium to be controlled. A good sensor must fulfill two important requirements. It must respond quickly to temperature changes and provide accurate values of variables that change over time. The self-operated regulator measures variables according to the three following principles:

- liquid expansion
- adsorption
- vapor pressure

These principles utilize the change in volume, in structure or the conversion of a matter's state of aggregation.

Liquid expansion principle

When measuring the expansion of a liquid, the quality of the results depends to a great extent on two factors: the sensor volume and the specific heat capacity of the filling medium.

1: sensor
2: operating element
3: cylinder

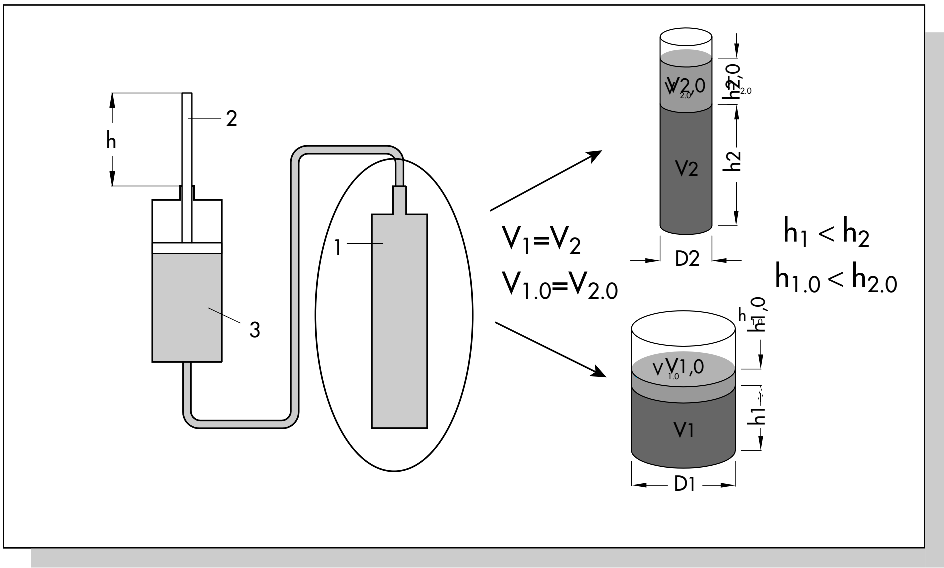

Fig. 2: Expansion of a liquid in a cylinder

- Sensor volume

Solids, gases and almost all liquids expand when the temperature increases. This physical principle of expansion is utilized by thermometers. An increase in temperature causes the liquid level in a capillary to rise and the height of the liquid column indicates the measured temperature.

expansion in the cylinder

A sensor operating on the liquid expansion principle is shown in Fig. 2. The liquid expands in the cylinder when the temperature rises. As the wall of the cylinder prevents lateral expansion, the liquid expands only in the axial direction, pushing the piston and the connected pin upward.

The increase in volume can be calculated as follows:

$$\boxed{\Delta V = V_0 \, \gamma \, \Delta T}$$

The expansion of the filling medium is determined by two factors - the specific coefficient of expansion γ which depends on the type of fluid used and the change in temperature ΔT.

expansion as a function of temperature

The height of the pin protruding from the cylinder is a measure for the expansion and represents a function of the temperature (h=f(T)). To achieve a particular travel of the pin Δh, the shape of the operating element must be considered and adapted as required. Generally, small sensor volumes yield larger travels than large volumes (Fig. 2). In instrumentation, small sensor volumes are preferred since the measuring span is better represented when the pin travel is large. In this way, more accurate measurement results are obtained. However, a disadvantage of small-volume sensors is the low power transmission. When sizing a sensor, a compromise must be found between the change in travel and temperature as well as the increase in force.

- Filling medium

small heat capacity for fast-responding sensors

To quickly obtain accurate measurements, the quantity of heat a sensor must absorb and release should be as low as possible. This can be achieved either by keeping the volume or the mass low, or by choosing a filling fluid with a low specific heat capacity. The quantity of heat stored in the fluid calculates as follows:

$$W = c_p \, m \, \Delta T$$

c_p is the specific heat capacity, m the mass and ΔT the change in temperature in °C. Note that the specific heat capacity is not constant, but changes with the temperature.

water not suitable as filling medium

Due to its high specific heat capacity, water is not suitable as filling medium. It has yet another disadvantage. With the exception of water, all liquids expand continuously with increasing temperatures and condense when the temperatures fall. Water, however, reaches its highest density at 4 °C and expands at higher as well as lower temperatures. Therefore, the temperature measured in these ranges would not be clear.

SAMSON temperature sensors use low-viscous, synthetic oil as filling medium. This liquid is harmless, i.e. it endangers neither health nor environment. It can be discharged with the waste water if leakage occurs (water danger class 0). Formerly used silicone oils were not accepted by the automotive industry since silicone oils cause wetting problems with water-based lacquer.

Apart from liquids, resins and elastomers can also be used as filling fluid. Expansion resins are particularly favorable when a great change in volume is to be achieved within a narrow temperature range.

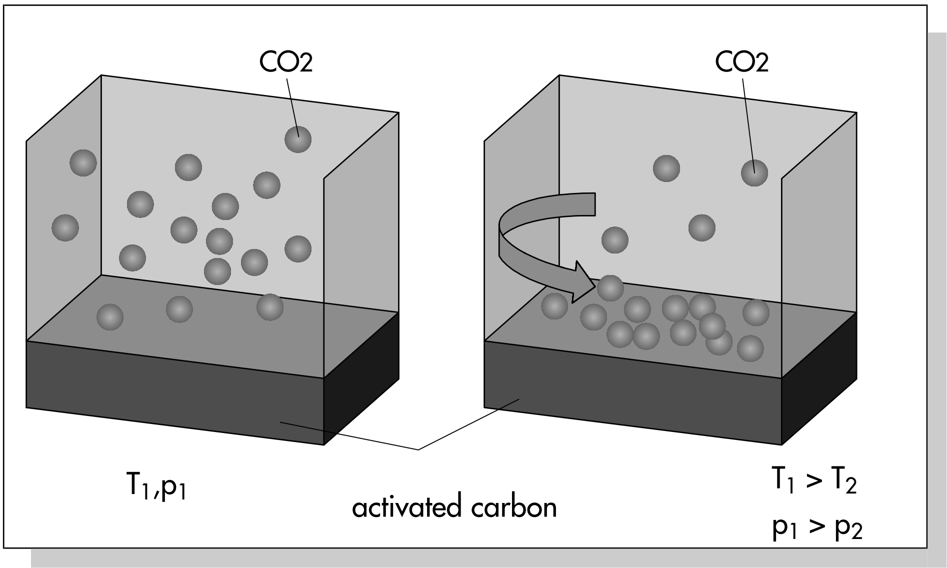

Fig. 3: CO_2 molecules depositing on activated carbon

Adsorption principle

The adsorption principle is based on a physical method. The temperature sensor contains activated carbon and carbon dioxide. When the sensor is heated by the medium to be measured, the activated carbon releases single CO_2 molecules. The pressure inside the sensor (Fig. 3) increases, representing a significant value for each temperature value. When the internal pressure is transmitted via a control line to the operating bellows, the valve position is changed with respect to the temperature.

