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Industrial Process Control Valves

Key components for plant safety and economic efficiency

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Contents

Designed for maximum performance

With its maximum speed of 330 km per hour, the German high-speed train ICE 3 has a braking power of more than 8200 kW provided by the electrical brake. A fascinating value – but only a fraction of what control valves, so to say the "brakes" in any industrial process, are able to achieve. A steam conditioning valve, for example, used in a typical bypass station for an auxiliary turbine (Fig. 1) with a nominal size of DN 400 throttles 71.6 t/h of steam from an inlet pressure of 38.5 bar to 0.9 bar absolute pressure. The calculated power loss at the valve is more than 21 100 kW. So this control valve, at DN 400 not particularly large, controls 2.5-times the extraordinary braking power of an ICE 3. On the one hand this constitutes the fascination of process control valves, but on the other hand it also represents a great challenge for the valve manufacturer. At points in the industrial process where so much power must be controlled, any mistakes in design and operation are extraordinarily cost-intensive.

2.5-times the power of the ICE braking system

Regardless of whether in power stations, in the chemical, petrochemical, foodstuff industries, or in gas supply and water supply and disposal, control valves are decisive points of intervention in process cycles. They ensure the manufacture of products of optimal quality under economically advantageous conditions. The intention of this book is to demonstrate the significance of control valves as important interfaces within complex industrial processes and as key components for plant safety and

Decisive points of intervention in the process

Fig. 1: Steam conditioning valve (angle-style)

economics. The focus of the presentation is on the group of control valves that are most widely used – the globe valves. The reader will find a compact overview that should aid his understanding of these high-performance valve modules.

Plant function and process integration

Intermediary function

In process circuits, control valves are the most common continuously operating elements used to influence and control the processes in a targeted manner. They are the connecting elements and the interfaces between electronic control technology and the process medium. At the same time, they function as connecting components between the individual process phases, thereby controlling the continuous process flow and balancing out the different pressure levels. Other control valves that are used, for example, in heating and cooling circuits, intervene indirectly in the process.

Basic functions of process control valves

The process control valve is on the one hand a participant in the flow of digital data and on the other hand an executive arm in the process

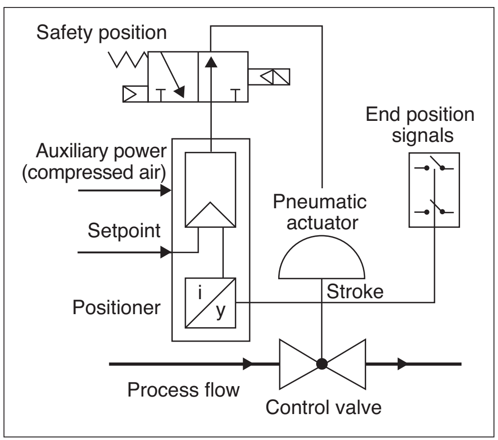


Fig. 2: Control valve interfaces and components

Pipe system component

flow (Fig. 2). In times of model-assisted process control and digital control technology, the control valve itself is only inadequately represented, however, in the field of control technology. Essentially, one is dealing with a pipe system component that interacts in a complex manner with the process-technological sequences. In the energy balance of each process, the pressure difference across the valve that is necessary for the control function appears as a performance loss; often, however,

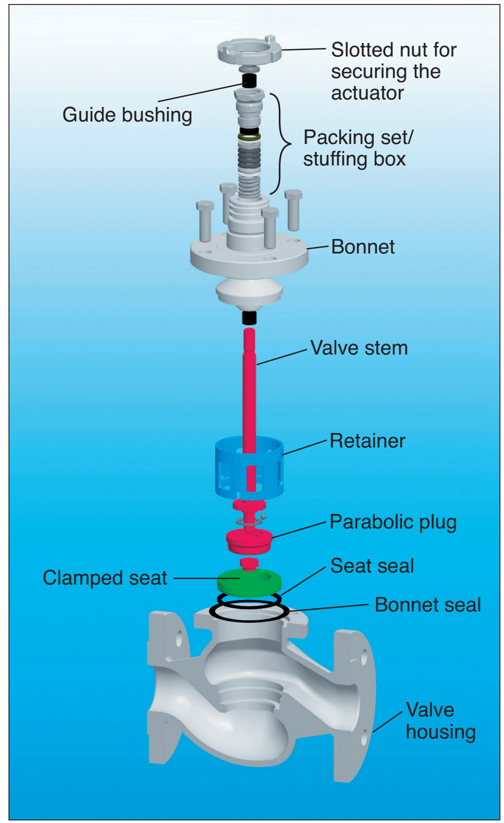


Fig. 3: Essential components of a control valve

the controlled pressure drop is the primary task of the valve, for example, when depressurising a pressure vessel.

Figure 3 shows the design of a modern control valve in terms of its essential components. In the design of a control valve, and independent of the actual task it has to fulfil in the process, there are four essential aspects to consider:

Main design aspects

- process-technological design of the necessary working points and operating conditions
- safety design and response to malfunctions
- process-control-related concept with communications path and actuator philosophy
- process-control-related concept with actuation dynamics and time response.

Working range of a control valve

Decisive phase of project design

The primary, and at the same time the most complex task in the design of a control valve is the determination of its working range. Here, accurate design and calculation really pays off, since it is essentially in this phase that the installed performance of the process components, pipe sizes and valve dimensions are determined. At the same time, the components installed upstream and downstream of the control valve must be taken into account up to the extent that allows a fluid mechanical decoupling of the parts of the plant.

Flow control as basic function

A control valve is always primarily a flow control valve, and the pressures that occur ahead of and behind the valve are the result of the upstream and downstream system components and their characteristics. What applies generally in control technology also applies here, namely that an optimised controlled loop is the most efficient and also the most economical controller.

Taking account of extreme situations

Besides the requirements of the process operating within its normal limits, special and extreme situations must also be taken into account in the control valve design. Amongst these is the behaviour in the event of a controlled shutdown (sealing function) and, in the same way, the behaviour in the event of signal interruption or the failure of auxiliary power. Furthermore, the leakage requirements for the closed valve must be established. Here, a limitation to requirements that are actually necessary is recommended, since the control and sealing functions are, if anything, contradictory demands from the design point of view and can therefore only be achieved using resource-intensive measures.

Valve capacity (flow coefficient)

Flow rate under standardised conditions

Calculation methods for the flow coefficients – defined by the *K_v value* – are described in many publications. In contrast to the ζ value used in the analysis of pipe systems, which describes the specific flow resistance of each pipe element, the K_v value used for control valves defines the flow rate of a control valve in m^3/h under standard conditions (water at 20°C and 1 bar pressure difference). The K_{vs} value (nominal flow coefficient) is the K_v value of the control valve at the nominal stroke. In the American standards, the C_v value is commonly used for the flow rate; this describes the flow rate in gpm (gallons per minute) at 1 psi (lb/in^2) pressure difference. The conversion factor between the two systems is given by: C_v 1 = K_v 0.865. Today, convenient calculation programs are almost exclusively used for such calculations. The empirical formulae given in the section on “Process valves terminology” provide rough estimates (see p. 68).

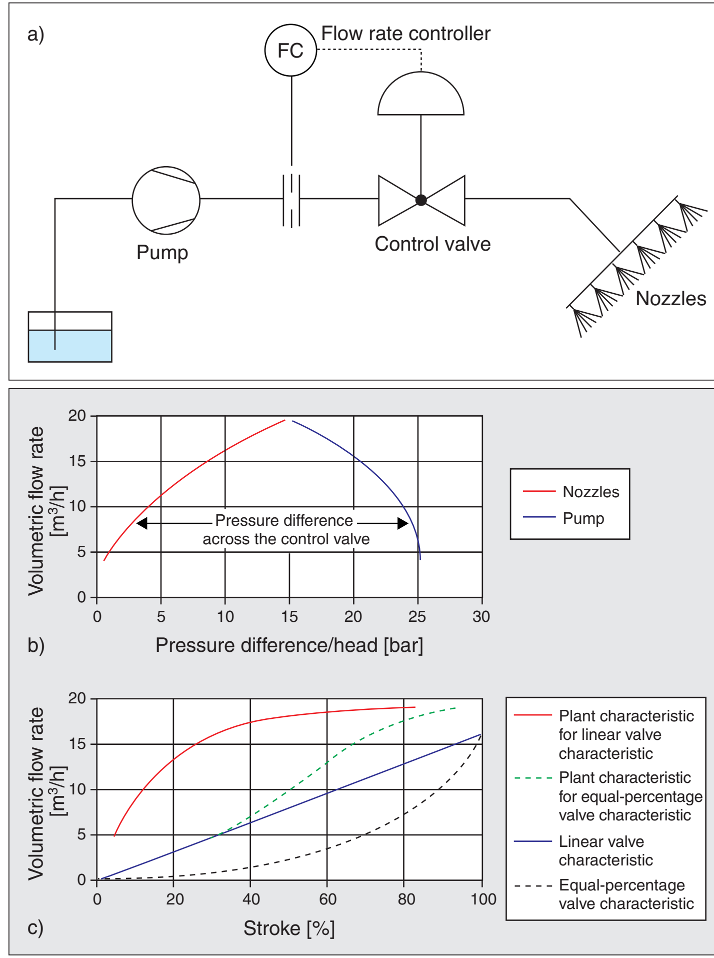
Transfer function and valve characteristic

Valve stroke as an important intermediate parameter

The transfer function of the valve, which describes the relationship between input and output signals, is important in the control design. But what in fact is the output signal of a control valve? The process parameters to be controlled such as pressure, level or temperature are in the final analysis only a result of the flow control provided by the valve, and this in turn is determined by the throttling process. Thus the static transfer function describes the relationship between input signal and the throttling area. The fundamental intermediate parameter in this signal sequence is the stroke of the valve, or in other words, the position of the valve plug. The valve plug has a contour that, according to the stroke setting, exposes a more or less large throttling area – starting from a controllable initial value up to a maximum value. The quotient of the initial value and maximum value is called the *rangeability*. This fundamentally defines whether the required process conditions can be achieved. The behaviour between these values is described by the valve characteristic. The choice of characteristics is the subject of many theories, while in practice the choice is usually only between linear and equal-percentage characteristics. The objective is basically to achieve a constant control amplification over the whole working range.

Figure 4 shows, for the example of a spray header control used to cool crude steel in a continuous casting plant (Fig. 4a), how three

Fig. 4 (opposite):
a) Spray header control
b) Spray nozzles and pump characteristic
c) Valve and plant characteristic for linear and equal-percentage characteristic



characteristics interact in each case. The characteristics of the spray nozzles and the pump can be seen in Figure 4b, while Figure 4c shows the influence of the *valve characteristics* (linear and equal percentage) on the *plant characteristic*. System limits are the tank level, assumed to be constant, and the ambient pressure behind the nozzles.

Standard: linear characteristic

If there is no clear technical priority for an equal-percentage characteristic, for globe valves a linear characteristic should be chosen for economic reasons. There is a tendency for control valves with an equal-percentage characteristic to be selected with a larger K_{vs} value. Perforated plugs in most cases require a larger seat diameter or a larger valve stroke for an equal-percentage hole pattern, and therefore require higher actuation forces.

Nominal valve size

Nominal size as a function of the K_{vs} value

The required flow rate coefficient and the design of the valve trim – i.e. plug shape (one- or multi-stage configurations) and characteristic – essentially determine the space requirement, i.e. the nominal valve size. In addition to the controlling stages, the housing may also possibly have to accommodate uncontrolled but fixed throttling stages (perforated discs, perforated cages, flow labyrinths).

Mechanical aspects

Besides these spatial requirements there are also mechanical aspects to be taken into account. As a rule, the nominal valve size should not be greater than the nominal pipe size; on account of bending and torsion moments within the pipe system, however, it should also not be smaller than half the pipe size. Furthermore, the flow velocities at valve entry and exit must also be taken into account.

Media containing solids require a particularly large amount of space. For these kinds of media, angle-style control valves are used which allow an unhindered outlet flow towards the valve exit. This type of design is also suitable for the rapid expansion of gaseous media as well as for fluids at temperatures close to the boiling point which vaporise when the pressure is lowered.

