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One valve for many purposes - reduced complexity by separation of functions

PIF - new challenges for pumps and systems

Ingo Dietrich, Technische Universität Darmstadt, Chair of Fluid Systems

Tim Müller, Technische Universität Darmstadt, Chair of Fluid Systems
Marvin Meck, Technische Universität Darmstadt, Chair of Fluid Systems
Lukas Zinßer, Technische Universität Darmstadt, Chair of Fluid Systems
Mehdi Nakhjiri, Industrial Science GmbH
Gerhard Ludwig, Technische Universität Darmstadt, Chair of Fluid Systems
Prof. Dr.-Ing. Peter Pelz, Technische Universität Darmstadt, Chair of Fluid Systems

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ABSTRACT

Manufacturers of industrial control valves face the challenge of increasing internal and external complexity. The customers craving for simple, plug-n-play, products that fulfil exactly his needs leads to a steadily increasing number of different products.

Classical methods of product development provide two approaches: functional separation to reduce internal complexity and functional integration to reduce external complexity. We use these methods to develop the concept of an innovative control valve, reducing both, the internal and external complexity, compared to a standard globe valve.

The derived concept is shown, explained and then evaluated in regards to function, effort, availability and acceptance. The function is the primary objective a customer is looking for, making it a boundary condition. The effort is measured in installation space and energetic losses. The availability is expressed as uncertainty within the design. The customer acceptance is ensured by sticking to industry conventions and increased by an easy way to individualize the valve characteristics. The evaluation yields, that the design concept is promising.

Keywords: control valve, product innovation, complexity, uncertainty, separation of functions, integration of functions

1 INTRODUCTION

125 different control valves are listed in the product selector on Samson AG's Homepage [1]. This number is symbolic for the capital goods industry. For customers, a high product individualization with low application complexity (external complexity from product's view) is of steadily increasing, high importance. For manufacturers of fluid components, this results in an enormous number of variants (internal complexity). Product development, manufacturing, logistics, and sales are faced with this challenge of internal and external complexity.

In this paper we present the concept of an innovative, modular control valve that we derived through a consistent mechanic-hydraulic separation of functions to meet these challenges.

Classical methods of product development provide two approaches: functional separation to reduce internal complexity and functional integration to reduce external complexity. The separation of functions allows a derivation of product construction kits and enables cost-effective individualization for the customer. By functional integration, sensors and actuators can be integrated directly into the product, resulting in a high degree of usability. For product designers it is always necessary to combine these two approaches effectively.

A newly developed product must be evaluated in regards to function, effort, availability and acceptance. Typically function, effort, availability and acceptance are evaluated sequentially in terms of time and not considered in parallel although this means neglecting optimality due to iteration for time and cost reasons.

However, the fulfilling of the function is the primary objective a customer is looking for. This means, that the function becomes a constraint, see fig. 1. Striving for an optimum, acceptance, effort and availability should be evaluated as parallel as possible. Following this concept, the developed innovative control valve is evaluated in regards to effort, acceptance and availability in an early design stage.

The effort can be measured in installation space and energetic losses. The customer acceptance depends on the possibility to individualize the product's features.

The availability strongly correlates with uncertainty within the system, for example number and kind of seals and unwanted vibration.

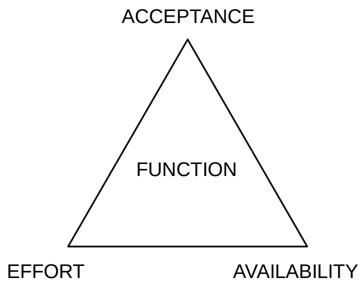


Figure 1: The fulfillment of function as constraint of a technical system.

2 PRODUCT DEVELOPMENT

2.1 Mechanic-hydraulic separation of functions

Modularization is a proven way to reduce the internal complexity of a product. It does not only help to derive a variety of different products from the same subset of parts, it also helps to divide the complexity during product development to manageable tasks. To derive a modular product one needs to achieve functional independency and physical independency of the products components (see fig. 2). [2]