activated carbon releases CO_2 molecules

The most important benefit of the adsorption principle is its good adaptation to the respective application. The measuring span of an adsorption sensor can be set in two ways:

flexible application...

- different types of activated carbon and gases yield different pressure-temperature curves;
- varied filling conditions yield different operating ranges. Four overlapping set point ranges are available, covering the range from 0 to 150 °C.

The disadvantage of adsorption sensors is that their thrust is much smaller than that developed by vapor-pressure or liquid-expansion sensors.

... but small thrust

Vapor pressure principle

The vapor pressure principle is based on a thermodynamic method. When a liquid is subjected to heat, it begins to boil at a certain temperature and steam is generated. The boiling temperature, however, depends on the prevailing pressure. The lower the pressure, the lower the temperature at which the liquid starts to boil.

Example: In an open vessel, water boils at 100 °C. The boiling temperature in a pressure cooker, however, is considerably higher because the pressure created in the airtight cooker is much higher.

sensor system utilizes steam pressure curve

The steam pressure curves of hydrocarbons are plotted in Fig. 4. When the temperature of the medium to be measured increases, the boiling pressure in the closed sensor system increases as well, following the rising steam curve. Depending on the measured temperature, a significant pressure is created in the sensor. The internal sensor pressure acts on a bellows in the thermostat, generating a thrust. The filling medium in sensors for self-operated regulators often is a mixture of hydrocarbon compounds (HC-compounds).

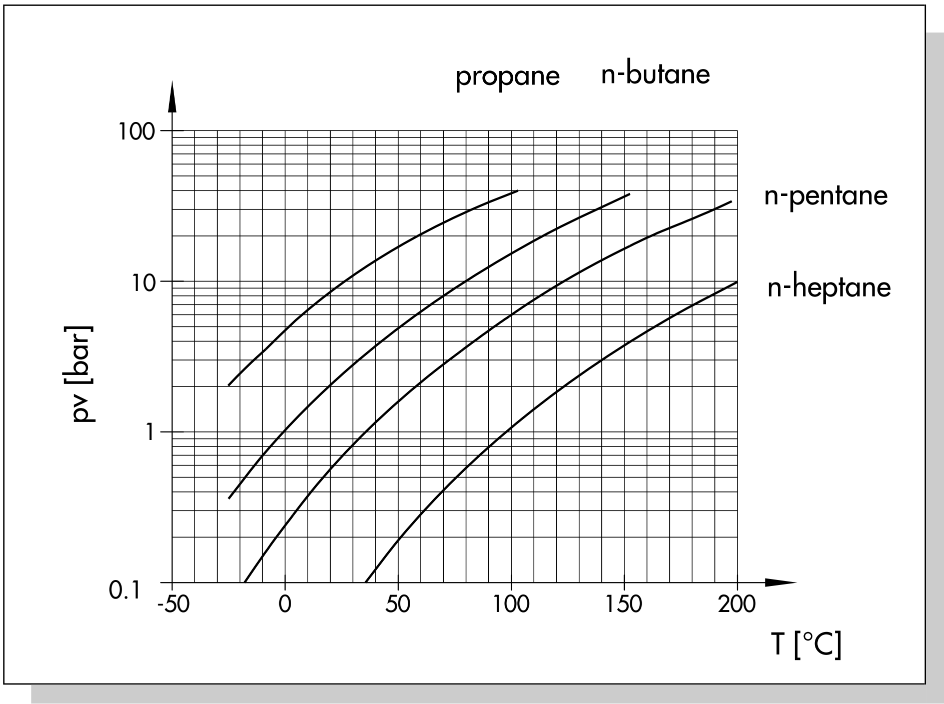

Fig. 4: Steam pressure curves of hydrocarbons

The maximum ambient temperature must be minimum 15 K lower than the set point to prevent the filling medium from vaporizing in the control line.

The basic properties of the different measurement methods are compared in the following table.

Sensor	**liquid expansion**	**solids expansion**	**vapor pressure**	**adsorption**
thrust	strong	strong	medium	weak
expansion behavior	linear	almost linear	not linear	linear
excess temp. safety	low	low	medium	high
mount. position	any	any	defined	any
time constant	medium	large	small	small

Table 1: Properties of different sensor systems

How the sensor design influences the dynamic behavior

Types of bulb sensors

Bulb sensors are in direct contact with the medium. The resulting heat exchange is characterized by the heat transfer coefficient.

sensors require large heat transfer surfaces

The heat transfer coefficients of liquids are remarkably higher than those of gases. Temperature changes of a liquid act therefore faster on the sensor case, the filling medium and finally the valve position. When sizing the temperature sensor, the surface provided for heat transfer must be as large as possible. While the cylindrical surface of a bulb sensor is sufficient for measuring water and other liquids, gases require a specially manufactured four-bulb sensor. In this sensor, the ratio between the sensor surface and the volume of the filling medium is larger than that of the bulb sensor.