Integration into the pipe network

Flanged or welded connections

The usual forms of connection of the valve into the pipe system are flanged, welded, or screwed connections. Flanged connections are far and away the most common form of connection, while welded connections are used primarily in high-pressure lines of water/steam circuits. The advantages of a directly welded connection lie in the hermetic and permanent sealing. A significant disadvantage on the other hand is the limited repair capability, since for modern valves, an easy replacement of worn-out components on site is required. Welded connections on valves are more expensive as a rule, because steel pipe stubs, so-called spool pieces, are welded on to the cast housing body in the factory in order to obtain an unproblematical pairing of materials at the interface with the pipe.

Maintenance during operation

In general terms, a control valve should be seen not only as a valve but also as an element of the pipe system. For this reason, it must be ensured by means of bypass and shut-off valves that in the event of a possible failure of the control valve, the latter can be extracted out of the circuit for maintenance and repair without interrupting plant operation.

Valve actuators

Valve actuators serve to position the valve plug according to the requirements of the control system. Three types of actuator design are well-established in process technology:

- pneumatic
- electric
- electrohydraulic.

Pneumatic …

Pneumatic valve actuators are cost-effective, can be used in potentially explosive areas without any problems, have low actuating times, a constant sealing force, as well as *safety positions* that can easily be implemented. They are therefore the first choice in process technology. Electrical valve actuators are dynamically stable and precise; direct control by means of the process controller is possible. Although the primary energy source is more cost-effective, a higher outlay is required for safety functions and for use in hazardous areas. Moreover, electrical actuators are relatively slow. Electrohydraulic actuators may be distinguished by very good dynamics and stability, by speed combined with high actuation forces, as well as by flexible safety functions, however, their disadvantage lies in the fact that they are expensive and resource-intensive to manufacture.

… electrical, and also …

… electro-hydraulic actuators

Depending on the type of valve selected and the requirements of the process, the following criteria must be taken into account in the selection of the actuator:

Criteria for actuator selection

- on/off or control application (what control accuracy is required?)
- primary energy source available (compressed air or electric power)
- safety position
- actuation force required
- stroke required (are adjustable end stops required?)
- requirements for the stroke stiffness of the actuator
- permissible deviation from linearity of the actuator characteristic
- ambient conditions (protection class, temperature, corrosion)
- manual actuation for emergencies (required or not required).

Positioner

Positioners serve to convert the standard signals usual in control technology with pressures of 0.2 to 1.0 bar or current levels of 4 to 20 mA into an actuation pressure (in the context of the compressed air supply available in the plant) that can be used for the valve actuator (usually a pneumatic actuator). Together with the actuator, the positioner thus forms a control circuit that is subordinate to the process control circuit.

Conversion into a usable actuation pressure

Microprocessor-controlled positioners (“intelligent positioners” or “smart positioners”) provide the possibility of adjusting many parameters both on site and also via the communications system. The link to the process control system is made via a bidirectional data exchange that goes beyond the normal control and feedback signals. The equipment used includes the Highway Addressable Remote Transducer (abbreviated to HART®), where the status information is modulated onto the analogue control signal in the form of a digital signal, as well as the “real” fieldbuses, Profibus® (PA) and Foundation Fieldbus™, with which both the actuation signal and also the status information are digitally transmitted.

Bidirectional data exchange

Positioner mounting

For mounting and fastening the positioners to the actuator, the Namur guidelines were developed by the chemical industry; these have also been internationally converted into IEC 60534-6-1. These guidelines make it possible to interchange the positioners of

Namur guidelines

different manufacturers. With the advent of intelligent positioners, however, the Namur mounting has proved to be no longer sufficiently robust. As a result, a trend towards "direct" or "integrated" positioner mounting systems has developed. Here, the factory standards of well-known valve manufacturers have become established to an increasing extent. In almost all cases, these standards also include a "pipe-less" air supply between positioner and actuator.

Direct or integrated mounting

A technically very interesting alternative for the positioner mounting is represented by the VDI/VDE 3847 guideline (Fig. 5) developed by a working group of manufacturers and

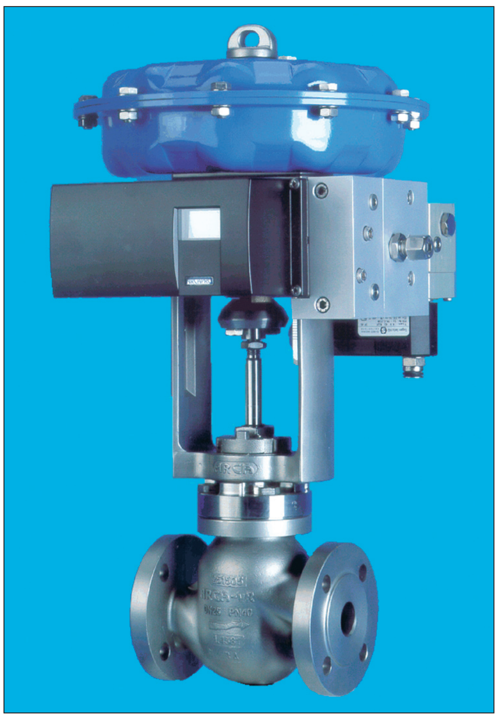


Fig. 5: ARCAPRO® positioner mounting according to VDI/VDE 3847

users. The "open-system" concept allows the positioner to be mounted both on single- or double-acting actuators; in addition, a connecting face for the direct mounting of a solenoid valve is generally present.

Integration of intelligent positioners into the control and/or maintenance system

Central assist management of the field devices

Increasing levels of functionality and growing parameterisation options for field devices as well as the simultaneous reduction of operating personnel require that an extensive level of control of all field devices is ensured, either centrally from the process control system or from a maintenance panel. Fieldbuses such as Profibus® and the Foundation Fieldbus™, and also modern HART® systems, enable individual addressing and data exchange with each field device.

Possibilities of visualisation

Over and above pure data exchange, however, it must be guaranteed that the superordinate system "knows" the properties and setting options for all field devices connected, and can also display these visually to the operator. In this respect, with Electronic Device Description (EDD) and Field Device Tool/Device Type Manager (FDT/DTM), two opposing philosophies have developed.

EDD concept

In the case of integration by means of EDD, one is dealing with a standardised text file which describes in detail the signals and properties of the field device. Here, the user interface is prescribed by the superordinate system and thus is not specifically matched to the device in question. Future versions of EDD should, however, compensate to a large extent for the disadvantage of this design feature.

FDT/DTM technology

The superordinate system using FDT/DTM technology provides FDT software (e.g. PACTware®, FieldCare®), in which as many DTMs of the field devices as required are integrated. In addition to information concerning the field device, the DTM also provides an individual representation of each field device. One can envisage the DTM as an equipment driver for computers which is also integrated into the operating system and which includes a special representation of each device. Today's generation of digital positioners offers FDT/DTM technology as an alternative to the EDD concept. The DTM developed on the basis of FDT specification 1.2 facilitates especially the use of the expanded diagnostics.

Instrumentation

Besides positioners, further instrumentation is necessary in individual cases. This can include:

Further instrumentation

- position switches and position indicators (in certain applications independent of the positioner)
- solenoid valves for safety-related valve settings (mainly on/off)
- power amplifiers (also called boosters) for reducing the actuating times of actuators with large air volumes
- pneumatic lock-up valves, which in the event of instrument air failure freeze the current valve position
- pneumatic filter regulators for preparation of the *instrument air*
- pneumatic quick-exhaust valves for rapid movement into safety positions.

Significance for economics and plant safety

Key role

The economics and safety of plants are very closely linked. Control valves assume key roles with regard to both criteria since they have a decisive influence on the quality of the processes and the availability of the plant. Life-cycle costs, safety for people and the environment, as well as explosion protection in plants, are essential factors in the assessment of control valves.

Influencing factors on the overall economics

Essential costs

Included in the life-cycle costs of a control valve are not only the costs for selection and planning and the investment itself, but also the costs for installation and training of the personnel. During operation, costs accrue for maintenance, wear and possible failure, repair, spare parts, and energy, as well as costs for possible environmental damage. Also to be considered are the costs for disposal and recycling.
The individual design of a control valve and the configuration of its actively moved parts have a significant influence on the consideration of life-cycle costs. With modern solutions such as:

Optimisation solutions

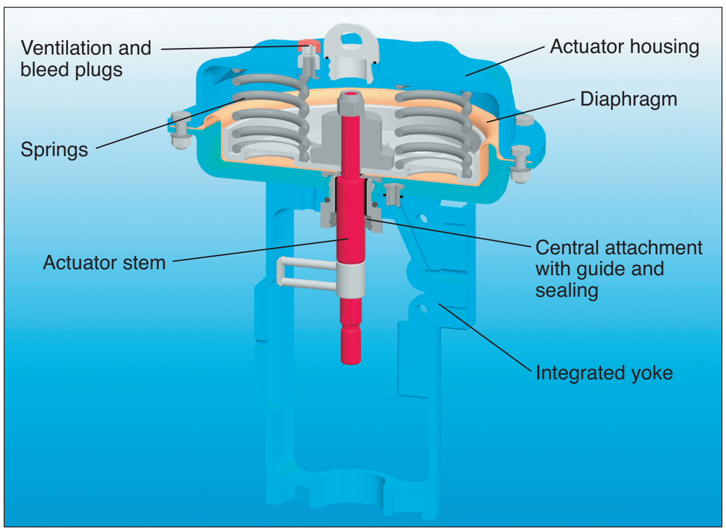
- multi-spring diaphragm actuators
- valve seat quick-exchange systems
- reliable stem sealing systems
- intelligent positioners with diagnostic functions and
- piezo-controlled positioners with negligible air consumption

it is possible to ensure that the quality of process control and thus the quality of the product manufactured is at the highest level, it is also possible to minimise operating and maintenance costs, and thus to optimise the overall economics of the industrial processes.

Compact multi-spring diaphragm actuator
Modern spring-loaded *diaphragm actuators* (Fig. 6) are not only configured in a particularly compact manner, but they also offer a number of design details which enhance operational security and durability and thus the economics. Features to be named include, for example:

- pipe-less positioner mounting
- ventilation system that utilises the "used" instrument air to protect the spring chamber from ambient effects
- rolling diaphragms with diaphragm clamping in the force bypass.

Fig. 6: Modern multi-spring diaphragm actuator



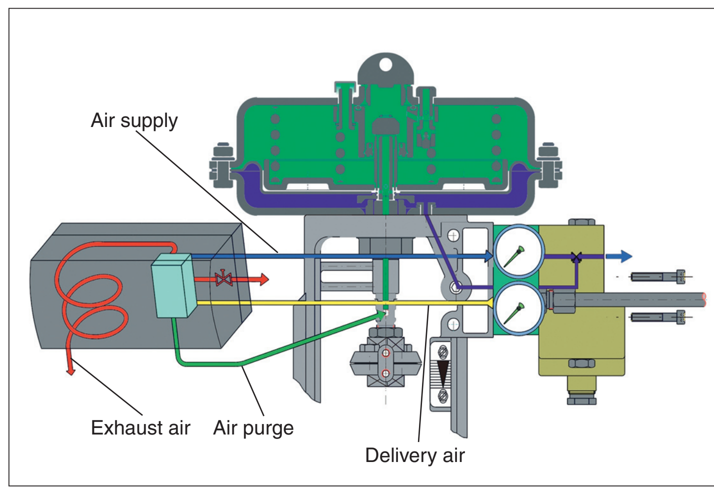
Pipe-less air connection

The pipe-less air connection between positioner and diaphragm chamber of the actuator guides the actuation air via internal passages through the actuator yoke in a functionally reliable manner. External pipework or screwed connections are not required for the air supply. Any bending of pipes or leakages at the screwed connections is thus excluded, as are any functional failures arising from these defects.