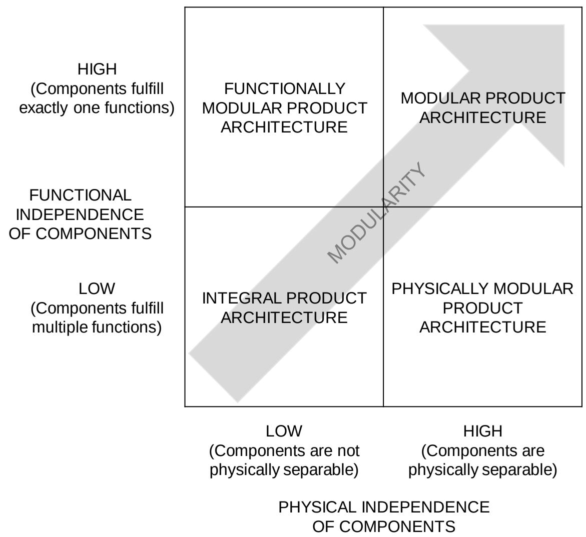


Figure 2: The relationship between physical independence, functional independence and modularity. [3] *translated from German.*

The main function of an industrial control valve is to throttle a fluid flow. However, to fulfill this main function some secondary functions are necessary.

These functions are fulfilled by different parts (see fig. 3a).

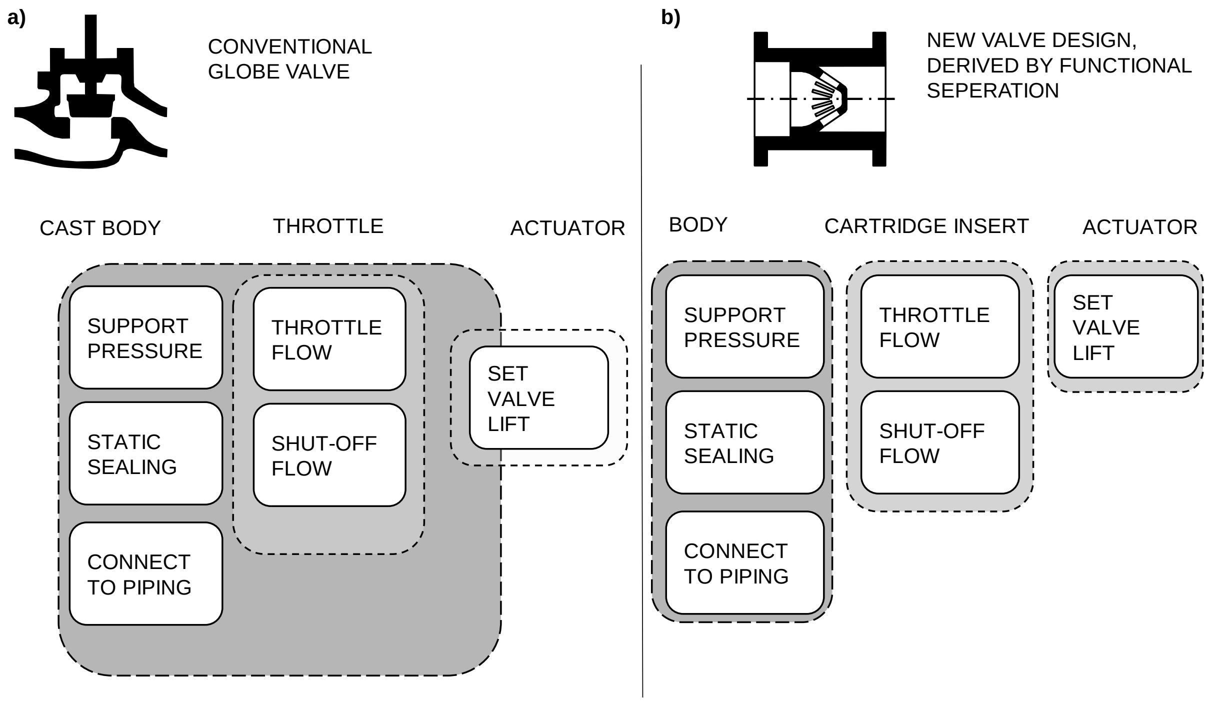


Figure 3: Functional and component structure of a) a conventional globe valve and b) the newly developed valve.

In state-of-the-art valves, the casing supports the pressure, seals against the environment and connects the valve to the piping. It also provides the seat - the sealing point for the valve plug. The throttle consists of the valve plug and the valve seat. The actuator is typically external, it connects to the casing and the valve stem and provides a linear displacement.