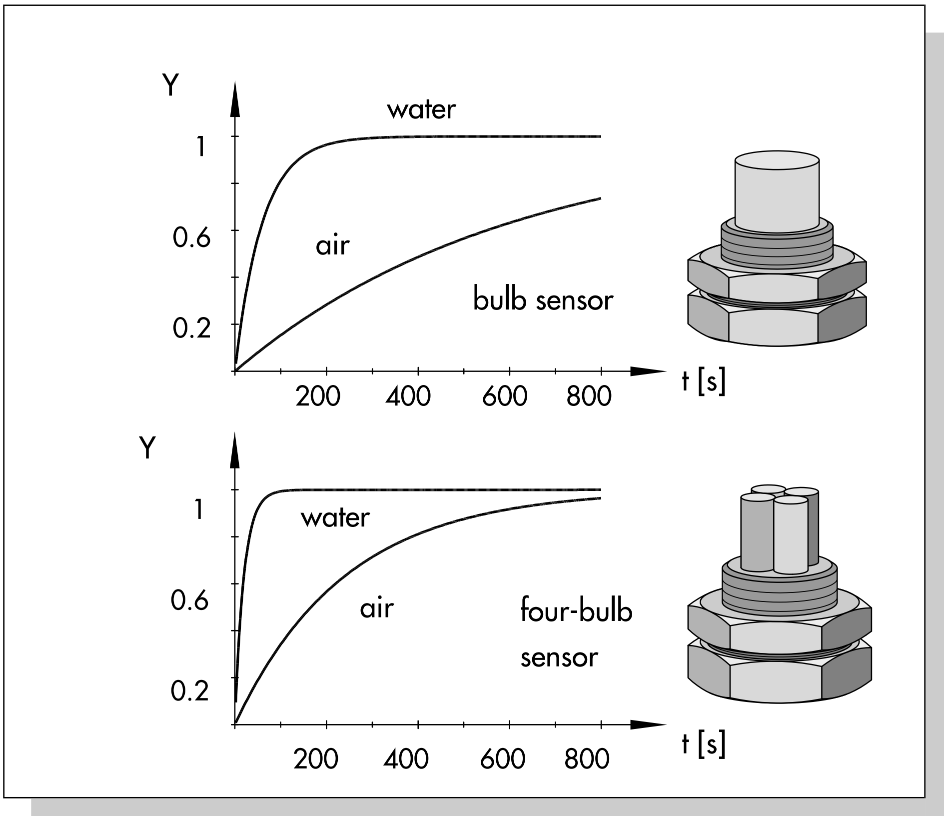

Fig. 5: Unit step response of a bulb sensor and a four-bulb sensor

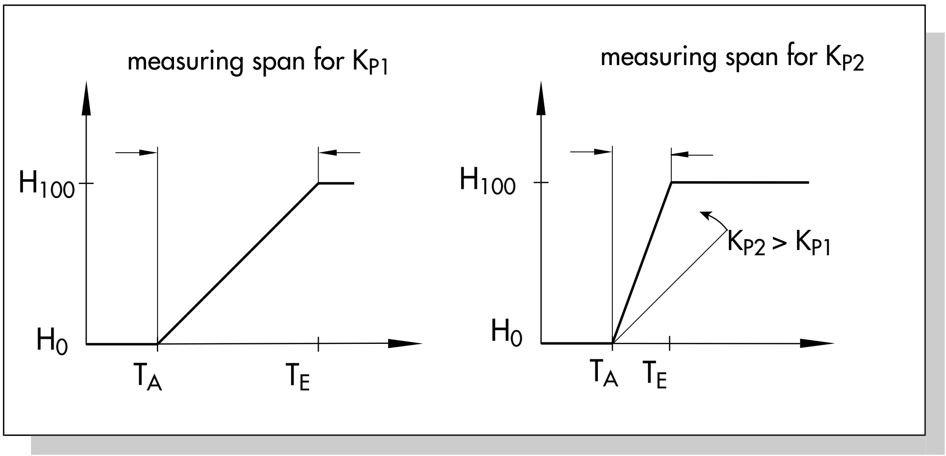

Fig. 1: Effect of K_P on measuring span

Fig. 5 compares the unit step response of a bulb sensor with that of a four-bulb sensor after they have been immersed into warm circulating water and into an air duct. The temperature difference is so big that the pin passes through its entire travel. Particularly in the air duct, the larger sensor volume proves favorable. The pin of the four-bulb sensor almost reaches its final travel after twelve minutes, while the bulb sensor takes 40 minutes, which is too slow for fast control loops.

Set point adjustment

control action of self-operated regulators

Self-operated regulators usually exhibit proportional control action (P regulators). In the case of self-operated temperature regulators, the P action causes the valve travel to change proportionally with the measured temperature T. The proportional-action coefficient is K_P (formerly: proportional band x_P; $x_P = 100\%/K_P$). The following equation describes the control action of temperature regulators.

$$\Delta h = K_P * \Delta T$$

large travel at small ΔT

As described in the Control Engineering Fundamentals (see also Lit [2]), P regulators have a steady-state error. When the steady-state error is to be kept small, a large proportional-action coefficient is required (small proportional band). This means for the temperature regulator that a large travel must be achieved at a small ΔT. The measuring span of the sensor becomes accordingly smaller (Fig. 6).

universal application requires set point adjuster

However, narrow measuring spans are an obstacle to the universal application of sensors. Therefore, the temperature regulator in Fig. 7 is equipped with a set point adjuster. In the sensor, an externally adjustable piston can be moved to change the volume of the system. When the piston is pushed into the right cylinder, the pin in the operating element is lifted, providing the required volume. As a result of the changed pin position, the travel position of the valve is changed, too.

Excess temperature

sensor protected against excess temperature

When the temperature reaches the upper limit of the set point range, the pin is fully extended. The valve is in its end position and the liquid fills the sensor completely. When the temperature rises above this value, the liquid in the sensor cannot expand further. If no equalizing volume is provided, the rising