Avoidance of corrosion

In conventional diaphragm actuators, the air displaced by the stroke movement of the actuator is balanced out by ambient air intaken by means of a breather opening. If the atmosphere is loaded with aggressive constituents, the air sucked into the actuator can generate a significant amount of corrosion within a short period of time by forming condensates. This is avoided in the case of modern actuators where the instrument air is not only used to operate the actuator, but is subsequently (as exhaust air from the positioner) used to ventilate the spring chamber and thus to keep it dry and free of corrosion (Fig. 7).

Fig. 7: Positioner mounting with air purge of spring chamber



At the heart of each diaphragm actuator is the diaphragm. Its service life is dependent not only on the quality of its material but also to a large extent on the kind of mechanical loading, in particular in the area of the diaphragm clamping. An uncontrolled clamping of the diaphragm and the resultant formation of creases together lead to a diaphragm movement with

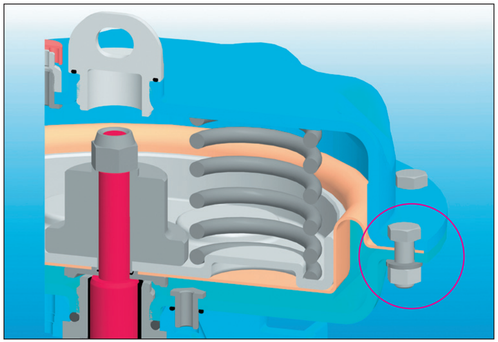


Fig. 8: Diaphragm clamping in force bypass

an increased flexion action which significantly reduces the service life. Clamping with a defined pressure in the force bypass (Fig. 8) ensures a defined diaphragm movement and thus provides the basis for high availability and a long service life.

Defined pressure

Valve seat quick-exchange system

The valve plug and seat ring are the most highly loaded components of a control valve. The degree of wear and the sealing function, as well as durability and ease of servicing of both components, are determined by optimal design and the correct choice of materials. As a simple, universally applicable and cost-effective solution, the control valve with the replaceable, clamped seat ring has proved to be effective; in this design, the valve plug is stem-guided in a conventional manner, or at a

Valves with clamped seat

higher pressure drop and larger nominal valve size, is shaft-guided. The advantages of this configuration can be summarised as follows:

Advantages

- A seat ring without a thread can be easily manufactured from special materials.
- The integrated form-fit alignment between bonnet and seat ring, and thus between stem guide and seat ring, ensures the prescribed seat leakage.
- The “floating” bearing support of the clamp seat prevents the transfer of pipe forces onto the seat ring via the valve housing. For *leakage class* V, this is an important advantage since in the case of screwed seats, the negative effect of pipe forces on the valve seat can be proven.
- The seat retainer guarantees an even outflow of the medium.

Valves with a clamped seat (Fig. 9) are easier to maintain than valves with a screwed-in seat ring (Fig. 10) since the clamped seat ring can be very quickly and reliably replaced without any special tools. It is therefore clearly superior to the screwed-in seat, since special tools are required to ensure the tightening torques required for the permanent avoidance of by-

Quick exchange

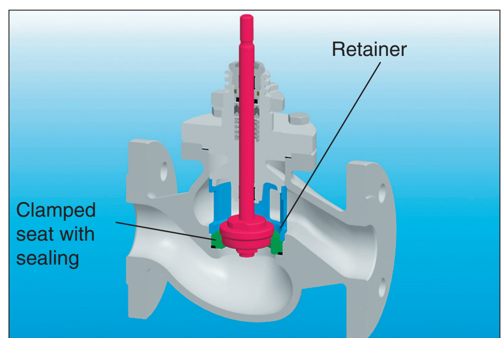


Fig. 9: Control valve with clamped seat

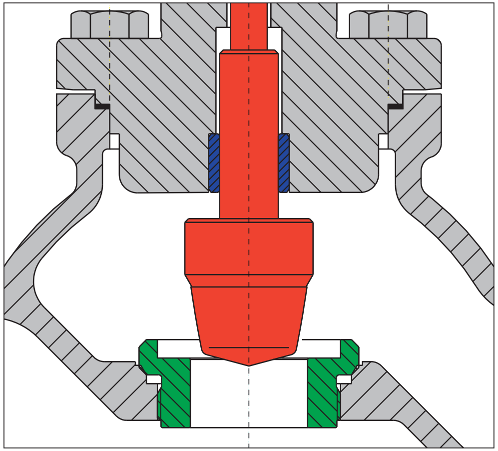


Fig. 10:
Control valve with screwed-in seat

pass leakages. The tightening torques are quite often well above 1000 Nm and are also strongly dependent on the material pairing and the condition of the thread. In contrast, in a valve with a clamped seat, the seating sealing force is unequivocally defined by the tolerance between housing, seat retainer and seat ring as well as by the design of the seating seal. Reproduction of the necessary tolerances can be ensured by means of CNC production technology. The replacement of the seat ring is confined to insertion of a new seating seal and a new seat ring, and a simple tightening of the bonnet bolting "onto the block".

Defined seating sealing force

Stem seal

One of the central requirements for any valve is permanently reliable sealing to the external environment. Just as significant is the choice of an economical sealing solution, in particular with regard to good operability and ease of replacement. Here, triple-stem sealing systems (Figs. 11a, b, c) have become established in the market. For the se-

Triple-stem sealing systems

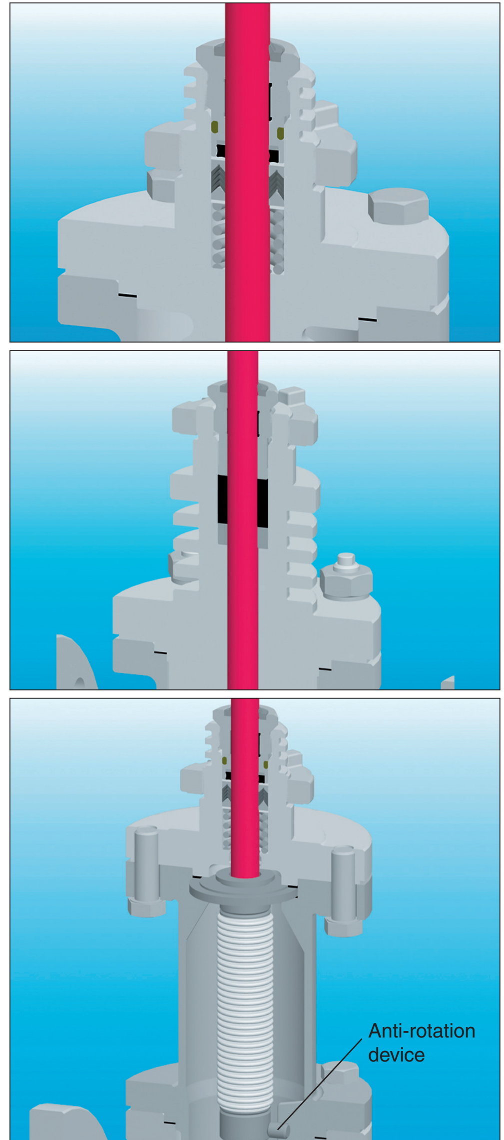


Fig. 11:
a) V-ring packing, self-adjusting

b) Graphite or PTFE packing, adjustable

c) Bellows seal with safety stuffing box lection of the suitable stuffing box system, the key parameters are pressure, temperature, process fluid and type of movement (rotary or linear).

An important component of the stuffing box system is the valve stem and its surface. To avoid wear, the surface should be as hard as possible and should exhibit a low level of roughness. As a rule, valve stems are fine-turned or ground and then roller-burnished. In this way, it is possible to achieve a surface quality of $R_z < 4$ to 5 µm. Too fine a surface, however, has the disadvantage, particularly in the case of graphite packing, that the undesirable *stick-slip effect* can occur as a result of adhesion forces. Moreover, with graphite packing in particular, care has to be taken in the selection of the materials for the stem and the stuffing box chamber in order to avoid galvanic effects that encourage corrosion. Thus it is possible, for example, to integrate good protection against galvanic corrosion with a bonnet completely made of stainless steel, or a stainless steel stuffing box chamber in the form of a screw-in sleeve. Further design features that contribute to a permanent stuffing box seal are effective scrapers and a distance between scraper ring and the stuffing box area that in all cases is greater than the valve stroke. These protect the stuffing box chamber from dirt particles and any damaged areas of the valve stem.

Risk of stick-slip

Cost savings by means of intelligent positioners

Modern microprocessor-controlled positioners provide the following operating modes: automatic operation, manual operation, initialisation, parameterisation and diagnostics. The parameterisation of:

- characteristics
- setpoint direction
- *split-range operation*
- actuator range limitations
- tight sealing function
- malfunction detection
- actuating times and
- dead zone

is done during initial commissioning, or is automatically determined by means of a test run. Alternatively, these parameters can be optimised on site or via digital communication with the control system. Thus even the replacement of a positioner while the plant is operating is very easily possible.

Optimisation of the parameters

Microprocessor-controlled positioners with a digital output (via piezo-controlled binary pneumatics) have significant advantages compared with conventional positioners, and also compared with microprocessor-controlled positioners with an analogue pneumatic output, especially with regard to the consumption of compressed air. While a conventional positioner consumes on average 6000 Nm^3 of compressed air in one year (costing approx. € 400 per year), a piezo-controlled positioner requires just 150 Nm^3 of compressed air per year, with correspondingly lower costs. The amortisation period for a unit of this kind is a maximum of two years.

Lower air consumption saves costs

If it is not possible to mount the positioner directly on the actuation unit for reasons of high temperatures or extreme levels of vibration, a positioner with an external position encoder is used. The very robust position encoder (ambient temperature up to 120°C) is fitted to the control valve, whereas the actual positioner is then placed at a suitable location that can be at a distance of up to 20 m.

Option of external position encoder

Control valve diagnostics
Digital positioners use parameters derived from normal operation, for example residual control deviation, variation of adaptive control parameters, variation of mechanical parameters such as stroke and fixed stops, as well as service life values such as stroke and direction changes, to aid in monitoring the control valve. All values cited are registered, evaluated and stored in the positioner, even in the event of auxiliary power failure. With appropriate software or an expert system, these values can be displayed and evaluations can be generated that accurately describe the condition of the control valve. This continuous monitoring helps to avoid unforeseen failures and enables the timely scheduling of spare parts or spare units. Digital positioners will in future replace the regular control valve maintenance cycles (which will then in most cases be completely superfluous) and will thus contribute very decisively to the reduction of life-cycle costs.

Exact description of condition

Plant safety and SIL classification

SIL

In line with European standardisation, plant safety is these days linked with the term *SIL*. SIL stands for “Safety Integrity Level” and specifies the requirements for the reliability of the safety functions of electrical, electronic and programmable electronic systems at four stages of safety. The task of the safety functions consists in removing process risks that can represent a hazard for people, the environment and objects. The SIL required for a safety system is established in the context of safety considerations which include, amongst other factors, the evaluation of possible damage to people and the environment in the event of plant malfunctions and the probability of people being present in the hazardous area. The basic standard for this purpose is EN 61508 (Parts 0-7) “Functional safety of electrical, electronic and programmable electronic safety-related systems”. Moreover, EN 61511, EN 62061, EN 954-1 and also ISO 13849-1 must be observed as application standards, in particular for mechanical components.

Based on EN 61508

The regulations cited above are extremely complex in parts, and often lead to a very free interpretation of design rules, and as a result to ambiguities between plant operators, planners and valve manufacturers. For this reason, the Verband Deutscher Maschinen- und Anlagenbau (VDMA) [= Association of German Machinery and Plant Manufacturers] has produced a set of “SIL Guidelines” for valves and valve actuators (www.vdma.org), the contents of which will be described here briefly.

SIL guidelines

The essential theme of these guidelines is that the SIL classification is established only for a complete safety system comprising sensors, control system and actuators. For the individual components (e.g. control valves), only key parameters (e.g. mean time between failures, *MTBF*, safe failure fraction, *SFF*, or diagnostic coverage, *DC*) can be defined. The key parameters in question for the individual components are quantitatively evaluated, and these then lead to an SIL classification for the overall system. It should be noted here that in the evaluation of the overall system, the control valve is weighted with up to 50% of the total failure probability. Based on this quantitative evaluation, it is up to the plant planners to achieve a prescribed SIL either by the selection of high-quality equipment or by the introduction of system redundancies into the sensors, control system and/or the valves.