Looking at the functional and physical structure of this conventional valve, we see an overlapping. Especially critical is the overlapping of the main function “throttling” and the cast body, which fulfills the secondary functions. This overlap leads to a high number of variants and increased complexity. It results in high costs for the manufacturers and it is only possible to react slowly to changing customer requirements.

Considering the same main and secondary functions we developed a concept that separates the main function and the secondary function into different components (see Fig. 3b).

Figure 4 shows a 3D-view of the new design. The casing still supports the pressure, seals against the environment and connects the valve to the piping. However, the throttling happens now in a cartridge insert, consisting of two parts. One part, the valve seat, is fixed to the casing. The closing part rotates within the valve seat. Through the rotation the cross sectional area of the windows changes.

The number and shape of the windows can be chosen freely.

2.2 Actuation and final concept

From the customer’s point of view, the internal complexity is not of interest. He values a product fulfilling exactly his requirements (individualization) that he can apply with as less effort as possible (also known as plug-and-play): he wants a low external complexity.

There are two main reasons why the actuator nowadays is sold separately from the control valve: (i) the dependency of the needed actuating force on the process pressure and (ii) the available energy source at the valve’s installation site, which might be pneumatic or electric. This leads to a complex system from which the customer needs to choose the best fitting product for his requirements.

To decrease external complexity, the opposite method of functional separation, the functional integration is useful. It allows us to integrate the actuation into the throttle cartridge.

To overcome the dependency of the needed actuating force on the process pressure we design the seals self-enhancing. By choosing the topology a) over b) in Fig. 5 the pressure difference $\Delta p = p_1 - p_2$, with $p_1 > p_2$ enhances the sealing between closing part and valve seat when fully closed.

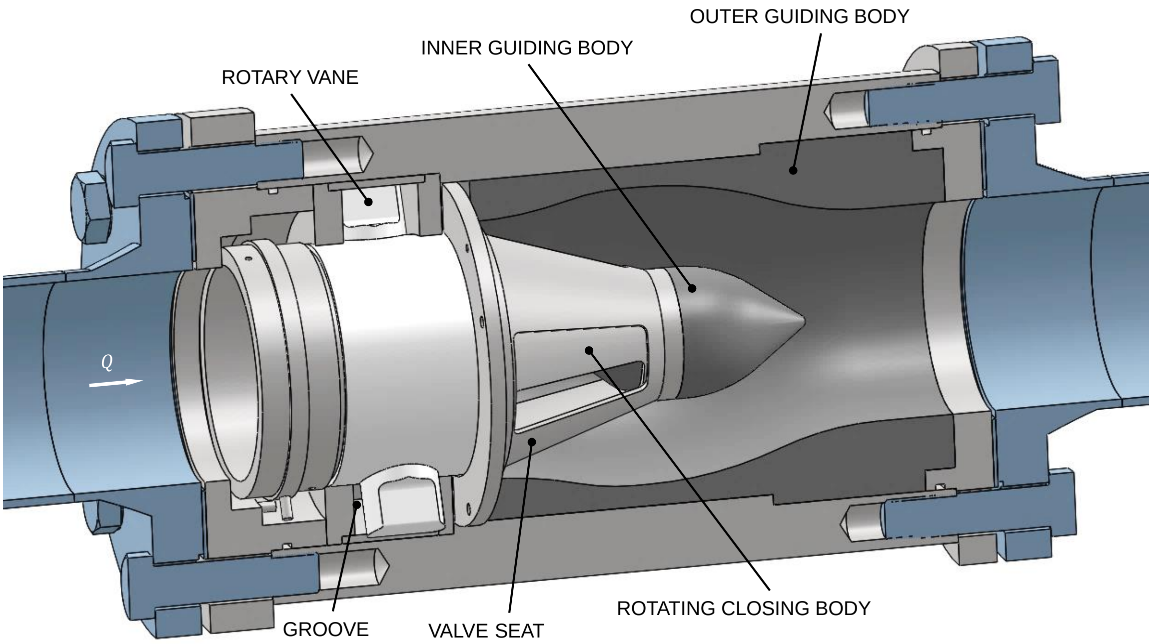


Fig. 4: Newly developed valve with standardized connections in blue. The rotating closing body is turned by the rotary vanes so that the cross-section of the windows changes. Flow-guiding bodies reduce the pressure loss in the fully open position.