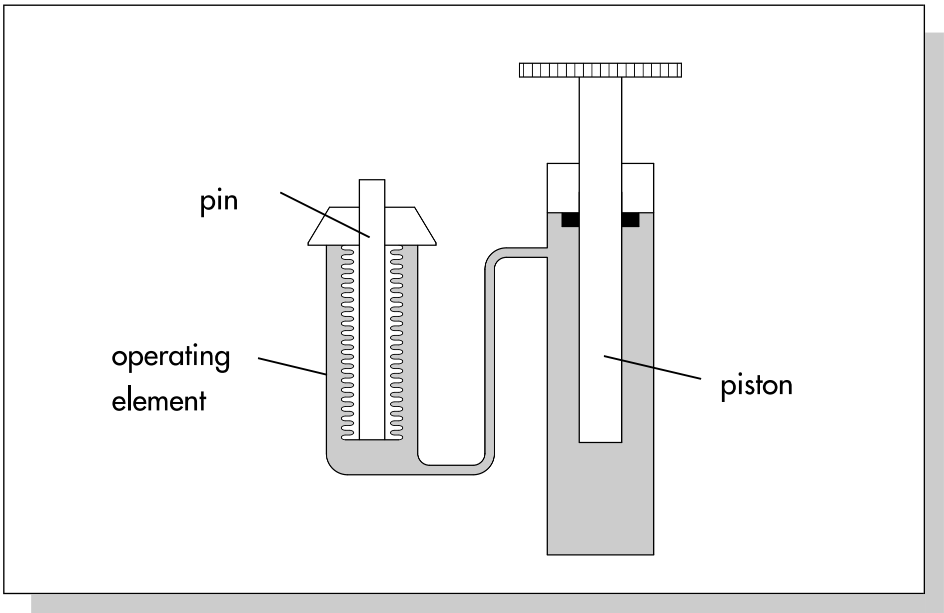

Fig. 7: Set point adjustment at temperature sensor

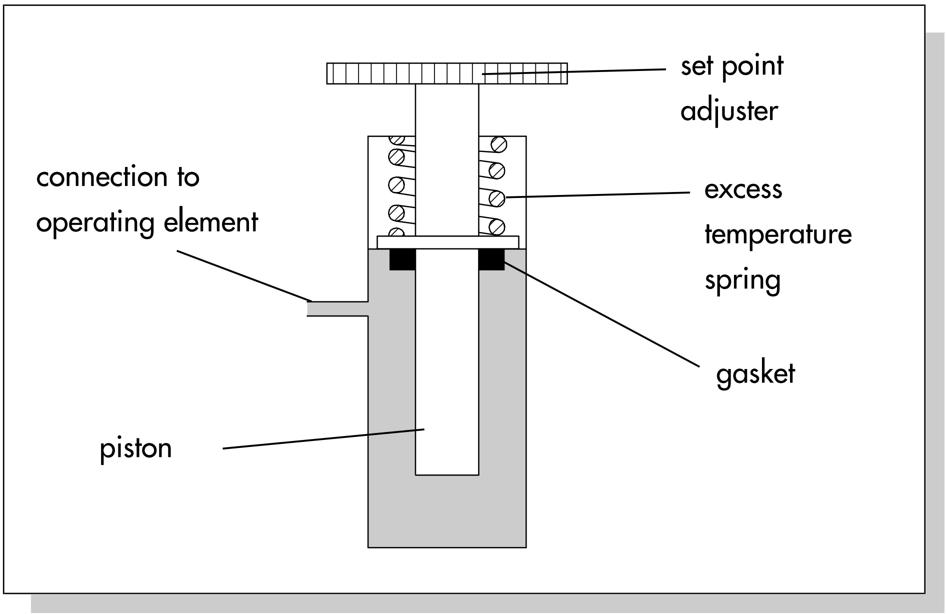

Fig. 8: Pressure relief fitting at sensor

internal pressure will damage the sensor. To prevent this, a pressure relief fitting is installed (Fig. 8).

When excess temperatures occur, the rising filling pressure acts on the piston bottom and pushes the piston out of the sensor against the force of the excess temperature spring. This increases the sensor volume. The excess temperature spring has no effect on the set point adjustment.

Mounting position

wrong position affects measurement results

A prerequisite for the proper functioning of temperature control systems is the optimum location of the sensor. It should be totally immersed in the medium to be measured. Fig. 9 illustrates various mounting positions. If the sensor is mounted perpendicular to the flow direction (Fig.9 d), the sensor surface is in contact with the medium only shortly. In this case, the absorbed heat quantity can be too small to yield accurate measurement results.

dead times must be avoided

Another important requirement is that the sensor measure nearly without dead time. Dead times occur, for example, in a heating system when the sensor is not located directly at the heat source, e.g. the heat exchanger, but far away in the heating pipe. In this case, temperature changes are measured with delay.

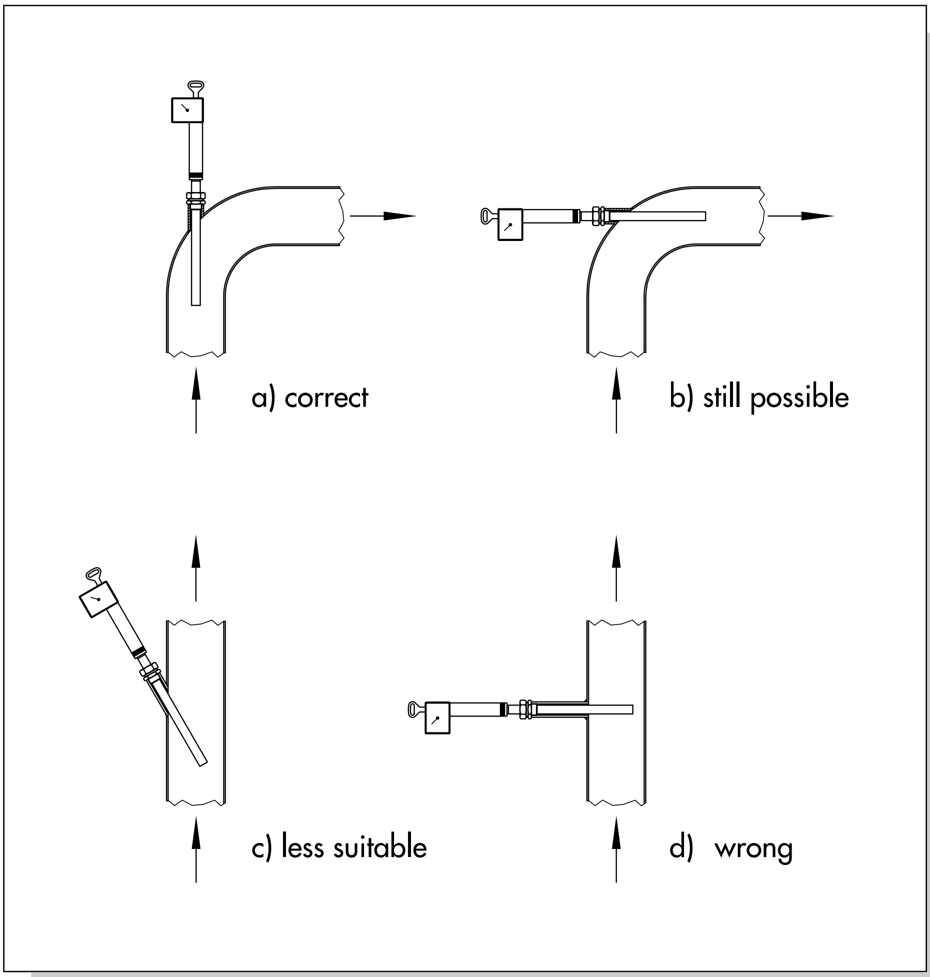

Fig. 9: Sensor locations

Dynamic behavior of sensors

The dynamic behavior of a self-operated regulator depends on the dynamic behavior of its sensor. The dynamic behavior is characterized by the time constant τ. The constant describes the time the pin needs to reach approximately 63 percent of the new operating point when forced by a step change in temperature.