SIL classification only for the whole system

Plant safety by means of explosion protection

As a result of the development of electrical and electronic control systems and the increasing complexity of chemical plant installations, the requirement has ensued that electric signals are to be used for the control of pneumatic actuation equipment. Research demonstrated that the electropneumatic converter providing the conversion of the electric into a pneumatic signal needs to be integrated into the positioner and designed so as to be protected against explosions. The principle of pressure-resistant encapsulation has been known for many years from the mining industry. However, the German chemical industry in particular developed its own type of ignition protection "EEx i – Intrinsic Safety", which in recent years has also become internationally established. Devices that are designed according to this principle prevent ignition by limiting the energy supplied into the hazardous area, are typically smaller, and may also be maintained while in the operational state. They are moreover less expensive overall.

Limitation of the energy supply

"EEx i – Intrinsic Safety" type of ignition protection

For conventional positioners which achieve an I/p conversion by means of a fixed or plunger coil and a mechanical-pneumatic control according to the force equalisation principle, the "Intrinsic Safety" type of ignition protection presents few problems. When the first intelligent positioners were developed, their power consumption was still relatively high. And because the power of intrinsically safe power circuits was limited to no more than approx. 150 mW, these positioners were unable at first to fulfil the "Intrinsic Safety" type of ignition

protection. It was not until the introduction of extremely low-power piezo-controlled valves in 1992 that it was possible to reduce the power consumption appropriately.

In order to design intelligent positioners according to the "Intrinsic Safety" type of ignition protection, a significantly higher level of complexity is required than in the case of conventional units. On the one hand the capacitances are not negligible, and on the other hand the power consumption of processor, memory and actuator are today still at least 50% higher than for conventional positioners, so that the self-heating effect in the event of failure assumes a greater significance.

More efforts required

"EEx d – Pressure-Resistant Encapsulation" type of ignition protection

The principle of pressure-resistant encapsulation is that any ignition occurring in the interior of the unit cannot propagate to the external environment. Means for limiting energy levels are therefore not necessary. Equipment enclosures and operating controls must be designed with so-called "ignition-propagation-proof gaps" which are subject to very tight tolerances and therefore require complex machining of the housings. Since as a matter of principle, the housings of pressure-resistant encapsulated units may only be opened under special safety precautions, a modern positioner must also allow on-site operation without the need to open the pressure-resistant housing. One possibility for operation from the outside, for example, is by means of a sight glass and control buttons that are designed for external actuation.

Ignition-propagation-proof gaps

Explosion protection for non-electrical equipment

With introduction of the 94/9 EC Directive *(ATEX)*, all components that are introduced into potentially explosive environment must be accompanied by a risk analysis with regard to ignition safety. Only “simple components” such as pipe elements, tanks or valves that, apart from a build-up of static charge, do not exhibit any further ignition sources, are explicitly excluded from this directive. For all complex components, in particular for all actuators and also for non-electrical installation parts, a risk assessment must be performed by the manufacturer. The result of this risk assessment is either a designation of the unit according to ATEX, or a declaration by the manufacturer that states that the unit in question is not subject to the ATEX requirements.

Execution of a risk analysis

Specification and selection criteria for control valves

The selection of a control valve that is suitable for the application in question is an interactive process that takes place between the operator or planner and the supplier. Here, the basis is always the data sheet for the control valves.

Data sheet for control valves

The data required for the selection is normally summarised in a data sheet for control valves in accordance with IEC 60534-7 or ISA. Mandatory basic data elements that must be prescribed by the planner or operator include:

Basic data

- nominal size and nominal pressure (of the pipe system), type of connection
- design pressure and design temperature
- data concerning the available auxiliary power and other requirements for process integration
- process fluid
- data for one, preferably three operating points (mass or volume flow, upstream pressure p_1, downstream pressure p_2, and fluid temperature T_1); at *steam conditioning stations* data for T_2 is also required.

Moreover, any properties of the process fluid that have a significant influence on the selection of the control valve should be defined. For liquids these are density and vapour pressure, for gases and vapours they are standard density, isentropic exponent, and also the real gas factor.

For a sensible choice of valves from the economic viewpoint, the particular task of the control valve within the overall plant also plays an important role. It has to be decided whether the control valve during intended operation of the plant is in constant use, or whether it is used only in special circumstances (during start-up/shut-down, or for safety functions). This information is normally not included in the control valve data sheets. It is therefore sensible in such cases if the planner or operator allows the supplier to see the R&I diagram in which the media flows and, in particular, in which the control circuits can be seen. Selection of an optimised control valve normally takes place in three stages:

Constant use or use in special circumstances

Three selection stages

- calculation of the required flow rate coefficient and the flow conditions present in the valve – selection of suitable valve trim style and the nominal valve size
- selection of the valve type and design
- selection of materials for the valve housing and valve trim as well as selection of materials for the sealing elements.

Calculation of flow coefficients, selection of valve trim and nominal valve size

Calculation programs

To determine the required flow coefficients, calculation programs from the valve manufacturers (such as ARCAVENA) or independent engineering tools (Conval® amongst others) are available. These programs basically feature:

- a calculation of the flow coefficient in accordance with IEC 60534-2
- an estimation of the sound level (under standardised conditions) in accordance with IEC 60534-8-3 or 60534-8-4, as well as

- predictions concerning the flow conditions in the valve

and in most cases:

- the required nominal valve size or
- the flow velocity for a prescribed valve size.

The calculation programs of the control valve manufacturers also usually enable the optimisation of valve types and trims with regard to their noise levels and cavitation characteristics.

Selection of valve trim for liquids

In the first calculation in which, as a rule, a single-stage *parabolic plug* is assumed, one of the following flow states is predicted:

Flow conditions

- subcritical (laminar or turbulent) flow
- cavitation
- vaporisation (flashing).

If *laminar* or *turbulent flow* is present, the single-stage parabolic plug is the correct choice.

For the case in which the first calculation predicts *cavitation*, it must be clarified whether the cavitation, which does not necessarily signify destruction of the valve, can be tolerated. The destruction of the valve as a result of cavitation is a complex process that is essentially a function of the energy conversion of the valve, the downstream pressure p_2 and the material and/or wear protection of the valve seat and valve plug. If destruction by means of cavitation must be assumed, usually accompanied by an intolerable sound level >85 dB(A), the only effective option for reducing the level of cavitation or reducing the damage caused by the cavitation is the distribution of the pressure drop, or more precisely the pressure ratio, over a number of control stages. In most cases the

Distribution of pressure drop to several control stages

optimal solution remains the use of a parabolic plug with up to five matched control stages in series (Fig. 12).
In the event of *vaporisation*, also called flashing, a mixture of fluid and vapour remains present behind the throttling point. On account of

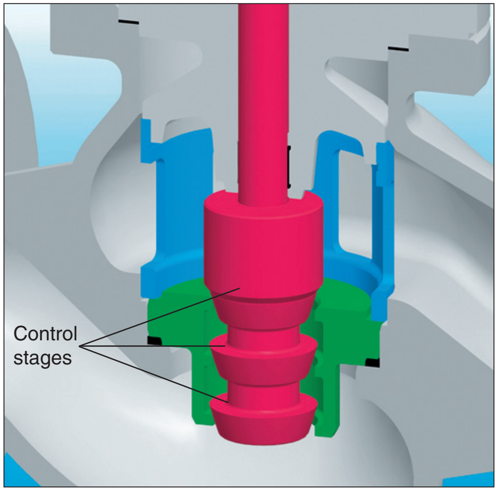


Fig. 12: Three-stage parabolic plug

the residual gas fraction, flashing is not linked with very high sound pressure levels; on account of the high velocity of the liquid/vapour mixture in the area of the throttling point, damage to the valve inner parts and in extreme cases even damage to the housing is possible as a result of droplet impact. Under these kinds of operating conditions *perforated plugs* (Fig. 13) are preferably used, in the case of very small K_{vs} values parabolic plugs are also used, the preferred "medium closes" *flow direction* preventing damage to a large extent of the functional parts of the valve such as the stem and the guide bushing as a result of droplet impact. Under extreme operating conditions, the risk of erosion on the valve

Use of perforated plug

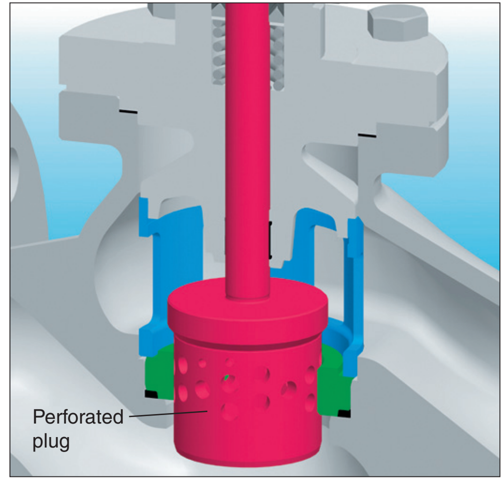


Fig. 13: Single-stage perforated plug

housing can be minimised by the use of angle valves, since the flow of the process medium behind the throttling point is not deflected any further.
When using parabolic plugs, in particular with liquids with a high pressure difference ratio (not necessarily linked with cavitation or vaporisation), vibration of the valve plug sometimes occurs which can often even lead to fracture of the valve stem. The cause for these vibrations is that the parabolic plug, submerged in the flow, is always in unstable equilibrium, as dictated by the Bernoulli effect. Thus if the plug deflects to one particular side, a higher flow velocity occurs at exactly this side and there is therefore further lowering of the pressure.

Bernoulli effect

Although this physical effect cannot be avoided in the case of a parabolic plug, it is possible to ensure the stability of the plug simply by means of a robust guide (usually double-guided plugs with one guide each above and under the plug). In conventional

Fig. 14: Double-guided parabolic plug (conventional system)

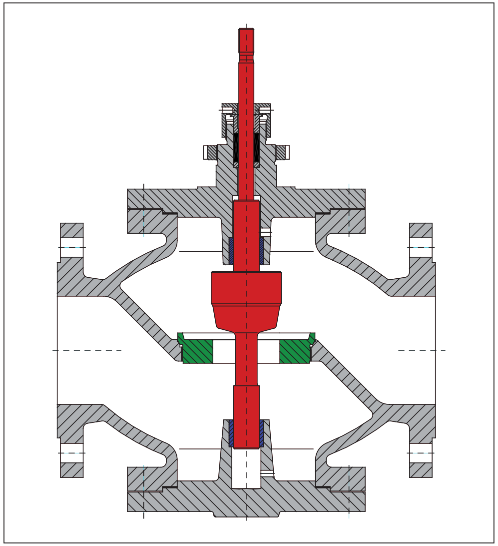
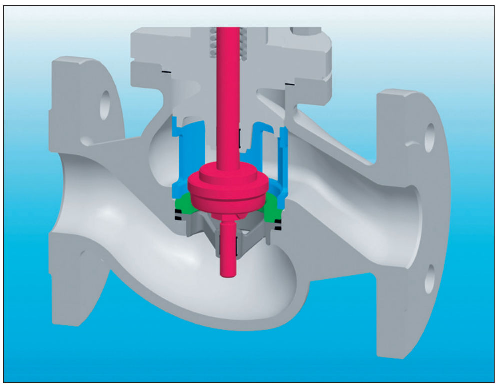


Fig. 15: Double-guided parabolic plug (quick-exchange system)



valves this is achieved with the aid of a special bottom flange; this, however, requires an additional static seal and is moreover very sensitive to contamination (Fig. 14).

Quick-exchange system

In the case of a quick-exchange system with a double guide (Fig. 15), these limitations do not occur. Here, no additional sealing point is

required, and the lower guide bushing is moreover open to the bottom and is thus insensitive to contamination. A further advantage consists in the fact that these trims can be simply and cost-effectively retrofitted as required.

