

# Miniaturization of Check Valves

M. Pendzialek, J. Schneider, K. Höhe and L. Zentner

**Abstract** This contribution deals with principles of developing and constructing technologies to enable the optimization of hydraulic components. The focus is on conventional check valves with a goal of achieving a reduction in size and an accompanying optimization of the housing. For this purpose, check valves, which up to now have had to be installed as additional equipment, are first analyzed, the requirements determined and then redesigned. Here, a conventional rigid-body valve is replaced by a compliant model, creating a monolithic component and uniting the functions of multiple elements, such as springs and closing members (steel balls). The model based development of the novel valve system was carried out by Finite Element Method (FEM). The new valve was improved, in relation to weight and design space, compared to the ball check valve.

**Keywords** Plate check valve • Miniaturization • Metallic layers • Compliant valve element • Hydraulic fluid

## 1 Introduction

The requirements for automobile suppliers and thus for their products have been increasing over the last few years. In essence, this trend stems from greater political emphasis on environment protection, where words such as “downsizing” and

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“efficiency optimization” are used. What is meant in general is a reduction of pollutant emissions and a decrease in fuel consumption for the same or even improved performance. A very effective method to fulfill these requirements is a reduction in weight or rather the miniaturization of assemblies or individual components (Löwer 2010). The design discussed here primarily places an emphasis on weight reduction.

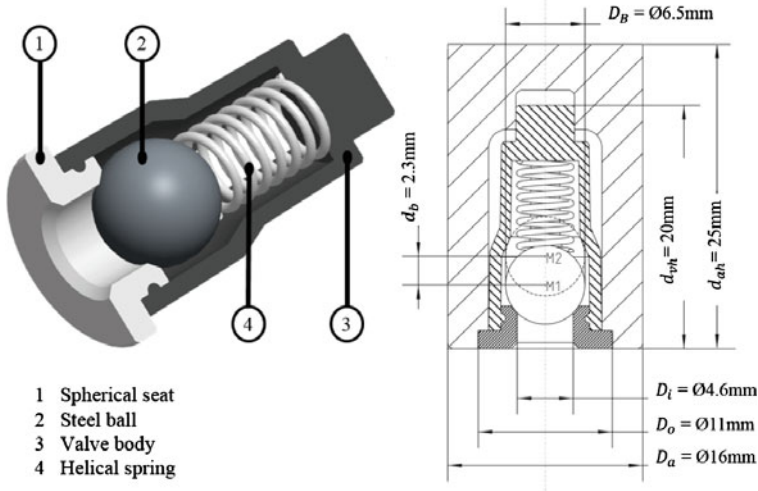
The analysis involves a check valve used to maintain oil flow in one direction and prevent back flow. Many different designs can be found, including those using either a ball or a cone as the closing member (Bauer 2011). The feasibility of a new type of compliant check valve for hydraulic fluids is to be investigated on the basis of an empiric investigation of a known ball check valve. The current state of the art contains a wide variety of solutions. As described in [DE 10 2009 056 135 A1 (27.11.2009)], a valve can be created by adding a compliant element connected on one side in order to achieve the one-way sealing function in combustion engines. Alternatively, this can also be done with a type of spring-loaded valve disk, which represent a one-way coolant flow valve for cylinder head gaskets, as shown in [WO 2006/002254 A3 (05.05.2007)]. Here, a solution is to be found for the rigid system of the ball check valve using a compliant valve element in order to achieve a reduction in weight and size.

## 2 Properties of a Ball Check Valve

The ball check valve (BCV) is used in this analysis because it represents a good example of a common hydraulic element. The new design intends to replace the BCV with a compliant valve element. The corresponding requirements were compiled from the following analysis of the BCV. It contains a valve body made of synthetic material which functions as its housing. The metallic spherical seat defines the inlet cross-section and accordingly the narrowest point of the valve.

The polished steel ball (2) in Fig. 1 is held in position and pre-loaded by a helical spring (4). When the resulting force of hydraulic pressure exceeds the spring pre-tension, the valve begins to open and deformation of the spring increases until the ball reaches its maximum point of deflection.