The actuator itself is a hydraulic swivel motor, which is operated with the process fluid and the pressure difference across the valve. The rotary vane is guided with a groove that has a slope in axial direction. This creates a thread drive that pushes the closing part against the valve seat while rotating towards the closed position. The slope is small enough, such that the thread is self-locking. This makes unwanted movement of the closing part impossible.

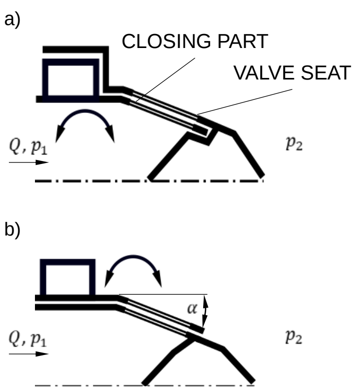


Figure 5: two different topology options, a) with an inner rotating part, b) with an outer rotating part.

The swivel motor is actuated with the pressure difference $\Delta p = p_1 - p_2$ across the valve. A small 4/3-way proportional valve acts as a pilot valve. Thus the main actuation energy is taken out of the process itself.

Figure 4 shows a CAD-model of the new control valve. The swivel motor consists of the rotary vane, moving inside the groove. A few other parts complete the valve. Two flange lids connect the valve to the piping and seal against the environment. Two guiding bodies provide a streamlined flow through the valve.

The angle α (see fig. 5))has to be big enough to avoid self-locking and jamming of the closing part in the valve seat. On the other hand, it is energetically beneficial to keep the flow cross-section area constant along the valve to minimize shock losses. This represents the upper boundary for the angle α.

3 EFFORT

The effort can be measured in installation space, energy consumption and energetic losses. In the following section, the design concept is evaluated against globe valves, the standard valve used for control applications.

3.1 Installation Space

To evaluate the needed installation space, we compare our invention to a commonly available globe valve, the *Valtek GS – "General Service Control Valve"* with a pneumatic actuator.

For the nominal size DN 80 this valve and actuator combination has a length of 310 mm, a height of 665 mm and the pneumatic drive has a diameter of 352 mm. [4]

For the same nominal size our new valve has the same length and a diameter of 200 mm (the diameter of standard DN 80 flanges).

Under the assumption that a cubic volume covering the outer dimensions of a valve is not usable for other equipment, the globe valve needs an installation space of 0.0726 m³ and the new valve of 0.0124 m³. This roughly equals a size reduction by 80 %.

3.2 Energetic losses

Control valves are available in different types, the most dominant being globe valves with either pneumatic, hydraulic or electric actuators. Depending on the type, controlling the flow rate is implemented in different ways, which consequently results in different types having various advantages and disadvantages over one another. Ball valves for example are better suitable for achieving low flow resistance at 100 % valve stroke compared to globe valves. However, adjusting the characteristic curve of a globe valve can only be realized with less precision. [5]

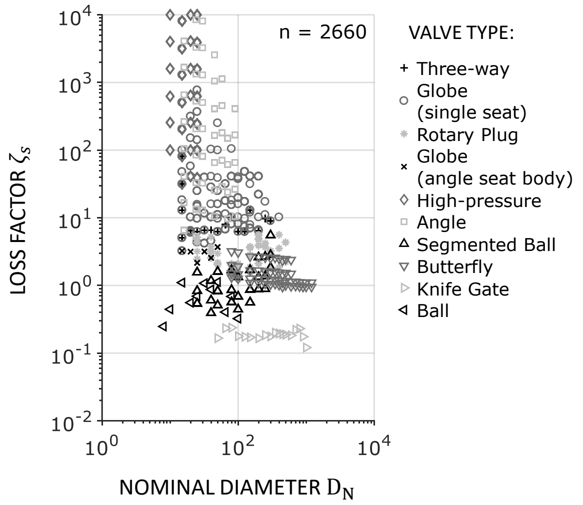
In order to quantitatively asses the differences between different builds a market study was carried out. The analysis is based on manufacturer's specifications taken from data sheets of 21 different product lines and a total of over 2600 individual products.
In order to achieve representative comparability, parameters had to be chosen that are non-specific to the type of valve but rather generally applicable: parameters for size, flow resistance, pressure rating or type of actuation.