Selection of valve trim for gases and vapours

Subcritical and supercritical expansion

Various flow conditions are also predicted by valve calculations in the case of gases and vapours. A differentiation is made between *subcritical* and *supercritical expansion (choked flow)*. The latter is distinguished by the fact that the sonic velocity of the gas is exceeded within the throttling point and the loss of energy no longer takes place through turbulence but in the form of compression shocks (similar to the supersonic boom of an aircraft). These act on the inner parts of the valve and can, for example, lead to fracture of the valve stem by vibration. In an analogous manner to cavitation, a supercritical expansion can only be avoided by distributing the pressure ratio over a number of expansion stages.

Sound reduction

In the case of gases, the supercritical expansion is almost always accompanied by a very high sound level. In the case of subcritical expansion, a sound level also very often occurs that is far above the values that can be tolerated, which as a rule lie between 80 and 85 dB(A). For gases and vapours, there are two possibilities of reducing the sound level:

- multi-stage expansion
- distribution of the total flow into as many flow passages as possible (see section on “Sound emissions”, p. 56 ff.).

Sound-reduced valves for gases work mainly with a combination of both options. There are, for example, designs with one- or multi-stage perforated plugs in combination with fixed-flow dividers (perforated discs and cylinders, wire meshes or labyrinth inserts). These designs should, however, only be used with "clean" process media. For gases (and of course also for liquids), which, for example, contain solids or contaminants, perforated plugs and labyrinth inserts can only be used to a limited extent. Compromises must be made here. In such applications, only valve trims should be used that cannot be affected by solids or by polymerisation.

Determination of the suitable nominal valve size

In most cases, the minimum nominal valve size is already prescribed when the K_{vs} value has been determined and the choice of the valve trim made. It must merely be checked whether the nominal valve size matches the specified nominal pipe size. This is the case if it is not larger than the nominal pipe size, and, for mechanical reasons, is also not smaller than half the nominal pipe size.

Matching to nominal pipe size

If control valves are being used for the expansion of gases at high pressure ratios, it is essential when selecting the valve size to be aware of the gas velocity with reference to the nominal size of the valve outlet. The outlet velocity should in no case be more than half, preferably no more than a third of the sonic velocity. If the outlet velocity is higher than the sonic velocity, there is a risk that the valve will be damaged by shock waves. A moderate means for reducing the outlet velocity consists in raising the downstream pressure by means of perforated discs arranged downstream. This assumes, however, that the nominal valve size is smaller than the nominal pipe size and that the perforated discs are installed downstream of the pipe expander. From a

Attention to the outlet velocity

fluid mechanics point of view – and indeed for all probable operating conditions – the perforated discs must always be considered in conjunction with the control stages installed in the valve.

Control valves in which fluids are expanded near their boiling point and in which a significant level of vaporisation occurs must likewise be considered critically with regard to their outlet nominal size, since the vapour fraction has about 800 times the volume of the corresponding liquid fraction. The vapour fraction downstream of the valve, and with it also the flow velocity at the valve outlet and in the downstream pipe, can be determined with the aid of thermodynamic calculation methods. Perforated discs cannot be used in such applications because of the droplet impact that is always present. Experience shows that the nominal pipe size in such cases is often underdimensioned by the plant planners. This cannot be compensated by the control valve alone.

Large vapour volume

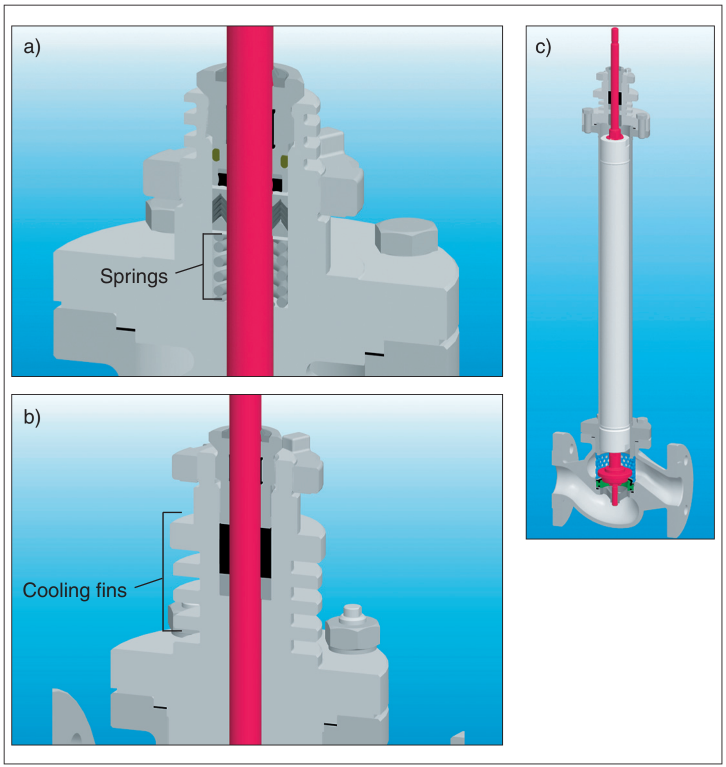
Selection of the valve design

The selection of a valve design suitable for the application in question is dependent on the design temperature, the design pressure and the properties of the process fluid. With regard to its universal applicability, the single-seat control valve in globe style (entry and exit on opposing sides) always represents the first choice. By means of appropriate bonnets and valve trims it can be matched to almost any application.

Single-seat control valve for universal use

In the selection of the bonnet, the permissible or optimal temperature in the stuffing box area, the possibilities for thermal insulation and – in the case of valves for cryogenic applications – also the introduction of heat, are key factors. The standard bonnet, is the typical bonnet for the temperature range between –10°C and +250°C. In the range up to +200°C and up to a nominal pressure (PN) of 40 bar, a self-adjusting spring-loaded stuffing box (Fig. 16a) is state of the art. At operating temperatures above 250°C, cooling fins (Fig. 16b) usually come into use, in conjunction with an adjustable graphite stuffing box. Although graphite stuffing boxes can actually be used up to a temperature of 450°C, for temperatures above 250°C, cooling fins are used as a matter of principle on account of

Fig. 16:
a) Spring-loaded stuffing box with standard bonnet
b) Bonnet with cooling fins for use at high operating temperatures
c) Insulation column



Bonnet with cooling fins

the better capability for insulation of the valves. If the operating temperature lies above 450°C , it must be ensured by an appropriate design of the cooling fins and by means of heat insulation of the valve that the temperature in the stuffing box area, even in the most unfavourable case, does not exceed 450°C.

Insulation column at cryogenic temperatures

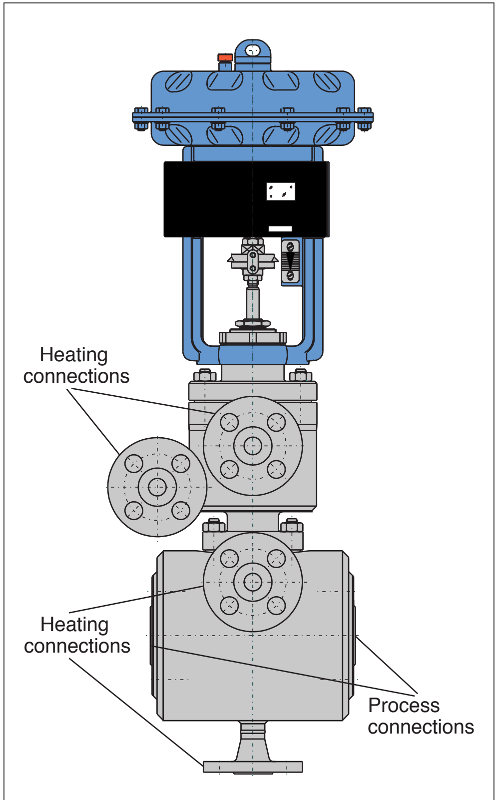
At cryogenic temperatures an *insulation column* (Fig. 16c) is used. This serves to ensure an energy exchange between the cryogenic process medium and the environment that is as low as possible, and also serves to protect the *stuffing box* from icing. According to requirements, the range of design stretches from a simple extension tube with a massive valve stem up to an insulation tube with a hollow stem filled with mineral foam that reduces convection both within and also outside the valve stem to the greatest possible extent.

In the case of severely “contaminated” process media, the control valves should be selected appropriately, i.e. any designs featuring fine open structures should be avoided as much as possible. For large nominal diameters or high pressure differences, double-seated valves provide a suitable alternative to pressure balancing systems.

Measures specific to the process fluid

With abrasive media, angle-style valves come into use on account of their free outflow conditions; in combination with suitable materials they achieve a high lifetime even under extreme conditions. If the process fluid has a tendency towards polymerisation, both the valves and also the pipe system should be heated (Fig. 17). For this purpose, *heating jackets* that use thermal oil or steam are suitable. Care must be taken that the stuffing box area and/or the bellows are also heated if necessary.

Fig. 17: Control valve with steam jacket for valve body and cover flange (ARCA ECOTROL®)



Selection of materials for valve housing and trim

The key factors for the selection of valve housing materials are:

Selection criteria

- operating pressure
- temperature range
- chemical resistance and interaction with the process fluid
- mechanical strength

- wear resistance (abrasion, erosion) and the
- regulations (DIN or ANSI, TRB 801).

If the material of the pipe system is defined in the specification, this material or a corresponding casting material should be used for the valve housing. If the process medium does not demand any particular measures and selection of the material is based only on operating pressure and temperature, the material selection reduces to a few material groups (Table 1).

European Standard	For temperatures	ASTM	For temperatures
1.0619 GP240GH	–10 to +400°C	A 216 WCB	–28 to +400°C
1.4408 GX5CrNiMo 19-11-2	–196 to +300°C	A 351 CF8M	–196 to +400°C
1.4581 GX5CrNiMoNb 19-11-2	–10 to +400°C	–	–
1.6220 G20Mn5	–40 to +400°C	A 352 LCB	–50 to +400°C
1.6982 GX3CrNi13-4	–120 to +400°C	–	–
1.7357 G17CrMo5-5	–10 to +530°C	A 217 WC6	–28 to +530°C

Table 1: Material selection for valve housing

Special alloys

The limits of use for the materials for pressure-bearing parts are usually represented as a function of the nominal pressure in pressure-temperature diagrams. If, in addition, there is also the risk of corrosion attack arising from the process medium, one must resort to the use of special alloys. Specialised casting foundries offer many alloys that have been developed purely for particular applications, as well as their corresponding corrosion resistance tables. Very detailed information can be found in the Dechema Materials Handbook (www.dechema.de). For certain process fluids, tight guidelines with regard to material selection and design requirements have been produced by the user organisations. Examples of these are the Eurochlor Guidelines

GEST 98/245 (www.eurochlor.org) or the Oxygen Guidelines of the European Industrial Gases Association (www.eiga.org).

With severely corrosive process media, it is not sensible to make a valve housing out of a homogeneous corrosion-resistant material for reasons of cost. Here, *lining* the valve housing with corrosion-resistant metallic, ceramic or polymer materials provides a solution. In this case, it is absolutely essential that the pressure-containing housing does not under any circumstances come into contact with the process medium. Particular attention must be given to the bearings, the inner parts and all sealing points.

Lining with corrosion-resistant material

For throttling elements and valve seats, either chromium steels (e.g. 1.4021/A473), austenitic chromium-nickel steels, chromium-vanadium or chromium-molybdenum steels are used. The material of the control valve functional parts should be of at least the same quality as the housing material, and if possible of even higher quality. The materials used for the valve trims and for the particularly highly loaded areas in the control valve are summarised in Table 2.

Different hardness values by surface treatments

By means of surface treatments such as nitriding or the Tenifer® treatment it is possible to produce hardness values that are specifically different in the friction pairs, for example in the perforated plugs and in the guide bushings of the valve. In particularly highly loaded areas of the valve trim and in areas of very high flow velocities, additional hard-platings and ceramic materials such as Stellite®, tungsten carbide, aluminium oxide, zirconium oxide or silicon nitride are used, in particular when abrasive process media and high pressure differences are present. An essential prerequisite for valve trims made of carbides or ceramics – in particular on account of the different thermal expansions of the materials used – is a “ceramics-compatible” design of the control valve as well as the experience of the valve supplier in selection of the suitable compound. Ideally, the supplier should make use of a modular system with which such solutions can be implemented in a flexible, replaceable and economical manner. Figure 18 shows a control valve from a modular system with a tungsten-carbide valve plug and a dual-sided tungsten-carbide valve seat; the modular system significantly reduces the costs associated with the use of the normally very expensive ceramic inner parts.

