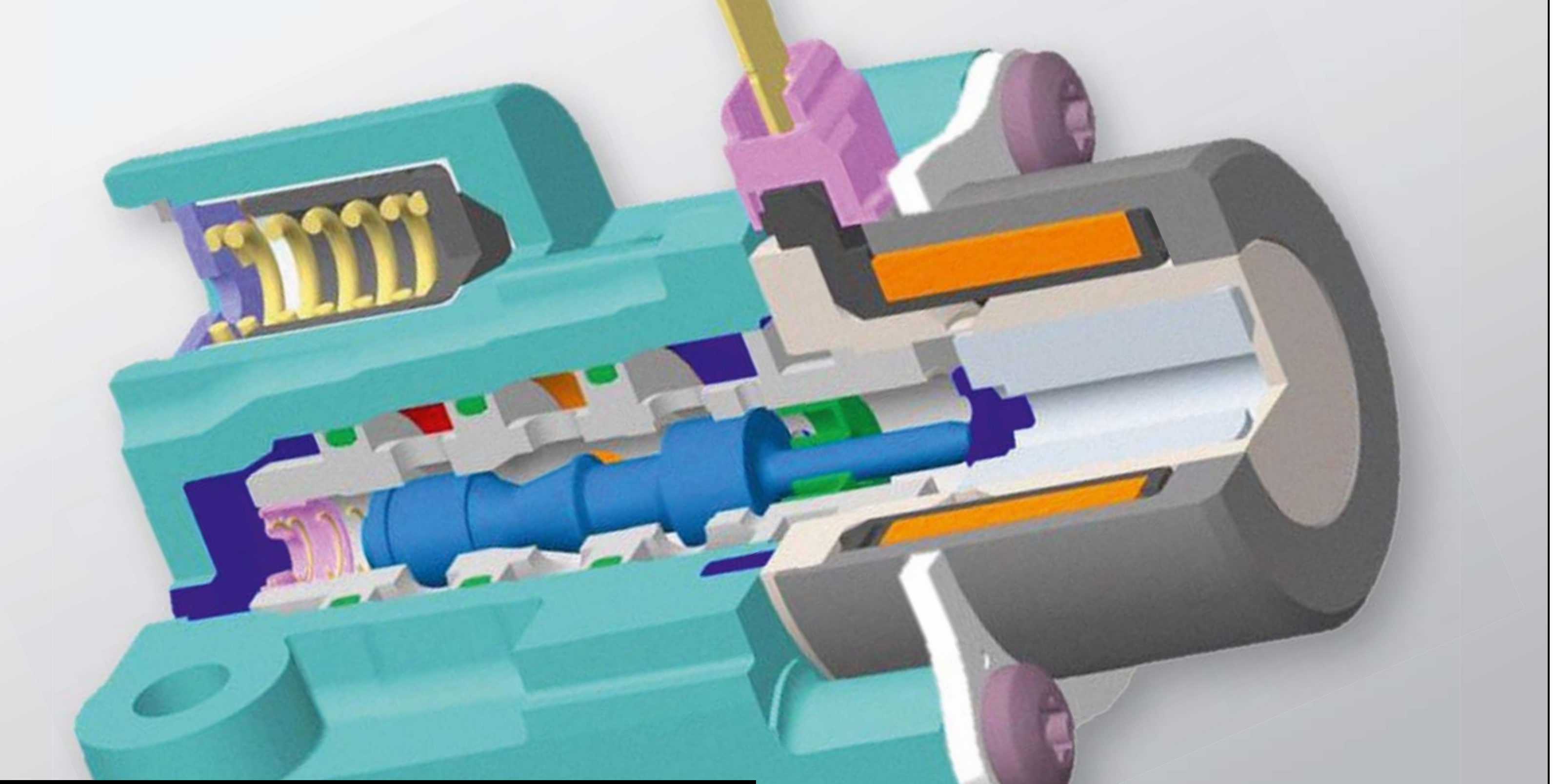


CUSTOMER STORY // MECHANICAL ENGINEERING

OPTIMIZATION OF A PISTON GEOMETRY IN A PRESSURE CONTROL VALVE

optiSLang supports the optimization of a piston geometry to improve the response time of the valve and the flow rate.

Task Description

The problem to be solved deals with a 3/2 proportional pressure control valve of a DCT transmission which regulates the filling of the clutch due to the valve. Inside the valve, a bucking occurs in certain situations during shift operations. Therefore, response times have to be improved in order to ensure a fast filling of the clutch. Better response times ought to be achieved by reducing the flow forces in the valve.

Fig. 1 shows the function of the valve as part of the clutch mechanism. As soon as the piston moves and the valve opens, oil flows from the P-port to the A-port finally filling the clutch. During this operation, opposite loads occur to the magnetic force, which moves the piston. Due to high loads, especially high pressures at small openings, the valve does not operate as fast as desired.

The operating speed of the valve is recorded as the response time. Fig. 2 shows the distribution of this period and its classification in the pressure curve. The time between the response of the valve and the first reaction of the pressure is called “dead time”. The duration of reaching 90 percent of the target pressure is called “filling time”. By reducing the flow force, the magnetic force causes more effect on the piston resulting in a faster response. This mainly affects the period of filling and leads to a lower overall response duration. At the same time and in addition to the flow force, the flow rate has to be monitored for keeping it as high as possible in order to ensure a quick filling of the clutch through the valve.