sensor and thermowell both exhibit PT$_1$ action

When looking at the sensor from the viewpoint of control engineering, the sensor can be regarded as energy store. Its dynamic behavior can be described by means of an exponential function using the time constant $T_1 = \tau$ (first-order delay). When mounting a thermowell, another energy store is added to the system. Hence, a second-order system is created. To describe

sensors:

A: vapor pressure

B: adsorption

C: liquid expansion

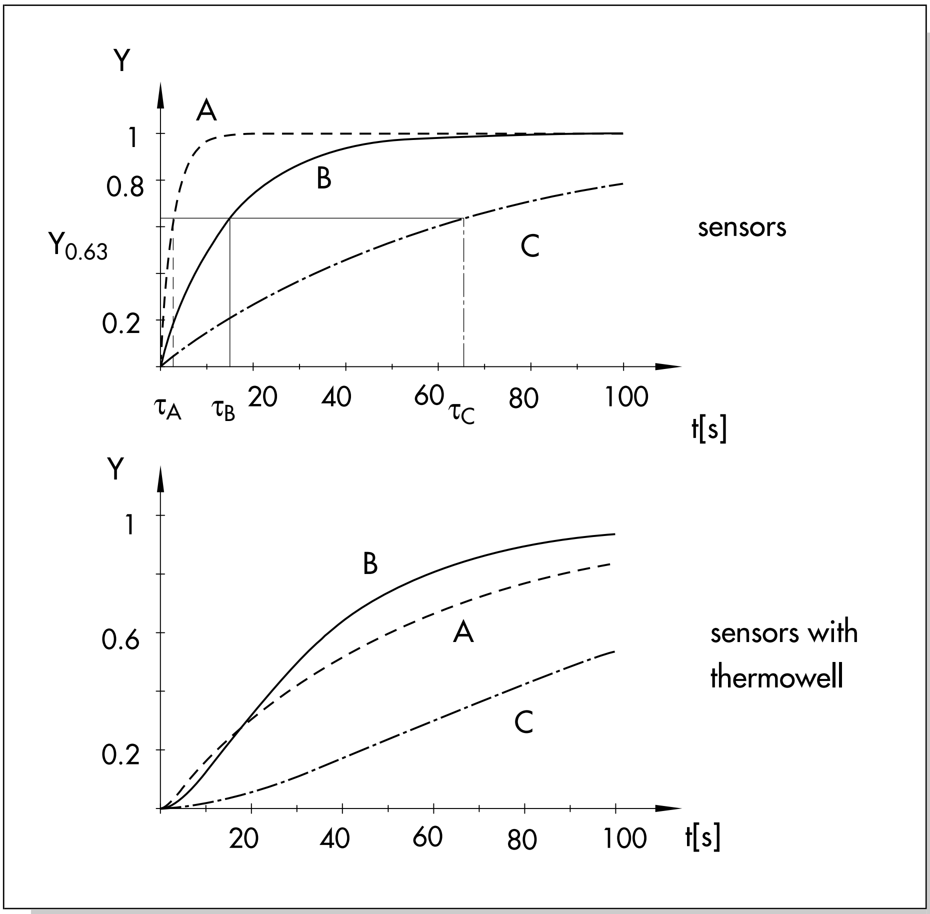

Fig. 10: Unit step responses of sensors

such a system, the time constant T_u and the build-up time T_g can be used. For further details, please refer to the Technical Information L102 EN.

As can be seen in Fig. 10, small time constants are typical to fast-responding sensors.

thermowells prolong the response time

Table 2 lists the time constants of the different SAMSON sensors. Measurements have been made in water. You can see from the table below that a thermowell used with an adsorption and a vapor pressure sensor causes long delays. So the fast response times inherent to those sensors are practically eliminated and they are almost as "slow" as liquid-expansion sensors.

Principle	type	without thermowell			with thermowell		
liquid expansion	2213	70			120		
	2231	70			120		
	2232	65			110		
	2233	25					
	2234	15					
	2235	10					
adsorption	2430	15	30		40	80	
	2212				40		
	2430-L			8			
	2439				40		
vapor pressure	2430-3	3		3	55		
	2403				40		
sensor diameters	d=	9.5	16	div.	9.5	16	div.

Table 2: Effect of thermowell on time constant

sensor material: bronze and copper

Standard materials for sensors and thermowells are usually copper or bronze because of their excellent conductivity. For aggressive media, stainless steel versions are used which, however, increase the time constants of the sensors by approximately ten percent. With thermowells, stainless steel does not affect the time constant.

Thermowells are not suited to be used with sensors for air. Due to the special sensor shape, a narrow air gap is formed between the thermowell and the sensor, which has an insulating effect. The time constant of an air sensor with thermowell would be much higher than that of a standard sensor with thermowell.

NOTE: You may find technical literature where variables, such as $T_{0.5}$ (half-value period) or $T_{0.9}$ (90% value) are used to describe the dynamic behavior of sensors. These values can be calculated for first-order systems using the equation below and the time constant τ:

$$y = (1 - e^{\frac{\tau}{T}})$$

$$T_{0.5} = 0.7\,\tau$$

$$T_{0.9} = 2.3\,\tau$$

Valves and their applications

Force-balancing

The signal pressure of self-operated regulators is generated by the expansion of the filling medium in the operating element. To make the interaction of the different forces understandable, a valve balanced by a bellows is described in the following example (see also Lit [3]).

spring and actuating force are balanced in a state of equilibrium

The upstream pressure p_1 and the downstram pressure p_2 acting on the valve plug are balanced by the bellows. As a result, the actuating force F_A is opposed only by the pre-loaded spring F_F (Fig. 11). Both forces are balanced in a state of equilibrium.