“Ceramics-compatible” design

Material	For temperatures	Typical application
1.4021 X20Cr13	–10 to 400°C	Standard applications with water, steam and non-corrosive media
1.4571 X6CrNiMoTi17-12-2	–196 to 400°C	Applications with increased requirements for corrosion resistance
Stellit® alloy 6 (often as weld-on hard facing)	–196 to 400°C	Increased mechanical strength with good corrosion resistance
1.4112 X90CrMoV18 (hardened)	–10 to 400°C	Steam and water with high differential pressure
1.4922 X20CrMoV11-1	–10 to 580°C	Especially for use above 480°C
Tungsten carbide Special ceramics	–10 to 400°C	In case of risk of erosion by solids in the flow medium

Table 2: Material selection for valve trims

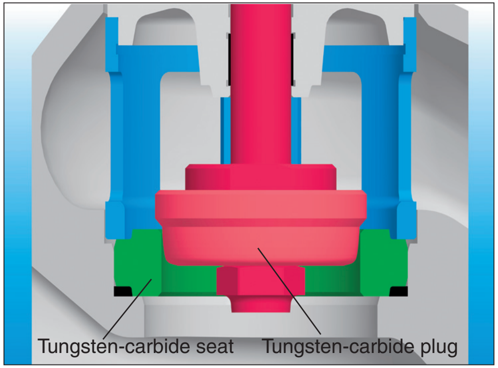


Fig. 18: Control valve with tungsten-carbide plug and dual-sided tungsten-carbide seat

Selection of materials for sealing elements

Graphite or …

… PTFE compound

For static sealing applications, high-quality gaskets made of graphite with a spiral insert have established themselves. Here, the spiral insert provides a defined pre-load that is mainly generated in the force bypass. If graphite is not permissible for process reasons, seals made of a PTFE compound can also be used. For the stuffing box area, *packings* made with a PTFE or graphite base material are mainly used (Table 3). PTFE packings are configured either as self-adjusting V-ring packings or as manually adjustable packings. Pure graphite packings are reserved for higher temperatures on account of their much less favourable friction properties.

Other seal materials used in control valves are located in the seat seal (in the case of soft seal "bubble-tight" valves), or in sealing rings for pressure balancing systems, or in O-rings for special sealing tasks. In the selection of materials for the sealing elements, knowledge of the limits of use of the material in question with regard to pressure, temperature and chem-

Max. temp. (°C)	Max. press. (bar)	Gasket form Process flange	Static valve gaskets	Packing type	Typical application
250	100	Simple flat gasket	Spiral-wound gasket with sealing filler (graphite or PTFE)	Braided PTFE packing	General engineering for uncritical media
		Flat gasket of specially treated PTFE		PTFE V-ring packing	Standard specification in chemistry, petrochemistry, apparatus engineering and power industry
480	160	Thin gasket of pure graphite	Spiral-wound gasket with sealing filler (graphite and/or PTFE)	Carbon-fibre/graphite braided packing	Standard specification in chemistry, petrochemistry, apparatus engineering and power industry
		Spiral-wound gasket with graphite sealing filler		Pure graphite foil packing (rolled)	High-temperature application especially with steam
250 to 480	160	Serrated gasket	Spiral-wound gasket with sealing filler (graphite and/or PTFE)	Carbon-fibre/graphite braided packing	Highly stressed valves in chemistry and petrochemistry
				Bellow sealing	Very high tightness requirements (TA Luft) and very corrosive media
>500	400	Metallic lens gasket	Metallic lens gasket	Bellow sealing	High-pressure and high-temperature application, also vacuum technology
	420	Metallic ring-joint-gasket	Metallic ring-joint-gasket	Carbon-fibre/graphite braided packing	Chemistry and petrochemistry, mostly in Anglo-American countries

Table 3: Static seals and their areas of application

ical resistance is indispensable. The tables of the well-known seal manufacturers provide appropriate information.

Emissions

The worldwide increase in awareness of environmental issues and the resultant emissions-related obligations for the operation of process technology plants in the form of legislative requirements, guidelines or standards affect all individual components of the plant, and in particular the control valves. For control valves, the following three features play key roles with regard to environmental compatibility: the external tightness, the internal tightness, and the sound emissions.

Three essential features

External tightness

The external tightness is an essential criterion from the ecological viewpoint and is clearly specified in numerous acts and standards (e.g. in ISO 15848) as a function of the medium that is being sealed. It is essentially determined by the pressure boundary parts such as housing, bonnet, bonnet bolting, and the sealing between valve housing and bonnet.

Standard: self-adjusting stuffing box

Here, the central role is played by the valve stem seal. The traditional valve stem seal is a self-adjusting or adjustable stuffing box. With a high-quality self-adjusting stuffing box, it is possible to achieve leakage values that meet the requirements of ISO 15848 Class B or the *TA Luft* (the legislative requirements in Germany for media that are injurious to health). These requirements are so strict that for a car tyre filled with helium, for example, they would correspond to a pressure drop of 0.1 bar over a period of 200 years.

If the sealing requirements on valve stem seals are even higher, so-called hermetic seals are used. In these sealing systems, only static sealing elements are present, the movement of the valve stem is accommodated by the deformation of a component especially designed for this purpose. The classic variants of a hermetic stem seal are the diaphragm seal (Fig. 19a) and the bellows seal (Fig. 19b).

Diaphragm seal

The *diaphragm seal* is used for pressures in the range up to approx. 10 bar. Amongst its important advantages are low price, compact configuration and also a potential sterilisation capability. The *bellows seal* has established it-

Bellows seal

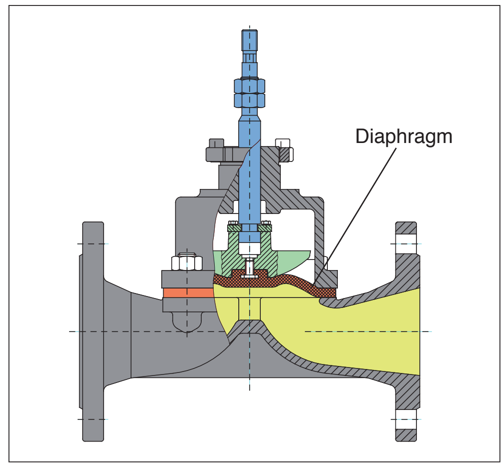
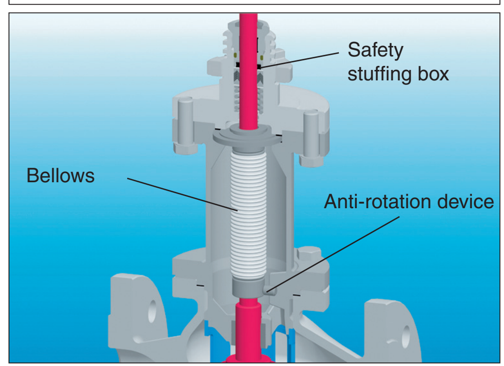


Fig. 19:
a) Diaphragm seal



b) Bellows seal with integrated anti-rotation device self as a universal stem seal for control valves. While it requires more space and is also more expensive than a diaphragm seal, if designed to meet high quality standards it provides, besides the guaranteed sealing function, a long service life (far in excess of one million strokes) and covers the complete range of operating pressures up to 400 bar and temperatures up to 500°C.

Adequate protection against torsion

An essential feature of a well-designed bellows seal is adequate protection of the bellows against torsion, which can significantly reduce the lifetime of the bellows. Torsion can arise as a result of incorrect installation (for example, when coupling valve and actuator), but also as a result of torques which, arising from the valve or the process, act on the valve trim and thus on the bellows. These torques should be eliminated by means of an anti-rotation device integrated into the bellows housing.

Hydraulically assisted diaphragm seal

A forward-looking development which combines the advantages of a bellows seal (pressure range and operational reliability) with those of a diaphragm seal (compact configuration and a sterilisation capability) is represented by the *hydraulically-assisted diaphragm seal.* In this type of seal, the diaphragm continues to function as a separating element between the process medium and the sealing fluid, but now no longer has to withstand the static pressure of the process medium (Fig. 20). The alteration in volume of the sealing fluid during the movement of the valve stem is compensated for by the corresponding deformation of the diaphragm. This is configured as a double diaphragm. This design ensures that it meets the most stringent requirements regarding plant safety and availability. Between the two diaphragms is located

Remote monitoring

a non-pressurised intermediate space that can be monitored by means of a testing connec-

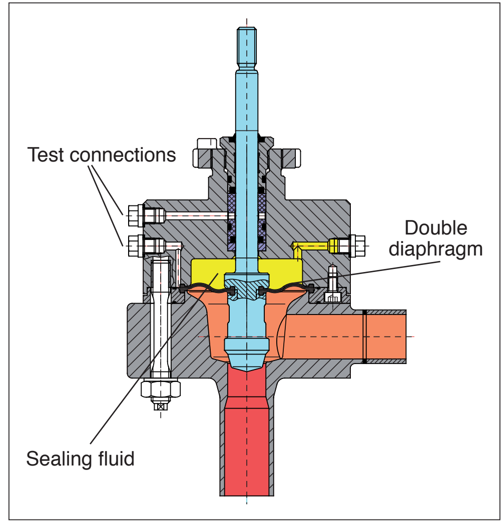


Fig. 20: Hydraulically assisted diaphragm seal (ARCA OPTISEAL®)

tion. This means that any fracture of the diaphragm on the primary side (the medium side) or on the secondary side (the sealing fluid side) is detected. In either case the hermetic seal remains intact, however, and no contamination of the process medium by the sealing fluid can occur. In this way, the valve remains fully functional up to the planned removal of the defect. Moreover, as a result of the hydraulic assistance to the diaphragm, this sealing design minimises the necessary actuator force and the size of actuator. Thus it combines:

- low overall height
- gap-free design
- absolute hermetic external sealing function
- a large pressure and temperature range as well as
- redundancy by means of the double diaphragm with diaphragm fracture monitoring

and is thus an economical, and in many cases also a technically better, alternative to the conventional bellows seal.

Internal tightness

The internal tightness describes the possible leakage of a valve between fluid entry and valve outlet when in the closed position. It is of decisive importance for the process and is determined by:

- the design configuration of valve seat and valve plug
- the form of attachment between valve seat and valve housing, and
- the dimensioning of the actuator.

For control valves the leakage classes according to IEC 60534-4 apply, and thus other testing methods than those for shut-off valves. This difference is based on the fact that the requirements in control operation (stability of the throttling element) and absolute sealing function represent somewhat contradictory requirements.

Sealing class IV …

Today, the usual sealing class for control valves is class IV, i.e. the leakage flow rate is one ten-thousandth (0.01%) of the flow rate at fully opened position (presupposing a constant pressure difference).

… or higher sealing classes

The higher sealing classes V ("metallic-lapped") and VI ("bubble-tight") are used mainly only when there are particular requirements, for example, in the case of valves which expand either directly into the atmosphere or (in the case of combustible media) via a flare, and whose leakage rate thus signifies a direct energy or product loss. As an example of such cases one can consider a flare valve with a nominal size DN 100 for hydrogen at a plant pressure of 40 bar. The following applies:

- DIN IEC 60534-4 Class IV corresponds to approx. 27.5 Nm^3/h
- DIN IEC 60534-4 Class V corresponds to approx. 0.038 Nm^3/h
- DIN IEC 60534-4 Class VI corresponds to approx. 0.009 Nm^3/h.

The internal tightness is tested individually as part of the final testing for control valves and is recorded in a test report. In the case of screwed valve seats, the internal tightness can alter so strongly in operation under alternating load conditions, even after a short period of time, that the reality no longer corresponds to the measured leakage value recorded in the test report. Clamped valve seats do not show these deviations with regard to the internal tightness.