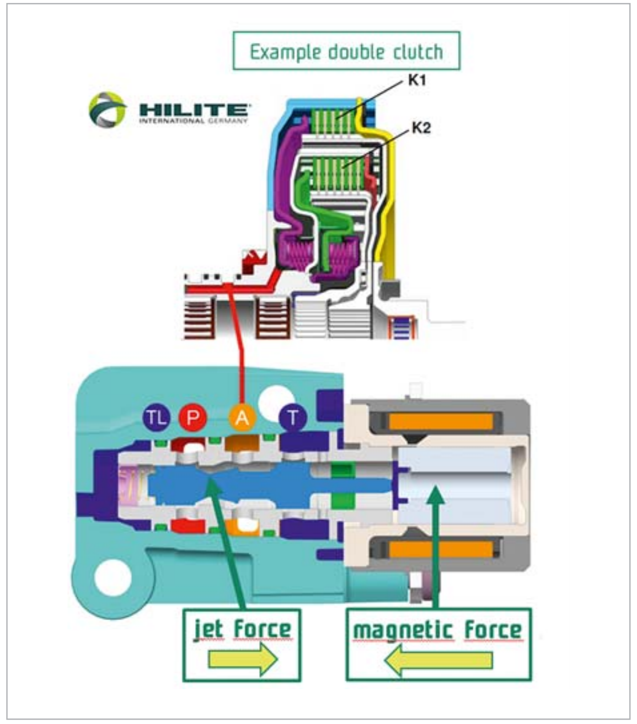


Fig. 1: Functional scheme of the pressure control valve in the clutch

Simulation and optimization

The flow optimization of the piston inside the pressure control valve is performed with optiSLang and ANSYS CFX. optiSLang determines the piston designs to be calculated, evaluates the results of the simulation and identifies new designs based on these results. The calculation of the flow force and the flow rate on the piston is conducted by ANSYS CFX. The calculated data is then transferred to optiSLang.

For the optimization, a model adapted to flow calculation is used. Here, all important geometry parameters can be varied. The model and the corresponding geometry parameters are displayed in Fig. 3. A range of acceptable variations is set for each parameter. Certain parameters, such as the initial pressure P, are not changed but set to a constant value of 20 bar.

The CFX model shown in Fig. 3 represents the space in which the fluid flows from the P- port to the A-port. On one side, it

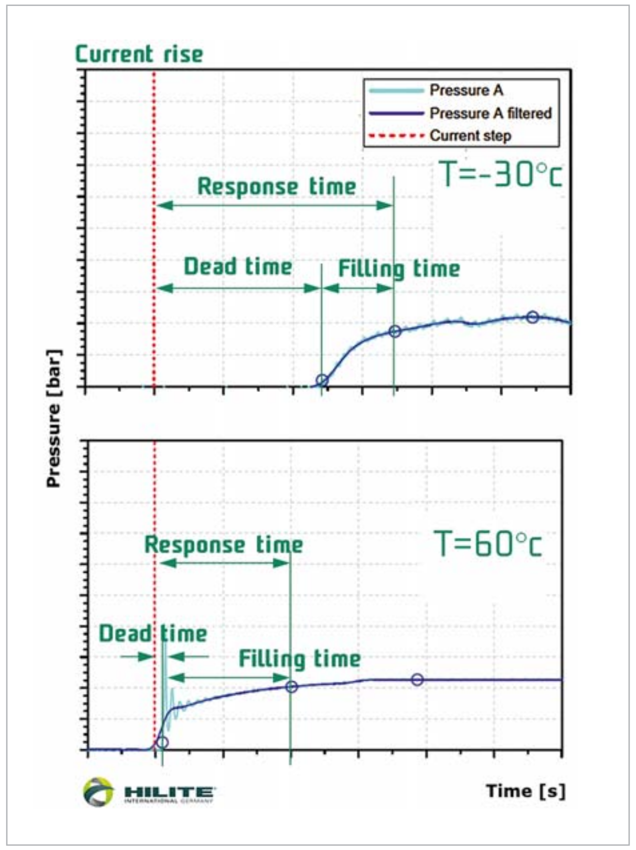
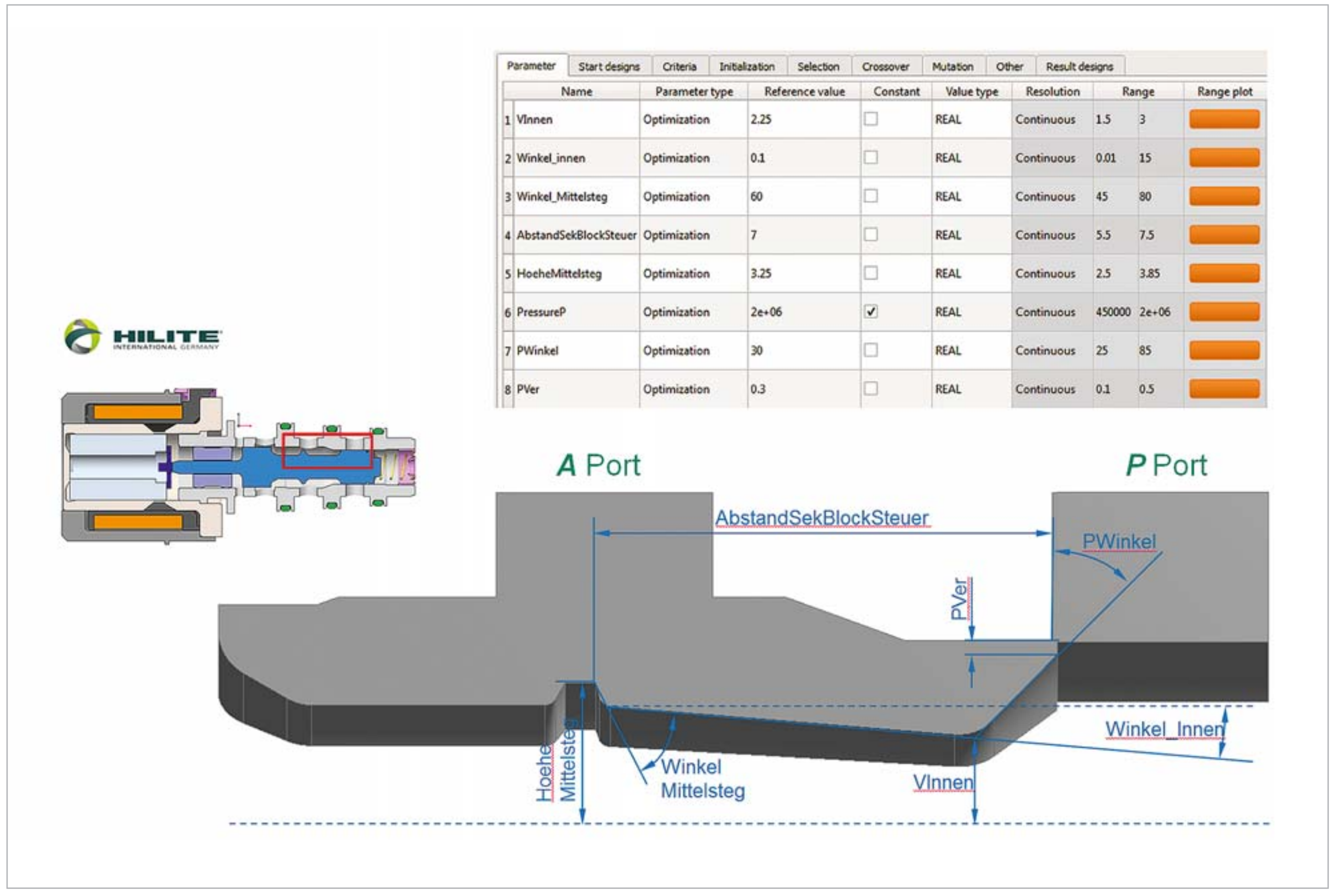