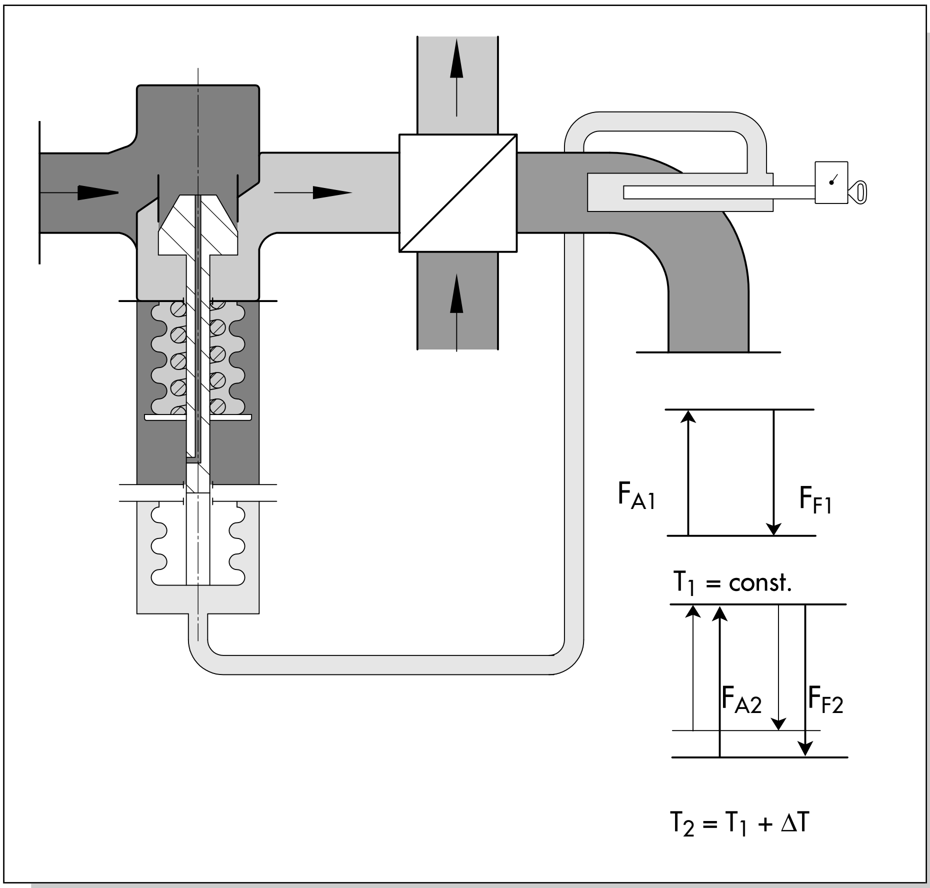

Fig. 11: Force balance after increase in temperature

The self-operated regulator is used to reduce or increase the flow rate when the temperature at the measuring point rises or falls.

The temperature is regulated as follows:

- When the medium is heated, the filling liquid in the operating element expands and exerts the actuating force F_A on the valve.
- The valve closes against the spring force F_F, reducing the flow of the heating medium.
- When the flow is reduced, the temperature falls until a new equilibrium of forces and, hence, a new valve position is reached.

NOTE: When sizing a system including a heat exchanger, the upstream temperature must be minimum 10 K above the set point temperature to ensure safe closing of the valve.

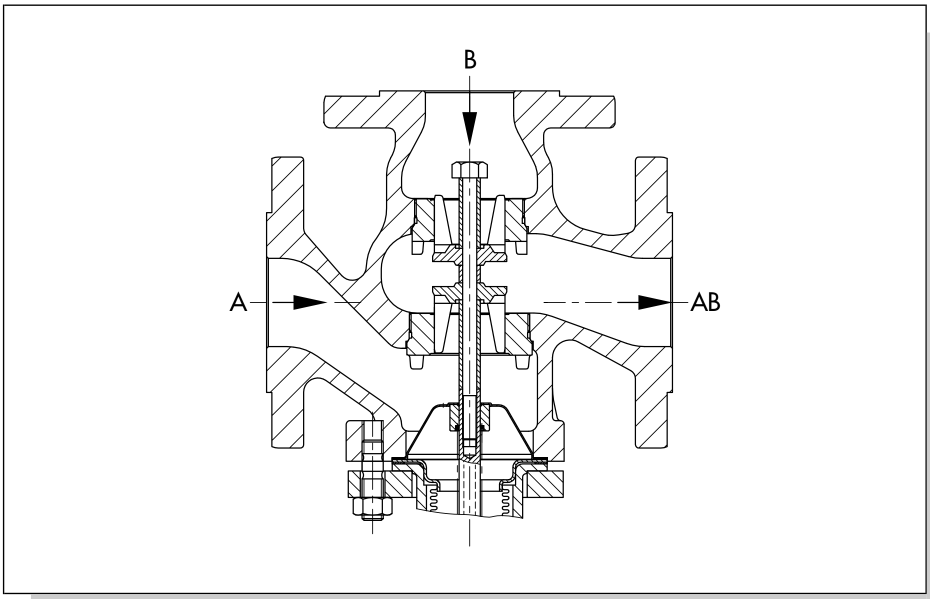

Fig. 12: Three-way mixing valve

Mixing and diverting valves

Heating and cooling control systems require different valve styles. Globe valves control one flow to adjust the desired temperature. Three-way valves, on the other hand, mix or divert two heat flows.