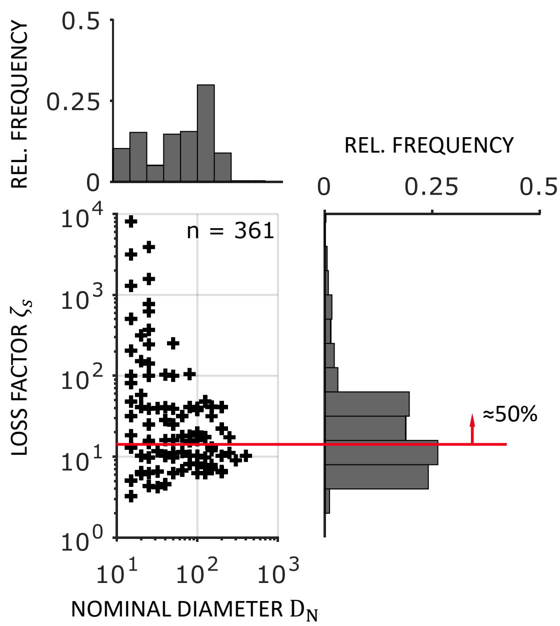
Commonly a valves flow resistance is given by the nominal flow rate K_v. The nominal flow rate is defined as the volumetric flow through a valve given nominal boundary conditions for given media and is typically determined experimentally. For example, using water with a temperature between 4 and 20 °C the nominal flow rate is defined as the volumetric flow that results in a pressure drop of 1 bar for a fully opened valve. Since the nominal flow rate scales with the nominal size DN we express the pressure loss in dimensionless terms using the loss factor $\zeta = 2\,\Delta p / (\rho\, u^2)$.

To compare the pressure loss in fully open position, we calculate the loss factor ζ_s from the nominal flow rate in fully open position $K_{v,s}$, nominal diameter D_N and the boundary conditions for measuring with water:

$$\zeta_S = 2\frac{\Delta p_0}{\rho_0}\left(\frac{D_N^2\,\pi/4}{K_{v,s}}\right)^2$$

The advantage of describing pressure losses with a dimensionless coefficient lies within the resulting reduction of influential variables. In our case, the loss factor merely remains a function of valve type and design as well as the valve stroke. By only comparing valves at a fixed stroke, we remain with the loss factor ζ being only dependent on geometric properties.





As shown in figure 6, globe valves, which are most commonly used in control applications, have the highest flow resistance compared to other build types. With an average (median) pressure drop coefficient of $\overline{\zeta_s} \approx 15$ globe valves provide a resistance that is (on average) one order of magnitude higher than that of ball valves ($\overline{\zeta_s} \approx 0.7$) and segmented ball valves ($\overline{\zeta_s} \approx 0.87$). Further, we can observe that the distribution over the value domain has a strong positive skewness. In practical terms this means that the pressure drop coefficient for the upper 50% of investigated valves, especially those with a small nominal diameter, can reach values that are a lot higher than the suggested average (see Figure 7). The highest observed pressure drop coefficient in the set had a value of $\zeta_s = 8.1 \times 10^3$ while the lowest only reached a value of 3.2.

Of course, it is a control valves function to provide a pressure loss. Without, a process control would not be possible. For the basic valve sizing standards exist [6]. In process plants pressure losses not only occur in valves, but also in other components. These components' characteristics are varying over time. To ensure a good controllability it is beneficial to have a large share of the pressure loss across the control valves. Thus a good controllability is always in conflict with a high energetic efficiency of the process. To ensure good controllability different rules of thumb exist, varying from 10 % - 30 % of the systems pressure loss, that should happen in the control valves. However, with the increasing use of frequency controlled centrifugal pumps a second controllable actuator establishes in the process industry. Fuchs presents in [7] a combination of a centrifugal pump and a globe valve in one controller – the so called flow unit. It is likely that these old rules of thumb will decrease and the loss factor in fully open position ζ_S will become more and more important. The new gold standard would combine the low resistance of ball valves with the controllability of globe valves.