Fig. 2: Activation of the clutch in the gearbox with pressure regulating valve - low temperature (top) - normal temperature (bottom)



	Name	Parameter type	Reference value	Constant	Value type	Resolution	Range		Range plot
1	VInnen	Optimization	2.25	☐	REAL	Continuous	1.5	3	
2	Winkel_innen	Optimization	0.1	☐	REAL	Continuous	0.01	15	
3	Winkel_Mittelsteg	Optimization	60	☐	REAL	Continuous	45	80	
4	AbstandSekBlockSteuer	Optimization	7	☐	REAL	Continuous	5.5	7.5	
5	HoeheMittelsteg	Optimization	3.25	☐	REAL	Continuous	2.5	3.85	
6	PressureP	Optimization	2e+06	☑	REAL	Continuous	450000	2e+06	
7	PWinkel	Optimization	30	☐	REAL	Continuous	25	85	
8	PVer	Optimization	0.3	☐	REAL	Continuous	0.1	0.5	

Fig.3: Input of geometry parameters in optiSLang (top), variable geometry parameters of the piston model in CFX based on a sample design with an opening of 0.1mm (bottom)

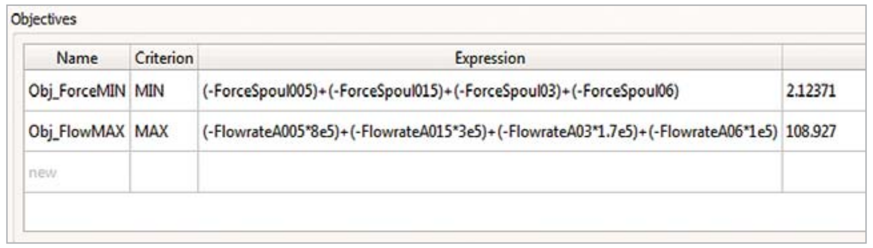
is bounded by the inner surface of the bushing and, on the other side, by the external geometry of the piston. If the geometry of this “negative volume” is varied, the form of the bushing or piston is also automatically changed.

There is a critical range at high pressure and small openings of the valve where the flow force has to be reduced. Thus, for the optimization, the maximum pressure of 20 bar should be initiated at the A-port and the flow forces should mainly be calculated at low openings. For each geometry generated by the optimizer, the flow force and the flow rate on stroke positions (opening at the P-port) 0.025 mm, 0.05 mm, 0.15 mm and 0.4 mm is calculated.

Here, the optimization goals are the reduction of the flow force on the piston and the increase of the flow rate. To pursue these two objectives simultaneously, an evolutionary algorithm is used, which seeks Pareto optimal solutions.

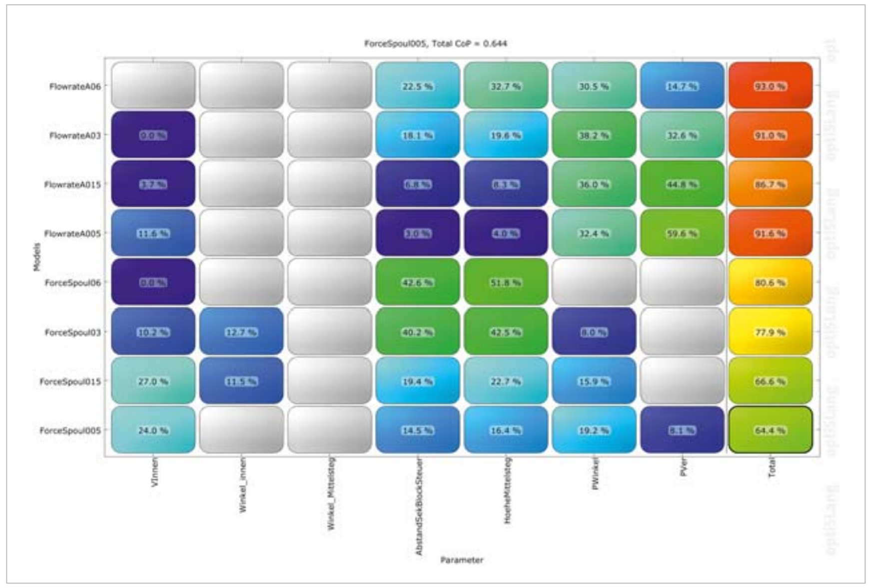
As Fig. 4 shows, only the three smallest response parameters are used for the objective of reducing the flow force (Obj_ForceMIN). The opening of 0.4 mm serves as a control parameter (constraint) ensuring the optimized design to be more efficient than the reference even at large openings.