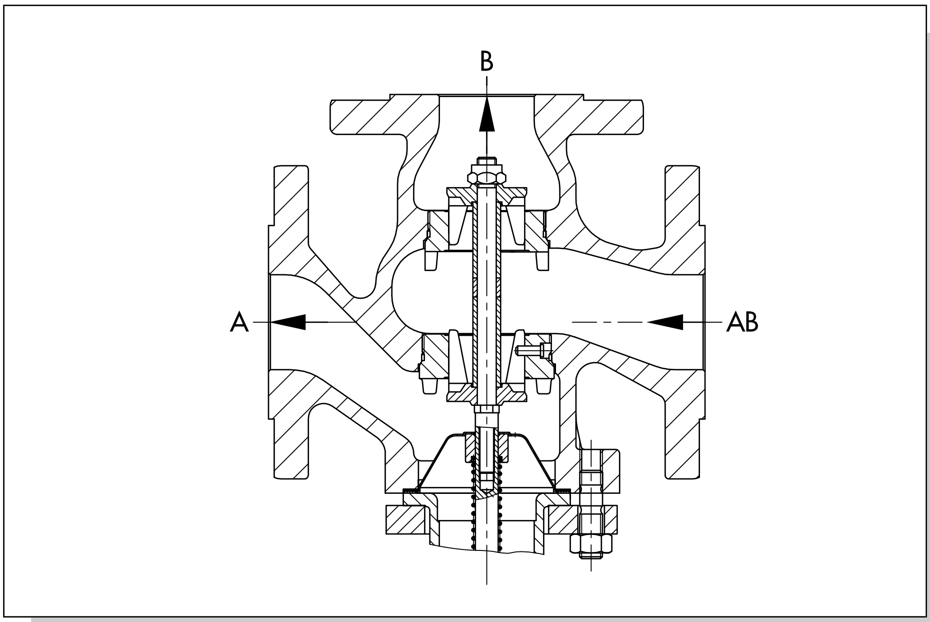

Fig. 13: Three-way diverting valve

medium flow through mixing valves

Three-way valves have three ports (A, B, AB), while globe valves have two. When no actuating force is exerted on the valve, a return spring ensures that the double plug is firmly placed on one of the two seats. In mixing valves (Fig.12), the heating medium enters at port B via the seat/plug assembly and leaves through port AB. Port A is closed. When an actuating force acts on the

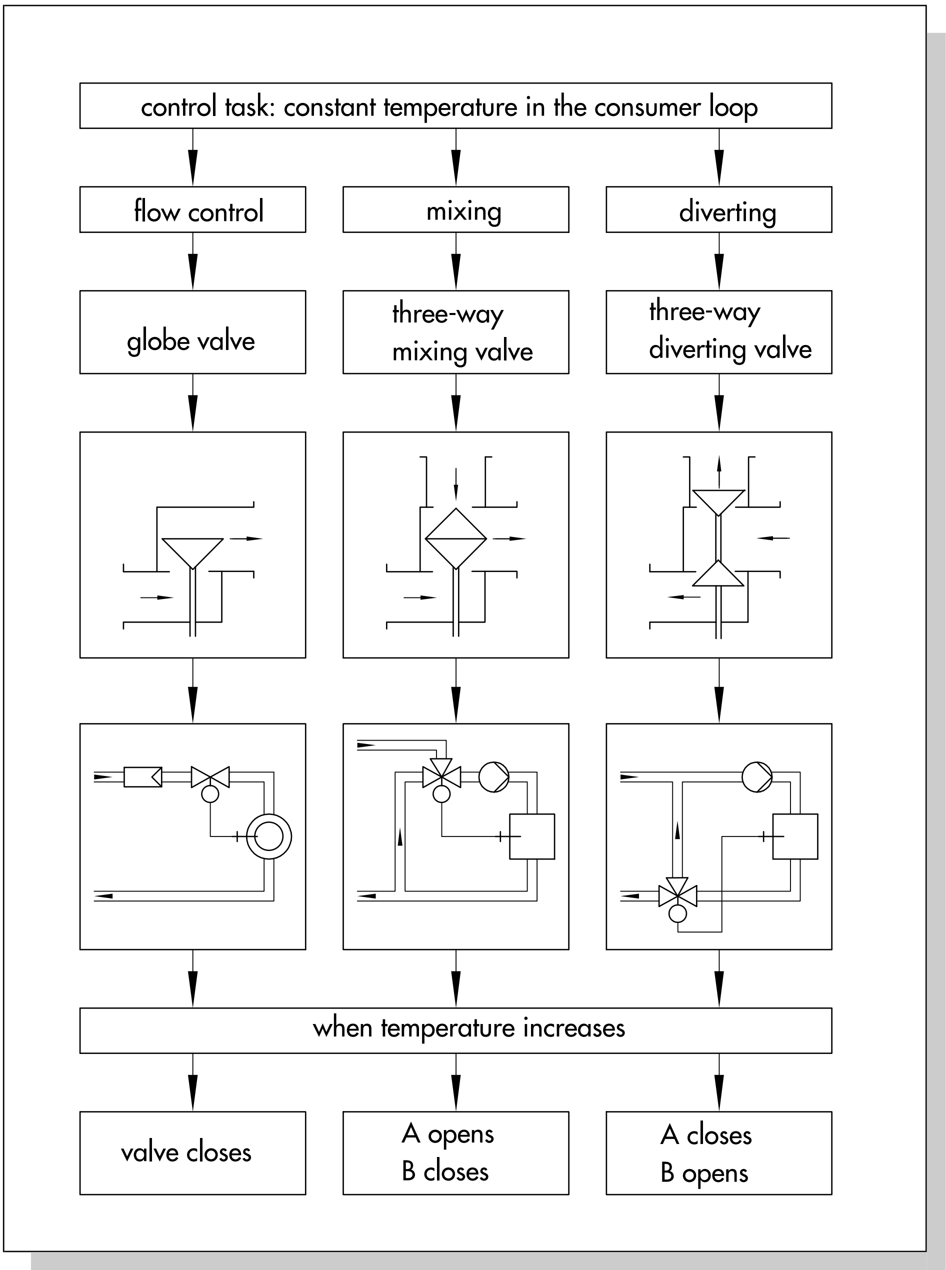

Fig. 14: Example of a heating system

plug stem, the valve moves towards its other end position, reducing the flow through the inlet port B and opening the inlet port A.

medium flow through diverting valves

The flow through diverting valves (Fig. 13) is quite different. Here, the cooling medium enters at port AB. The streams are diverted according to the valve position and finally leave through the ports A and B.