Given the importance of the pressure loss in fully open position, we carried out some basic 3D CFD-simulations to compare our design against a globe valve. Both computed models consist of the respective valve and a $25d$ and $15d$ length of pipe attached to the inlet and outlet of the valve. The nominal size of both valves is DN 65. The numerical grid for the chambers and the ducts inside the valves were generated with ICEM, a pre-processor of ANSYS. An unstructured grid was used, consisting of approximately 2.2 million cells. The grid is significantly refined near the wall and in the throttle region. The velocity at the inlet $u = 3.35\ \mathrm{m}/s$ (representing $K_V = 40\ \mathrm{m}^3/\mathrm{h}$) and the pressure at the outlet $p = 9.98\ \mathrm{bar}$ where set as boundary conditions, the fluids density was set to $\varrho = 997.05\ \mathrm{kg/m}^3$. The model is isothermal and incompressible and the realizable k-ϵ turbulence model was used. OpenFOAM has been used to perform the numerical computations.

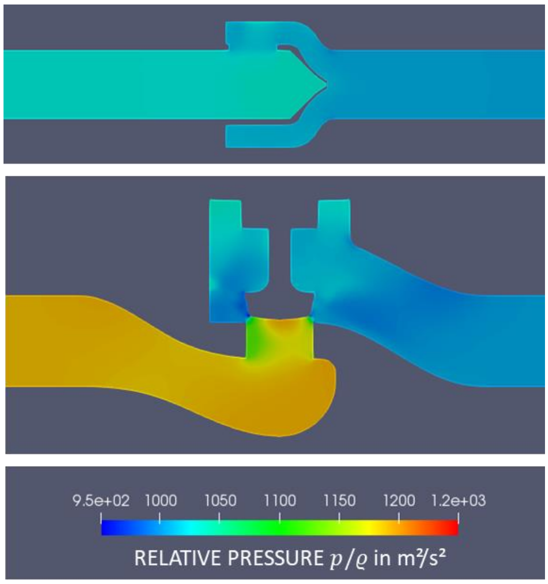


Figure 8: pressure field of new concept (top) and standard globe valve (bottom).

Figure 8 shows the simulation results for the pressure field. To compare both simulations the loss coefficient was determined according to DIN EN 60534-2-3 [8]. The pressure was measured 6 times the nominal diameter DN downstream of the valve and 2 times upstream of the valve.

The simulations show that the loss coefficient ζ_S of the standard globe valve is ~7 times higher than the ζ_S of the new concept. Of course this represents a very rough estimation but it shows that it is a promising concept.

4 AVAILABILITY

4.1 Vibrations and Noise

A known challenge in globe valves are flow induced vibrations. The flow is accelerated in the gap between valve plug and the valve seat, and slowed down in the cavity afterwards. This leads to radial and axial forces acting on the valve body. These forces may induce vibrations of the valve body and the valve stem, which are transmitted to the bearing, the casing and adjacent components. In worse cases, the valve body may hit the valve seat. Valve vibrations lead to damages at the valve or even the whole plant. Before leading to failures the plant is typically shut down. [9]

Due to the rotary movement instead of a linear movement and the functional integration of the actuator into the throttle, the new design shows no long beams with connected masses like valve stem, valve plug combination. Thus we expect it to be more robust against flow induced vibrations in general.

Vibrating parts, but also flow induced noises, lead to acoustic emission from a valve to its surrounding. If the source of sound cannot be eliminated a sound insulation is applied to the valve. For a globe valve this means, that the actuator needs to be insulated as well, leading to a rather complex geometry and a large volume that needs to be insulated. For our new design, the insulation is rather simple. Standard piping insulation, with rotational symmetry, can be applied.

4.2 Seals

A globe valve's seal inside the throttle is loaded with the pressure difference across the valve. The actuator needs to constantly apply a force in the fully closed position, or a pressure balanced design is necessary. [10] For safety applications, where the valve must not open if the actuation energy is lost, this leads to an increased effort on the construction side. It also requires special designs to achieve better leakage-classes as defined in DIN EN 60534-4 [11]. The sealing function depends on the process parameters, which are mostly unknown to the valve manufacturer. This represents a source of uncertainty.

In our design this uncertainty is reduced by a self-enhancing seal inside the throttle (c.f. section 4.2 and fig. 5). This way the sealing becomes independent from the process parameters.

Another source of uncertainty in globe valves are the dynamic seals at the valve stem. The actuator is external and the valve stem performs a linear motion. A large variety of packing materials and designs exist, just to seal the valve against the environment. Process fluid, environmental conditions and expected operation cycles need to be considered choosing the right packing. Furthermore a lot of packings require a very accurate manufacturing of the valve stem, being part of the seal. Some packings even require a manual readjustment in given service intervals. [10]

By shifting the function *"throttle flow"* into a separate component, the presented design requires no dynamic seal. Thus, it eliminates the uncertainty in packing material and application conditions.