For reaching the objective of maximizing the flow rate (Obj_FlowMAX), the results of all four stroke parameters are used. For an improved optimization potential, the flow rates are weighted differently in order to obtain homogeneous individual values. In the case of achieving both optimization objectives, the valve should respond and operate at a significantly improved response time, with the clutch to be filled faster and the problem of bucking to be solved. Additional constraints, which are not shown here, ensure the calculation of only solvable geometries. Invalid geometry combinations are sorted out beforehand.


Objectives

Name	Criterion	Expression	
Obj_ForceMIN	MIN	(-ForceSpoul005)+(-ForceSpoul015)+(-ForceSpoul03)+(-ForceSpoul06)	2.12371
Obj_FlowMAX	MAX	(-FlowrateA005*8e5)+(-FlowrateA015*3e5)+(-FlowrateA03*1.7e5)+(-FlowrateA06*1e5)	108.927
new			

Fig. 4: Definition of optimization goals (objectives) in optiSLang


ForceSpoul005, Total CoP = 0.644

Models	VInnen	Winkel_innen	Winkel_Mittelsteg	AbstandSekBlockSteuer	HoeheMittelsteg	PWinkel	PVer	Total
FlowrateA06				22.5 %	32.7 %	30.5 %	14.7 %	93.0 %
FlowrateA03	0.0 %			18.1 %	19.6 %	38.2 %	32.6 %	91.0 %
FlowrateA015	3.7 %			6.8 %	8.3 %	36.0 %	44.8 %	86.7 %
FlowrateA005	11.6 %			3.0 %	4.0 %	32.4 %	59.6 %	91.6 %
ForceSpoul06	0.0 %			42.6 %	51.8 %			80.6 %
ForceSpoul03	10.2 %	12.7 %		40.2 %	42.5 %	8.0 %		77.9 %
ForceSpoul015	27.0 %	11.5 %		19.4 %	22.7 %	15.9 %		66.6 %
ForceSpoul005	24.0 %			14.5 %	16.4 %	19.2 %	8.1 %	64.4 %

Fig. 5: CoP matrix of the sensitivity analysis regarding the CFX examination of the pressure control valve

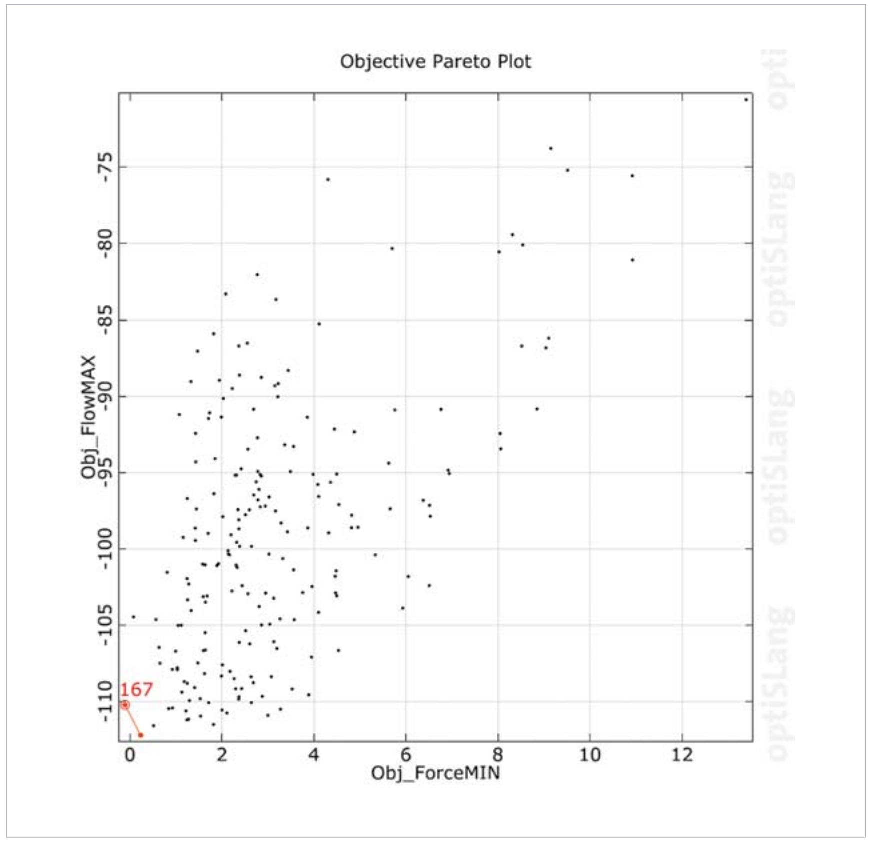


Fig. 6: Pareto plot of the piston VKP designs in the sensitivity analysis

To limit the optimization space and to be able to identify potentially relevant parameters in advance, a sensitivity analysis is performed before the actual optimization. In this case of flow optimization, the analysis includes approximately 200 designs covering the parameter space of the seven variable geometry parameters. The computational time of one design takes about 20 to 30 minutes.

Because the objectives for the optimization have already been integrated in the sensitivity analysis, the results can be analyzed and used as starting values for the optimization. Thus, computing time is saved and optimal geometries can be found faster if the result space is limited before. In the subsequent optimization of the piston, another 70 designs are calculated to find the optimal design.