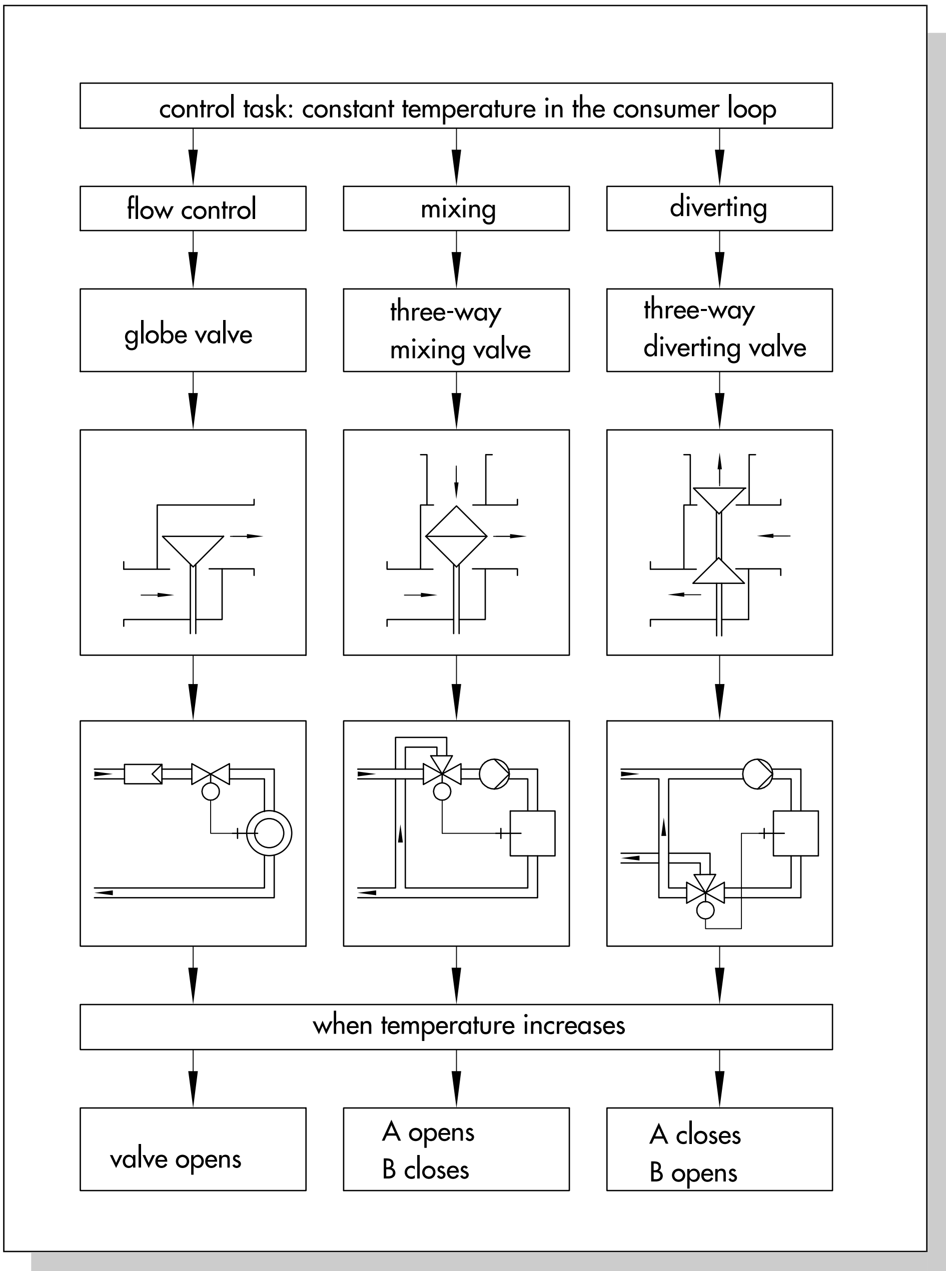

Fig. 15: Example of a cooling system

The operating principle of the valves and their application in a heating and a cooling system are illustrated in Figs. 13 and 14.

installing valves in heating or cooling systems

The Figs. 13 and 14 show typical installation examples where the valves can be installed either in the flow pipe or in the return pipe. In heating systems with high temperatures and low pressures, cavitation can cause problems, therefore the valve should be installed in the cooler return pipe.

When engineering the heating or cooling installation, make sure that the process medium flows in the opening direction of the plug of the mixing or diverting valve so that "vibrations" near the closing position are prevented. Otherwise the small surface, the high velocity and the low pressure would cause the plug to be seized in the seat and released again when the flow is interrupted.

Globe valves in cooling service

reversing device changes operating direction

The globe valves described above close when the temperature at the sensor rises, hence, they are suitable for heating service. In cooling installations, however, a valve is required that opens with increasing temperature. This can be achieved either by changing the seat/plug position or by installing a reversing device (Fig. 16) between the sensor and the bellows housing of a "normal" globe valve. In the latter case, the valve is closed by the spring force and opens when the temperature rises.

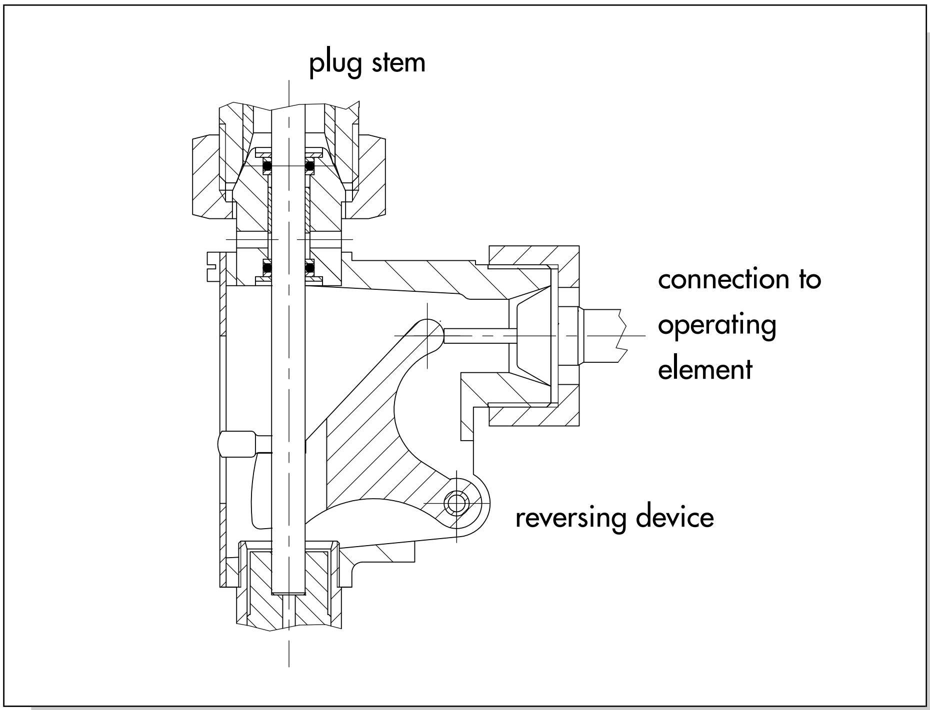

Fig. 16: Reversing device

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] Self-operated Regulators
Technical Information L202 EN; SAMSON AG

Figures

NOTES

NOTES

SAMSON right on quality course

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