Additional metallic sealing

In the soft sealing shown in Figure 21, an additional metallic sealing between the valve seat and the valve plug ensures that the permissible surface load of the PTFE soft seal element is not exceeded, even for over-dimensioned actuators, and therefore no so-called "cold flow" of the PTFE material occurs. The defined pre-load of the sealing element is permanently guaranteed by means of an O-ring spring system. This soft seal configuration has proved itself under the most difficult condi-

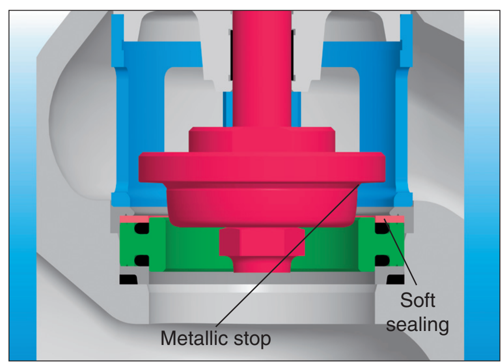


Fig. 21: Soft sealing with additional metallic sealing (ARCA patent)

tions over more than one million operating cycles (see section on “Control valves for pressure swing adsorption plants”, p. 62 ff.).

Sound emissions

During the pressure reduction in a valve, part of the energy of the process medium is converted into sound energy and radiated both from the valve itself, but also primarily from the pipe system. Guidelines as well as health and safety at work legislation are pushing towards “quiet” valve solutions; sound level requirements of 70 to 75 dB(A) are not unusual.

“Quiet” valve solutions

The increasing demand for lower sound emissions from process plants often come up against not only economic boundaries but also technical limitations. Low-noise valves require not only more complex inner parts, but often also a larger housing. This is reflected in significantly higher costs.

Extreme levels of sound emission are always also an expression of mechanical stress. Whenever considering sound emission it must always be borne in mind that while the sound is in fact generated in the valve, the sound radiation actually emanates from the downstream pipe system. With reference to sound generation, a differentiation must be made here between incompressible and compressible media.

Sound radiation into the pipe system

Sound generation

For liquids, the sound sources are in the turbulent flow conditions at the throttling points and downstream. Here, the energy of the fluid is converted into not only heat but also sound energy. If the pressure ratio across the valve exceeds the *critical pressure ratio*, cavitation sound also occurs. While the sound level resulting from turbulent flows generally lies

Turbulent flow as the reason

within tolerable limits, cavitation sound can easily exceed these limits, even in the case of small valves. In addition, cavitation must always be seen as a possible cause for the destruction of the valve inner parts.

Cavitation sound

For gases or vapours the main cause of sound emission is, for subcritical expansion, the partial conversion of the energy into sound energy. Because of the significantly higher flow velocities compared with liquids, the sound pressure level increases sharply with rising pressure difference. Even for relatively small valves, it can already lie above permissible limits and cause impairments to health. If the pressure ratio across the control valve exceeds the X_T *value*, shock waves are the main cause of sound emission in the expansion zone.

Rise of sound pressure level

Primary sound reduction measures

In gaseous flows, a reduction of the level of sound generation is achieved by distributing the throttling area into many smaller individual flow passages (perforated cage, perforated plug, multi-slot plug). In this manner, the sound-generating source is divided into many individual sound sources. On account of the lower extent of the turbulence zone and the higher frequency range, these generate in total a lower level in the A-weighted sound spectrum relevant to human hearing. The second effective measure is the distribution of the throttling process into a number of stages. In this manner, a lowering of the flow velocities, which are causally responsible for the sound generation, is achieved in the individual throttling stages. Here too, the sum of the individual sound levels adds up to a significantly lower overall level in comparison with the single-stage throttling process. Included in the multi-stage throttling design concept are also uncontrolled (static) throttling stages such as

Distribution into many individual flow passages

Multi-stage throttling

perforated cages and perforated discs. In particular, if cavitation and supercritical expansion are present, distribution of the throttling process is always to be considered as a primary measure. In spite of their "open" flow areas, perforated discs, perforated cages and perforated plugs also have an encapsulating effect on the sound generated by the upstream stages and thus act further to reduce sound levels. Figure 22 shows a three-stage valve with

Additional encapsulating effect

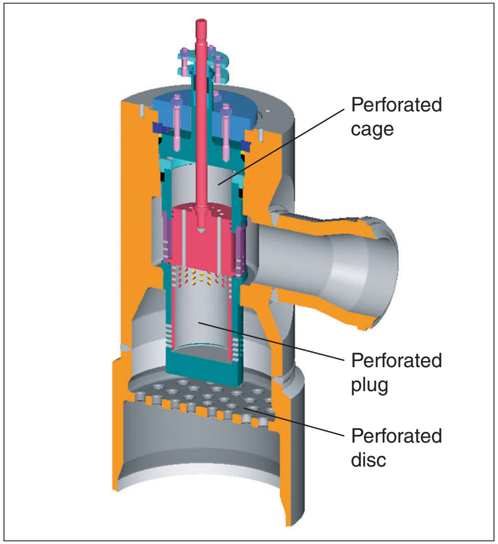


Fig. 22: Three-stage control valve with controlled perforated plug/cage combination, pressure balancing system and downstream perforated disc

a controlled perforated cage/perforated plug combination and a downstream set of perforated discs that is integrated into an enlargement of the housing. With combinations of this kind, it is possible to achieve sound level reductions of 10 to 30 dB(A), relative to a single-stage parabolic plug. Even a simple perforated plug can result in a sound level reduction of up to 15 dB(A), depending on the pressure ratio.

Secondary sound reduction measures

Reduction of sound radiation

Secondary sound reduction measures are concerned not with sound generation but rather sound radiation. The components used for this purpose are mainly insulators, downstream sound dampers or acoustic enclosures. Since the sound radiation of the acoustic energy generated in a control valve occurs over a very long length of pipe, extending sometimes more than one hundred metres, the introduction of secondary sound reduction means is resource-intensive and should therefore always be considered as an additional measure only.

Sound-optimised installation location

Sound-amplifying interactions can occur between the valves and any pipe bends that are located too close downstream, and also any other items installed in the pipe system. For this reason, consideration must be given at an early planning stage of the pipe system to a sound-optimised installation of the valve. The sound predictions given by the valve manufacturers, however, are related to "idealised" upstream and downstream conditions. The pipe system itself must also always be considered as a potential sound source whenever the flow velocity exceeds Mach 0.25.

Modern solutions for special areas of application

The range of control valves is extraordinarily large and the number of applications is correspondingly numerous. In the following sections some applications are described as examples.

Control valves in power generation

In power stations, control valves are used in all areas. These extend from regulation of the fuel through to control of flue gas cleaning plants. However, one of the most interesting areas of application for control valves is the feed water/steam circuit.

Use for fill-up or start-up procedures

Under normal operating conditions, control valves in the feed water circuit do not cause any problems whatsoever. An interesting challenge arises, however, if control valves are used not only to supplement the feed water that has vaporised, but also to fill-up or start-up boilers. In this event, the high-pressure feed water under start-up conditions is firstly reduced to atmospheric pressure. Here, the control valve passes through all stages of flashing and cavitation and is extraordinarily highly stressed. Only with the aid of special design measures can these operating conditions be controlled with “normal” feed water control valves without the need for an additional filling and start-up valve.

During the start-up of the boiler, saturated steam vapour firstly enters into the steam system and is then exhausted via the *start-up valve*. Only special control valves with a very wide rangeability are suitable for this purpose. The steam is then fed into the superheater. Here, the temperature is adjusted by means of injection coolers, or also by means of 3-way control valves, before the steam enters the turbine. A whole series of control valves operates in the turbine environment (e.g. sealing steam control valves, drainage control valves) through to the extraction and by-pass stations, which in each individual case is represented by a pressure control valve with integrated cooling water injection to maintain a prescribed temperature. These valves maintain correct boiler operation if the turbine itself is not in operation. Thus various low- and medium-pressure systems must also be supplied, or the live steam must be completely condensed and fed to the water-steam circuit.

Temperature control

Steam is also required for the heating of various heat exchangers and supply systems up to the heating of the feed water tank, and is precisely controlled by many control valves according to the required process and the peripheral conditions. Wherever thermal energy is extracted from the steam and converted to condensate, control valves are used for the control of pressure and temperature.

Valves with quick-exchange systems

Here, easy-to-maintain valves with clamped valve seats that can be used on both sides (quick-exchange systems) have proved to be particularly advantageous, especially during commissioning, since in spite of taking the greatest care, it is not possible to flush the pipe system so that it is really clean. Thus contaminants remaining in the system inevitably lead to damage of the valve seating surfaces during the start-up of a plant. In this case, the valve can be opened without special tools and the clamped seat turned over. This particular advantage of the quick-exchange system ensures that commissioning can be continued without further delay.

Control valves for pressure swing adsorption plants

PSA plants (PSA = Pressure Swing Adsorption) are used to separate and clean gases such as hydrogen, helium, nitrogen. In the case of hydrogen, it is possible to achieve cleanliness levels of 99.9999% by means of the PSA method. The method is very energy-efficient since it takes place at ambient temperature. At the heart of this method are 4 to 12 pressure tanks that are filled with an adsorbent. This adsorbent has the property of adsorbing certain gases at a particular pressure and of releasing them again at a lower temperature. By means of a systematic transfer of the gas between the individual adsorbers, the gas is cleaned in a staged manner. The typical cycle time of a PSA plant lies between 20 seconds and several minutes and thus places high requirements on all plant components – particularly on the control valves. These must work reliably for more than one million operating cycles per year and moreover must guarantee a bubble-tight shut-off. Control valves optimised for alternating pressure plants:

More than one million operating cycles

- are made of superior quality cast steel with a reduced carbon content to minimise the risk of hydrogen embrittlement
- have a reliable soft seal function and
- at nominal valve size of 80 (3") and higher provide a reliable pressure balancing system, since the travel times required are possible only with relatively small pneumatic actuators.

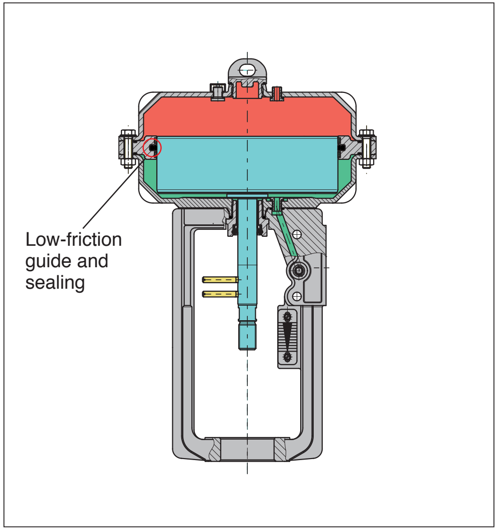


Fig. 23: Double-acting piston actuator

The trend to ever larger actuator forces within ever shorter switching times leads to the preferred use of double-acting *piston actuators* (Fig. 23). In recent years, this type of actuator has proved itself in a large number of installations.

Double-acting piston actuator

Anti-surge control valves on turbocompressors

In turbocompressors, a control valve is installed in the bypass that blows the compressed volumetric flow of gas back into the intake of the compressor, or (if the process medium is air) blows it off into the atmosphere. These valves are used in the first instance during the start-up and shut-down of the compressor. During critical running conditions, or with fluctuating consumption in spite of a constant rotational speed, they are also used in order to blow off excess gas quantities.

Function as a safety device

Their most important task, however, is to act as a safety valve in surge limit control functions.

Anti-surge control devices have the task of preventing so-called “pumping” in turbocompressors under all circumstances – this word describes the stalling that occurs at the compressor blades if a minimum flow through the compressor is not maintained. Stalling can cause vibration of the compressor rotor and thus damage to the bearings, to the rotor itself or to the blades. In the compressor characteristics, the blow-off line is therefore established at a certain safety distance below the surge limit. For economic reasons this distance should be as small as possible. Reduction of the safety distance inevitably raises the requirements on the anti-surge control valve. The control valve must on the one hand be sensitive, but on the other hand must also open within the shortest possible time without overshooting, i.e. without opening fully in the blow-off case.