Results of the piston flow optimization

Sensitivity analysis of the pressure control valve piston

The sensitivity analysis provides an overview of the influence of geometric variations of the flow rate and flow force on the piston (ForceSpoul) regarding the objective functions. In contrast to the optimization, different values of valve openings, here 0.05 mm and 0.15 mm for small openings and 0.3 mm and 0.6 mm for large openings, are used to cover the entire opening range as much as possible.

The only parameter in the predefined range of variation having no impact in the analysis is the angle at the center bar. The height at the center bar is particularly sensitive with larger openings regarding both goals “ForceSpoul” and “FlowrateA”. The same behavior can be observed during the variation of the distance between the central bar and P-port (“AbstandSekBlockSteuer”).

The angle at the P-port (“PWinkel”) and the height of the edge of the P-port (“PVer”) mainly affects the flow rate. In addition, there is also an effect on the flow force with small openings.

The variation of the inner radius of the piston (“Vinnen”) particularly influences the flow force at small openings. The corresponding angle (“Winkel_Innen”) also changes the flow force, but this is only significant at an opening of 0.15 mm to 0.3 mm.

Already during the sensitivity analysis, the optimization goals have been implemented in optiSLang. Therefore, the calculated designs can be analyzed accordingly. Fig. 6 shows the resulting Pareto plot, in which all geometries calculated in the sensitivity study are evaluated regarding the corresponding values of the objective functions. Here, the clear trend can be seen that certain geometries are distinguished by a particularly low force and a high flow rate. Those designs with the best inclusion of both objectives are marked as Pareto optimal (red dots) and are located in the lower left corner.

They are used as starting parameters for a subsequent optimization. Thus, the algorithm already starts in a pre-located space and can find the optimal piston geometry more easily and quickly.

Flow optimization of the pressure control valve piston

Due to the two optimization goals and the sufficient start designs, after 70 designs, i.e. the 5th generation after the starting design, an optimal piston geometry could be found. The three designs DP08, DP43 and DP48 fulfill all constraints and are characterized by a reduced flow force. Fig. 7 shows the optimized design accordingly organized to their quality of results. In the left lower corner, the top three variants are marked in red. Each of the three geometry variants has its pros and cons.

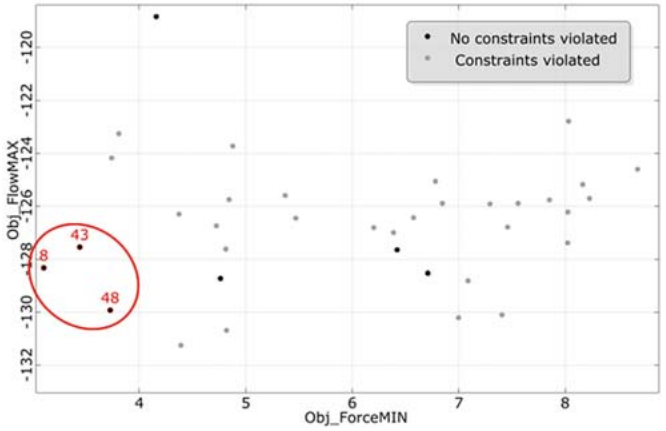


Fig. 7: Result of the optimization with evolutionary algorithms - optimal designs marked in red

Design Point 08 (DP08) is characterized by the lowest flow force (Obj_ForceMIN), but shows an unfavorable force curve and no optimum flow at the maximum opening.
DP48 shows the largest flow rate (Obj_FlowMAX) at the maximum opening and is characterized by a very uniform force curve. However, this design causes the highest flow force in comparison to the others.
DP43 is characterized by low flow forces especially at very small openings. Furthermore, the force characteristic is very balanced like DP48, but shows a lower flow force. The disadvantage of this piston geometry is the low flow rate.

The optimization results of the three selected piston geometries can be seen in Fig. 8 and 9 (see next page). Due to the favorable characteristics and the low flow forces, design number 43 is considered to be the most suitable piston geometry.

Compared to the reference valve, the resulting changes in the optimal design are particularly visible in Table 1. The biggest adjustments can be seen in the range of the two angles

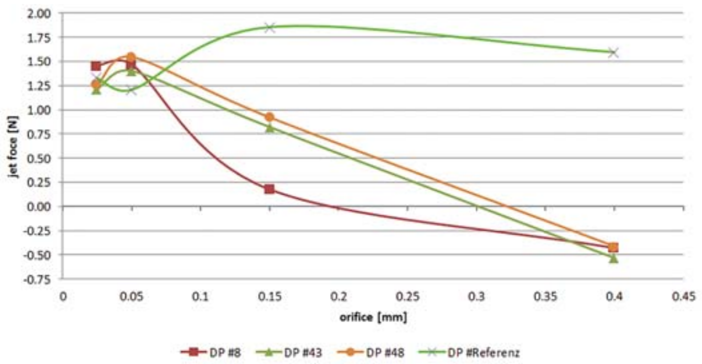


Fig.8: Results of the calculated flow force in the ANSYS CFX Designs DP08, DP43 and DP48 (jet force plot of optimal designs)

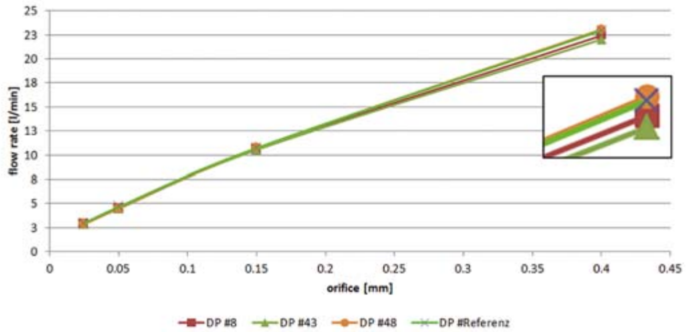


Fig. 9: Results of the calculated flow rate rate in the ANSYS CFX Designs DP08, DP43 and DP48 (flow rate plot of optimal designs)