5 ACCEPTANCE

After regarding effort and availability for our new design, we complete the evaluation by taking a look at the customer acceptance, according to fig. 1.

5.1 Sticking to industry conventions

The industrial valves industry is a common goods business. Control valves are mandatory for a desired process, but do not represent the main function of a process plant. Typically, a process is designed and all necessary units, e.g. chillers, rectifiers, filters, reactors, are identified and sized. Then the pressure losses for these units are determined and finally the control valves are chosen. Until this final step, the plant designers work with black boxes for valves. [12]

That is the reason for standardized sizing parameters. For a given nominal pipe diameter DN, the length for a control valve is given by DIN EN 60534-3-1 [13], and the flange size by DIN EN 1092-1 [14]. By sticking to these standards, the existing plant design process is satisfied.

5.2 Valve characteristics

A further characteristic of the plant design process is, that the valve sizing process is standardized, for example in DIN EN 60534-2-1 [15]. The main parameter for choosing a control valve is the nominal flow rate K_{V} and the type of flow characteristics (linear, equal percentage or quick opening). [10] In our design, the nominal flow rate can be adjusted by changing the flow cross sectional area. To reach different flow characteristics, the shape of the windows in the closing part and the valve seat can be varied.

Besides linear, equal percentage or quick opening characteristics the customer might want an individual characteristic, coping exactly his needs. In the presented valve design, the flow characteristics is mainly determined by two parts, the closing part and the valve seat. By varying the shape of the opening windows the ratio $dA/d\varphi$, for which the flow cross sectional area A changes with the rotational angle φ of the closing part, can be varied. For rectangular windows $dA/d\varphi$ is constant.

Another considerable factor is the rangeability of a valve. It represents the ratio of the largest flow coefficient $K_{\mathrm{V,S}}$ to the smallest flow coefficient in which the deviation from the specified flow characteristic does not exceed the stated limits [10]. A large rangeability helps the process controller of a plant. For globe valves, the rangeability is limited by the design options. For our design, it is easier to vary the flow characteristics at certain positions of the angle φ. The CFD-simulation in section 3.2 promise a high $K_{\mathrm{V,S}}$ value for our design, benefitting the rangeability as well.

6 CONCLUSIONS, DISUCSSION AND FURTHER DEVELOPMENT

In this paper we present an early concept of a new control valve, which was derived by the well known design methods „separation of functions“ and „integration of functions“. These methods where used specifically to reduce the complexity of the product “control valve”.

By separating functions we removed the dependency between physical and functional structure. We reduced the internal complexity, creating a modular product architecture. To reduce the external complexity (the view from customer’s eye), we simplified the product by integrating the actuator into the control valve’s throttle. The resulting control valve design is shown in Fig. 4.

To evaluate our design we compared it to standard globe valves in an early design stage. This evaluation considered effort, availability and acceptance.

The effort can be expressed as installation space, or packaging, and energetic losses. We showed that our design can reduce the installation space by factor 6, compared to standard globe valve – actuator combinations. For the energetic losses, CFD simulations yield, that the new design is very promising to achieve very low loss factors ζ_S.

To evaluate the availability in this early design stage we took a look at the uncertainty within the system. We show, that our design is less likely to show unwanted vibrations during operation and it is easier to insulate against noise emission. By using a self-enhancing seal, fail-safe design is easier to accomplish and it should be easier to achieve better leakage classes. By eliminating the dynamic seal (conventionally located at the stem of globe valves), no special packaging is required and no service for this packaging is necessary.

The acceptance is ensured by sticking to industry conventions for valve sizing. Geometric parameters are kept according to standards, and the process of choosing the right control valve stays the same for the customer. Our design allows the fulfilment of all three, typical flow characteristics (quick opening, equal percentage, linear). Furthermore, it is possible to create individual flow characteristics for the customer, when needed and thus increase the acceptance.

The first design evaluation yields promising facts & figures for the new design. Due to the very early design stage some of the evaluations are based on assumptions and need to be verified in the ongoing design process.

For the further development, we will stick to the fail-fast principle. Fast prototyping will help to verify the evaluation in this paper and to identify the most promising aspects of the new design.

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