Prevention of stalling

Single-seat control valves

Single-seat control valves with a linear or modified characteristic have proved themselves as anti-surge control valves in turbocompressors. Instead of parabolic plugs, perforated throttling elements are used today ever more frequently, since these guarantee sound reduction, even for valves that blow off into the atmosphere.

Since turbocompressors are becoming ever more powerful, the nominal diameter of bypass valves has in recent years extended up to DN 1200 with correspondingly large actuators. Here, the following travel times are achieved:

Stroke times

- opening via solenoid valve < 1 to 2 seconds
- opening via positioner < 3 to 5 seconds
- closing via positioner 6 to 20 seconds.

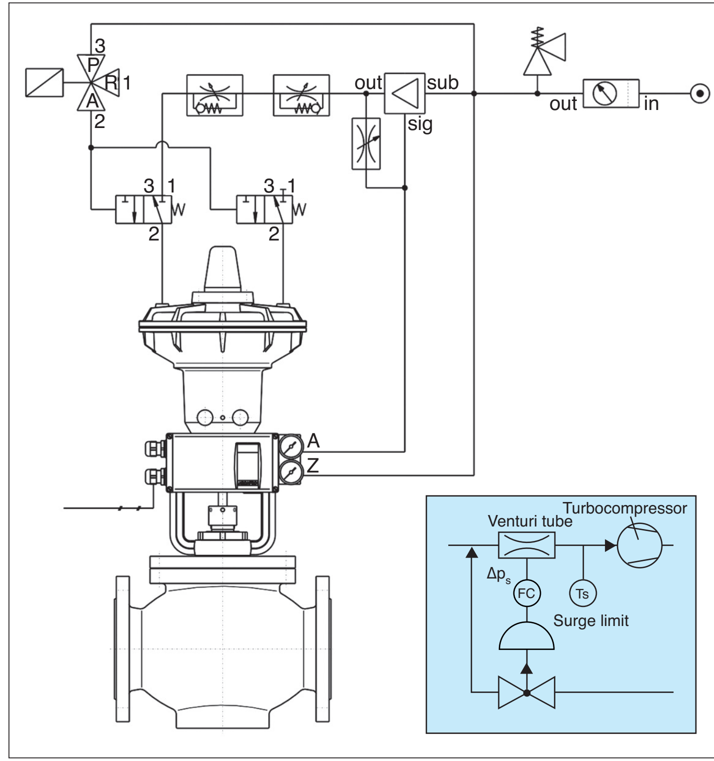


Fig. 24: Pneumatic schematic of an anti-surge control valve with volumetric flow rate as measured parameter

This requires reliable control of the valves by positioners, boosters and solenoid valves, and careful selection and matching of the pneumatic components and pipework (Fig. 24).

Process valves terminology

Acceptance testing The testing procedures defined in the regulations and standards to guarantee safety, function and quality of the valve.

Acoustic conversion factor Coefficient for the ratio of the power loss generated by the control valve that is converted into sound. In subcritical flow, the acoustic conversion factor is of the order of 10^{-6} to 10^{-4}, depending on trim and valve shape.

ATEX European directive for the correct use of equipment in potentially explosive environments.

Bellows seal Hermetic sealing on the valve stem against hazardous media by means of a metal or polymer bellows.

Cavitation Occurs when there is a temporary pressure drop in liquids below the vapour pressure. The collapse of the vapour bubbles generated at the throttling point leads to shock waves that can cause erosion damage when they impinge on valve bodies and internal parts of the valve. Cavitation is reduced by the use of multi-stage throttling bodies. To increase durability, hardened materials are used (see Fig. 25).

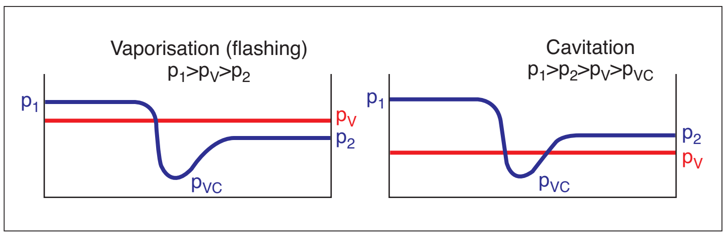


Fig. 25: Pressure distribution in the valve at flashing and cavitation

Characteristics These describe the ratio between valve position and opening cross-section prescribed by the shape of the throttling element. Linear or equal-percentage characteristics are customary.

Choked flow See *flow rate limitation*.

Critical pressure ratio See *flow rate limitation.*

Cryogenic temperature valve Special valve for liquid gases at temperatures between –196°C and absolute zero (–273°C).

Diaphragm actuator Pneumatic control actuator in which the pressure chamber is sealed off by a diaphragm. The diaphragm allows (particularly when compared with a piston actuator) a frictionless stroke movement and thus a very uniform actuation movement.

Downstream pressure increase For the purposes of sound reduction, the downstream pressure of the valve is increased by the use of fixed throttling stages (perforated discs and perforated cages) downstream of the valve. Lower pressure differences thus occur within the valve and, in the case of gases, reduced outlet velocities.

Flow direction In globe valves, this is predominantly against the closing direction of the plug. In the closing direction, sealing is assisted, but involves the risk of unstable (pneumatic) actuators and, in particular in the case of liquids, of *pressure shocks*.

Flow rate limitation Beyond a certain pressure difference ratio $x = (p_1-p_2)/p_1$, the mass flow through a valve can no longer rise by means of further reduction of the downstream pressure p_2. Sonic velocity then occurs at the narrowest throttling cross-section.

Flushing trim Place holder (mainly only for welded-in valves) mounted as a substitute for the inner parts to protect the valve during pipe flushing and pickling processes.

Heating jacket Pressure-tight enclosure of the valve body and the bonnet through which steam or heat transfer oil flows. Heating jacket valves are often used in smelting and for polymerising media.

Hygienic valve A valve for applications in the food and pharmaceutical industries with a special form of housing that counteracts the accumulation of deposits and enables simple cleaning.

Hysteresis In a control valve, the difference between the stroke positions that ensues with the same required stroke signal but with opposing directions of movement.

Installation position An installation position with a vertical stem (actuator on top) is preferred, because valve actuators cannot then exert any lateral forces or bending moments on the axisymmetrically aligned valve trim and their seals.

Instrument air Dry and oil-free air is indispensable for the fault-free operation of positioners and other pneumatic components (IEC 770).

Insulation column Extension of the valve stem used with cryogenic temperature media in order to protect the packing, actuator and positioner from icing caused by the cold medium, as well as to enable effective insulation.

K_v value Coefficient for the flow capacity of a control valve. 1 K_v corresponds to a flow rate of 1 m^3/h of water (20°C) at a pressure difference of 1 bar (see Figure 26 on page 68 for empirical formulae for calculation purposes).

Pressure loss	K_v	For fluid	For gas with temperature correction	For vapours
$p_2 > \frac{p_1}{2}$ $\Delta p < \frac{p_1}{2}$	K_v	$= \frac{Q}{31.6}\sqrt{\frac{\rho_1}{\Delta p}}$	$= \frac{Q_N}{514}\sqrt{\frac{\rho_N\, T_1}{\Delta p\, p_2}}$	$= \frac{G}{31.6}\sqrt{\frac{v}{\Delta p}}$
$p_2 < \frac{p_1}{2}$ $\Delta p > \frac{p_1}{2}$	K_v	$= \frac{Q}{31.6}\sqrt{\frac{\rho_1}{\Delta p}}$	$= \frac{2 Q_N}{514\, p_1}\sqrt{\rho_N\, T_1}$	$= \frac{G}{31.6}\sqrt{\frac{2v}{p_1}}$

Q	Volumetric flow rate	m^3/h
G	Mass flow rate	kg/h
p_1	Upstream pressure	bar abs
ρ_1	Density at the operating condition	kg/m^3
Q_N	Standard volumetric flow rate of gases	Nm^3/h
p_2	Downstream pressure	bar abs
ρ_N	Density at the standard condition	kg/Nm^3
T_1	Absolute upstream temperature	K
v	Specific vapour volume at T_1	m^3/kg

Fig. 26: Empirical formulae for the calculation of flow coefficients

Laminar flow Characterised by the uniform flow of flow particles along neighbouring paths without turbulence. Laminar flow only occurs in control valves at extremely low flow rates or with high-viscosity fluids.

Leakage class In a closed valve, there is always some leak flow between seat and plug. The requirement for the seat tightness and test methods is established in international standards (EN 60534-4).

Lining The pressure-containing metallic housing of the valve is clad on the side exposed to the medium with a chemically-resistant material.

Packing Dynamic sealing of the valve stem against the external environment.

Parabolic plug Simplest shape of a control plug that in conjunction with a circular opening (valve seat) forms an annular throttling point.

Perforated plug Control plug, configured as a perforated cylinder, that slides in a seat ring and according to its position opens up more or less holes and thus alters the throttling area.

Piston actuator Pneumatic actuator that possesses a dynamic piston seal instead of a diaphragm. Is often double-acting and is used for long strokes.

Plant characteristic The characteristic that ensues from the characteristic of the control valve, taking into account the pump characteristic as well as all pipe components. The *valve authority* is calculated from the plant characteristic.

Pressure balancing Elimination of the hydrostatic valve plug forces by means of pressure equalisation between the upper and lower sides of the valve plug. Requires complex design of the control plug into a piston-cylinder system with a sliding radial seal.

Pressure shock (Joukowski Shock) Sudden pressure rise evoked by the rapid deceleration of a flowing fluid in the pipe system caused as a result of closing a valve. The pulse of the flowing mass has a powerful potential for destruction.

Rangeability Generally the ratio of the largest to the smallest controllable flow rate. The inherent rangeability corresponds to the ratio of the largest to the smallest flow coefficient.

Reversing For pneumatic actuators, the change of the *safety position* (spring force) in the event of air supply failure.

Safety position Valve position prescribed in the event of failure of the actuator energy source: closed, open or locked.

SIL Abbreviation for *Safety Integrity Level*. Provides a classification to protect the health and well-being of people, the environment and of goods. Control valves are essential components in the assessment of process technology in this respect.

Silencer Static downstream throttling stages for sound reduction purposes (see *downstream pressure increase*).

Split-range operation Distribution of the flow between a large main control valve and a small fine control valve if the *rangeability* of the large valve is not sufficient to cover all working points

Start-up valve Additionally installed valve whose prime function is to start up the process. It is characterised by extreme operating conditions, but is not subject to constant load.

Steam conditioning station A valve for the combined pressure and temperature reduction of superheated steam by means of simultaneous throttling and injection of cooling water.

Stick-slip effect The difference in frictional forces during sliding and releasing the radial seals can, in conjunction with weakly (i.e. purely statically) designed pneumatic actuators, lead to undesirable jerky movements that prevent an exact positioning of the valve stem and plug.

Stuffing box Module for sealing of the valve stem with the *packing* as an essential component.

Subcritical pressure ratio The pressure difference across the throttling element is relatively small, so no *flow rate limitation* or *cavitation* occurs.

Supercritical pressure ratio The pressure difference across the throttling element is relatively high and causes *flow rate limitation* or *cavitation*.

TA Luft Abbreviation for “Technische Anleitung zur Reinhaltung der Luft” (Technical Instructions for Maintaining Clean Air). German regulation that places increased requirements on the stem sealing function in particular.

Turbine bypass station Steam conditioning station which in the event of failure of the turbine takes over its throttling and cooling functions.

Turbulent flow Irregular non-parallel flow. Flow-conditioned pressure differences are generated within the fluid and thus turbulence is generated.

Two-phase flow A mixed gaseous and liquid (e.g. wet steam/condensate) flow or a fluid flow with solid components (e.g. cellulose).

Valve authority A key figure that describes the influence of the valve on the process parameter to be controlled.

Valve characteristics These describe the ratio between valve stroke and opening area prescribed by the shape of the control plug. Linear or equal-percentage valve characteristics are customary.

Vaporisation Partial conversion of a liquid medium into the gaseous state during the throttling process to a pressure that lies below the vaporisation pressure of the liquid (see Fig. 25).