“PWinkel” and “Winkel_Innen”. Other major changes are made in the parameters “AbstandSekBlockSteuer” and “Vinnen”. The result of the changes can be seen by comparing the piston geometries in Fig. 10. The geometry of the reference design is depicted at the top and the optimized design at the bottom. The interaction of the parameters results in a significant change of the piston geometry. The former straight graph (Fig. 10, top) now shows a “V-shape” (Fig. 10, bottom). By the aerodynamically favorable shape, the force is reduced over the entire opening range and causes a balanced force characteristic. However, depending on the entrance angle of the flow, the forces on the piston are also changing in this geometry. This becomes very clear when looking at the flow force curve. Fig. 11 and Fig. 12 represent an accurate recalculation of the force and flow characteristics over the entire range of valve openings for the reference and the optimized piston. The flow forces affecting the piston during the opening are depicted blue in the optimized geometry, the forces of the reference geometry are marked in red. Depending on the applied pressure, the characteristics become darker. Pressures of 5 bar, 10 bar and 20 bar are shown.

The optimization aims at the reduction of the flow forces, especially at low openings. Unfortunately, this goal could not be reached entirely in the optimization. For very small openings, only slightly smaller forces could be achieved.

ID	Distance Sek BlockSteuer	Hight center bar	PVer	PWinkel	VInnen	Angle center bar	Angle inner
Reference	7.00mm	3.25mm	0.300mm	30.0°	2.25mm	60.0°	0.0°
Optimized Design DP43	6.63mm	3.20mm	0.397mm	66.4°	1.837mm	76.7°	12.7°

Table 1: Geometry parameters of the reference and the optimization of the pressure regulating valve piston

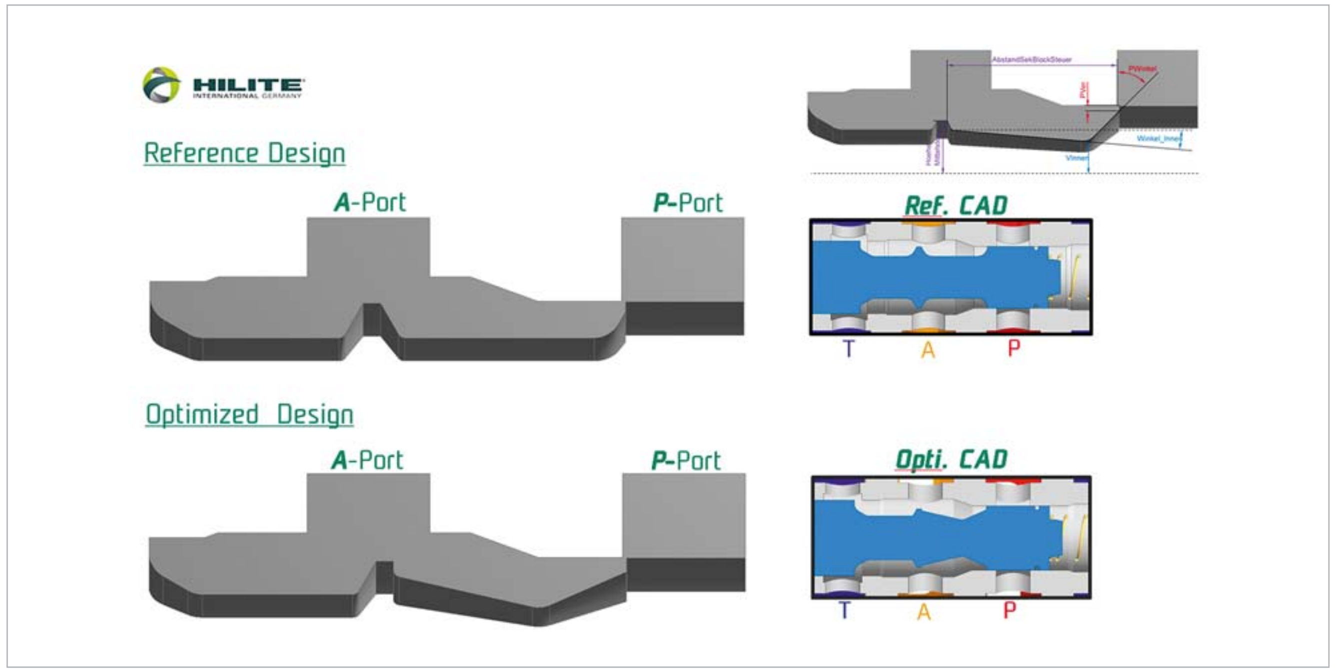


Fig. 10: Reference geometry (top) and optimized geometry (bottom) of the VKP piston at 0.4mm opening

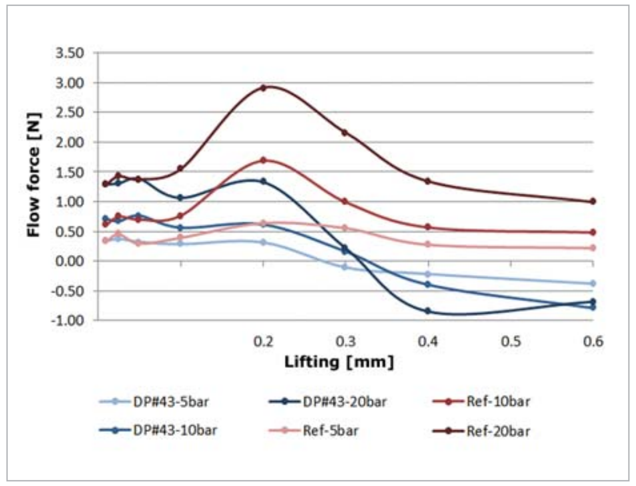


Fig. 11: Comparison of the course of flow force on the VKP piston for the reference (red) and the optimized (blue) Design

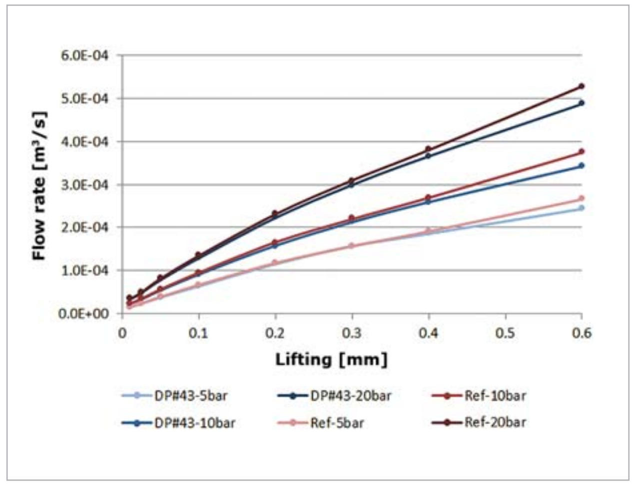


Fig. 12: Comparison between courses of the flow rate in the VKP - reference (red) and optimized (blue) Design

If the valve is opened wider and, thus, conveying more fluid, the advantage of the new geometry becomes obvious. The reference design shows an increase in the flow force from 0.1 mm opening, whereas the optimized design reduces the affecting flow force on the piston. The maximum applied flow force is reduced according to the pressure by up to 50%. Due to the new geometry, not only the amount of the maximum applied force changes, but also its occurrence being now at a smaller opening.

Up to about 0.4 mm opening, the flow force counteracts the magnetic force. If this point is exceeded, the closing flow force on the piston turns into an opening one supporting the magnetic force.

Although an optimization goal for improving the flow rate has also been defined, it is not possible to combine the reduction of the flow force with an increase of flow rate. The initially small differences between the reference and DP43 are constantly increasing with a wider opening. The maximum reduction of the flow rate of 7% is only reached at the maximum opening of 0.6 mm. Since this position is relatively rare in operation, the difference from the reference is usually less than 7%.

The pressure curve, which is plotted in the left section of Fig. 13, is similar in both piston variants. In this case, there are differences between the positions of the pressure concentration. The pressure reduction is concentrated in the opening range at the P-port of the optimized variant showing a balanced characteristic. At the top of the “V-shape”, an additional high pressure zone can be seen because, here, the flow is diverted in a different direction.

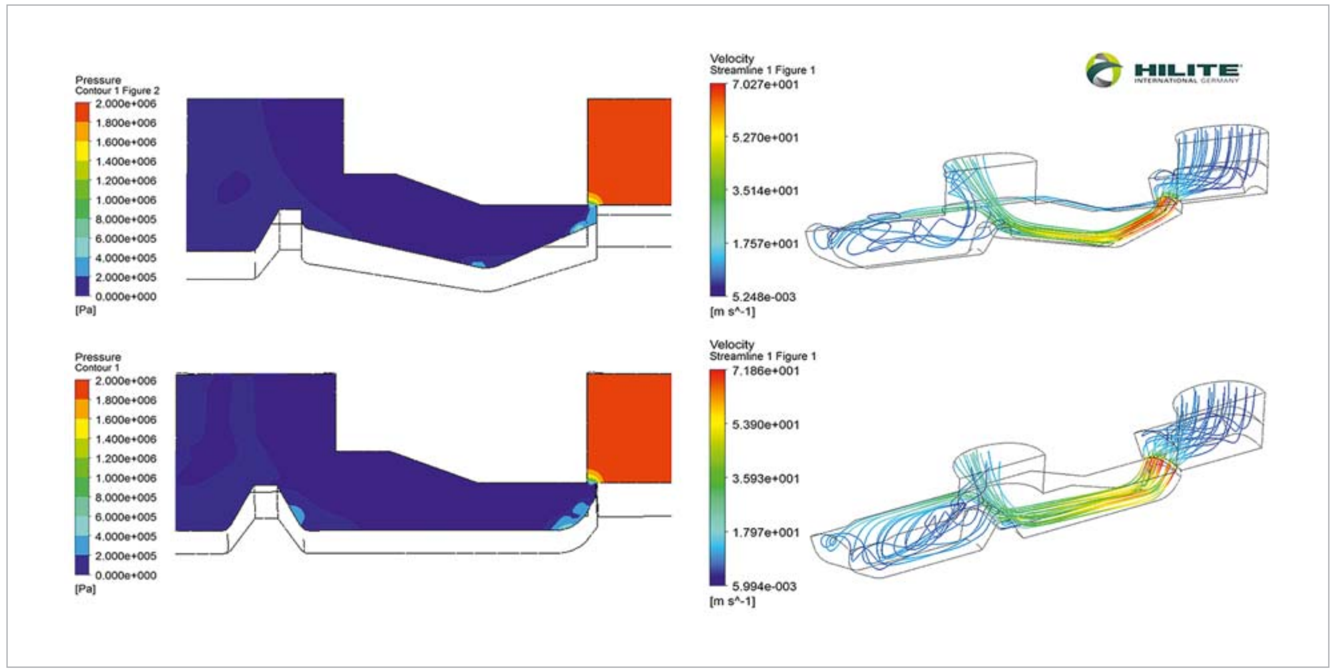


Fig. 13: Comparison of the pressure and the velocity of the VKP for the reference and the optimized piston

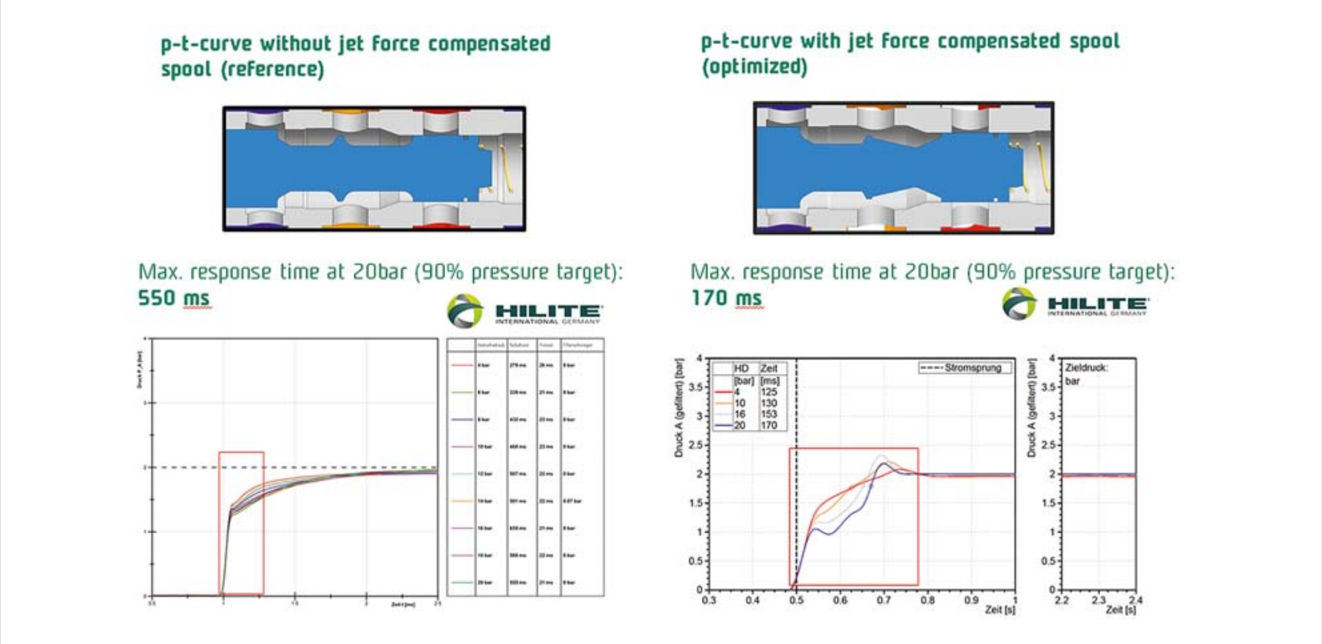


Fig.14: Comparison of the p-t curve with and without flow-compensated piston

The velocity profile of both pistons is shown in the right section of Fig. 13 (see previous page). Here, the flow on the optimized piston shows a larger and longer lasting speed due to the improved shape. The fluid is not slowed down too fast, which is clearly indicated by the longer red areas of the speed curves.

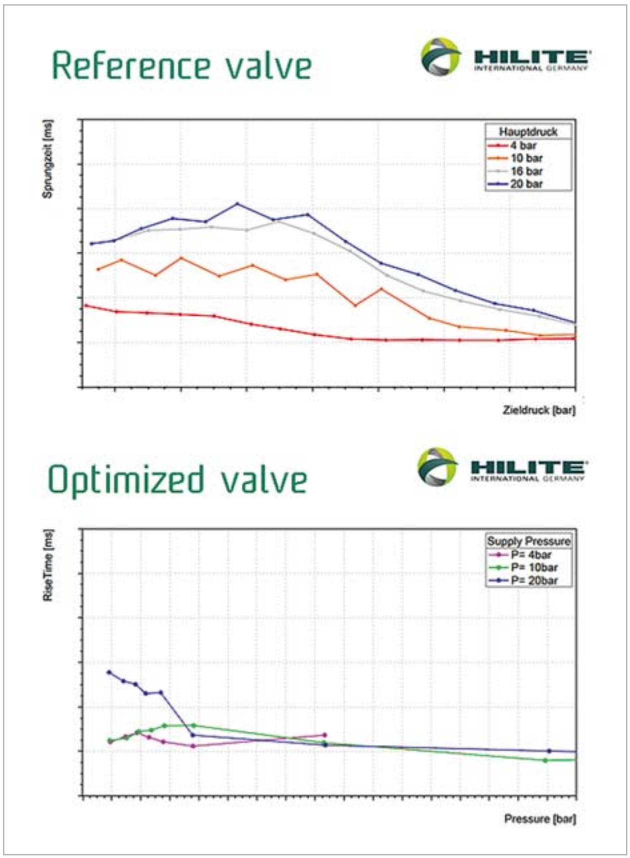


Fig. 15: Comparison of the skip times of the pressure control valve with and without flow-compensated piston

For the calibration of the simulation, prototypes of the valve with the optimized piston are tested. It turned out that the flow compensated piston of the pressure control valve also obtained a significant improvement in the experiment. The response time in Fig. 14 as well as the jump times in Fig. 15 show the gain in speed as a result of the optimization.

The p-t curves shown in Fig. 15 indicate the measured filling time of the optimized and non-optimized valve at different pressure jumps. 90 percent of the pressure jump of 20 bar is achieved with the valve of the standard piston in 550 ms. When the optimized variant is used, the time is reduced by almost 70 percent to 170 ms.

Regarding the jump time, Fig. 15 shows a similar picture. The maximum jump time (maximum step response) at 20 bar supply pressure is reduced by 1/3 from 420 ms with the standard piston to 280 ms using the flow-compensated piston.

The pressure dependence is located within a range of less than 200 ms and, thus, was reduced by 50 ms to 100 ms.

By the optimization using optiSLang and ANSYS CFX, a piston design could be found where the objectives are considered and the optimization eliminates the problems successfully. The expected improvement is confirmed both in tests and in vehicle prototyping. The problem of bucking during vehicle operation is solved.

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