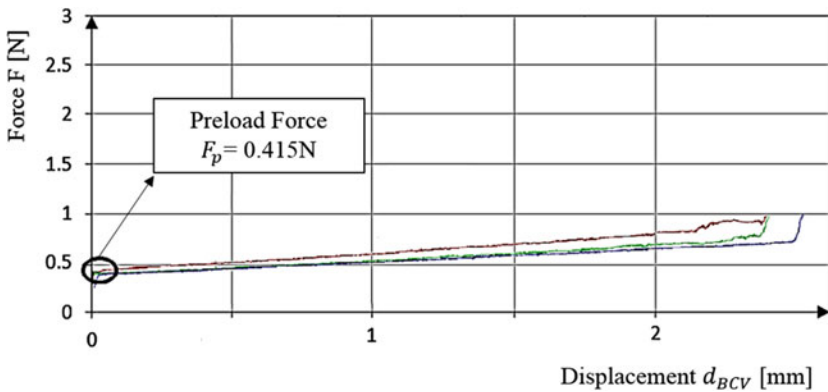
An important parameter with respect to weight reduction is the mounting volume  $V_{BCV}$  required to mount the BCV and for it to fulfill its function. For simplification, the shape is assumed to be a cylinder, whose diameter is the largest outer diameter  $D_O$  of the ball and whose height is  $d_{vh}$ . This represents the actual space required by the valve. However, in order to calculate the total volume, a ring-shaped base (not shown) of surrounding material must be added to the volume to allow the element to be installed. For this, an estimated allowance of 5 mm for the assembly is assumed for both diameter  $D_O$  and height  $d_{vh}$  to generate  $D_a$  and  $d_{ah}$ . The mounting volume of the BCV was determined to be  $V_{BCV} = 5026.5 \text{ mm}^3$ .



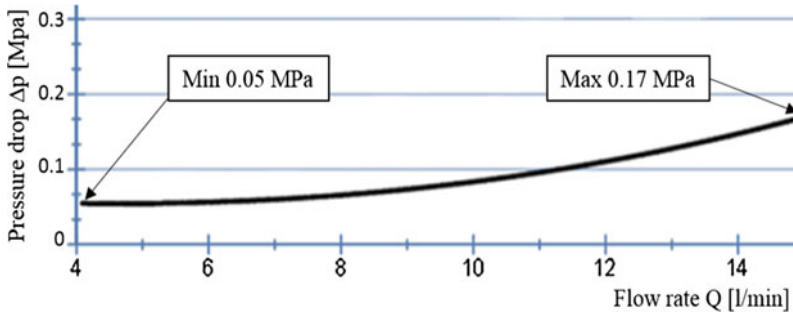
**Fig. 1** *Left* Partial cutaway with component overview; *right* section drawing of the assembly with dimensions

Relevant factors for valve function include the spring preloading force  $F_p$ , and the maximum possible deflection  $d_{BCV}$ . The spring was measured while installed in the BCV. An analysis of the force-displacement curve of the helical spring yielded the following results using a material testing machine manufactured by Zwick GmbH & Co. KG [Fa. Zwick GmbH & Co. KG (10.2.2016)]. The measurement results are shown in Fig. 2.

Together with the inlet cross-section  $D_i = 4.6$  mm and the spring preload force  $F_p = 0.415$  N, it is now possible to calculate the opening pressure  $p_{open}$  of the BCV.



**Fig. 2** Force-displacement curve of the BCV with spring preloading force  $F_p$



**Fig. 3** Pressure-drop-flow-rate curve at the hydraulic test bench

$$p_{\text{open}} = \frac{F_p}{A_{Di}} \quad (1)$$

Here, opening pressure  $p_{\text{open}} = 0.025$  MPa refers to the minimum pressure that must act on the ball (2) in order to cause a displacement. Starting at that pressure  $p$ , oil flow  $Q$  is ensured. Another important parameter for a check valve is the pressure-drop-flow-rate curve ( $\Delta p = \Delta p(Q)$ —curve), which represents the hydraulic resistance of the open valve within the system.

The goal is to keep that resistance as low as possible in order to avoid losses and deterioration of the efficiency of the entire system. The curve shown in Fig. 3 was determined by installing the BCV in an experimental setup and exposing the valve to a hydraulic flow  $Q$  while maintaining a constant temperature. The system pressure  $p$  is then ramped up to 8 MPa. The volumetric flow rate  $Q$  was measured with an accuracy of 0.3 % of full scale using a VC 3 F1 P S volumetric flow sensor from Kracht GmbH [Fa. Kracht GmbH (15.3.2016)].

The basis of the new design is formed by three main pillars: The required mounting space, the spring parameters from the force-displacement curve and the characteristic curve from the pressure-drop-flow-rate diagram.

These pillars represent the target values for the new design requirements. In particular, the values should lead to a reduction of the mounting volume required. At the same time, the functional parameters, such as opening pressure  $p_{\text{open}}$  from the force-displacement curve or parameters from the pressure-drop-flow-rate curve (Figs. 2 and 3), should remain close to the values determined for the BCV.

### 3 System Requirements for a New Valve

The new design is based on the function of classic check valves. The initial form requirements originate from research into the state of the art as well as from the BCV parameters determined above. On the one hand, a high value is to be placed

on the miniaturization of the mounting volume in the new design, through which the efficiency can be improved, too.

On the other hand, the parameters from the force-displacement curve and the pressure-drop-flow-rate curve needs to be reproduced as close to identical as possible. The following list serves both as a basis and as a guide for the optimization.

#### Requirements:

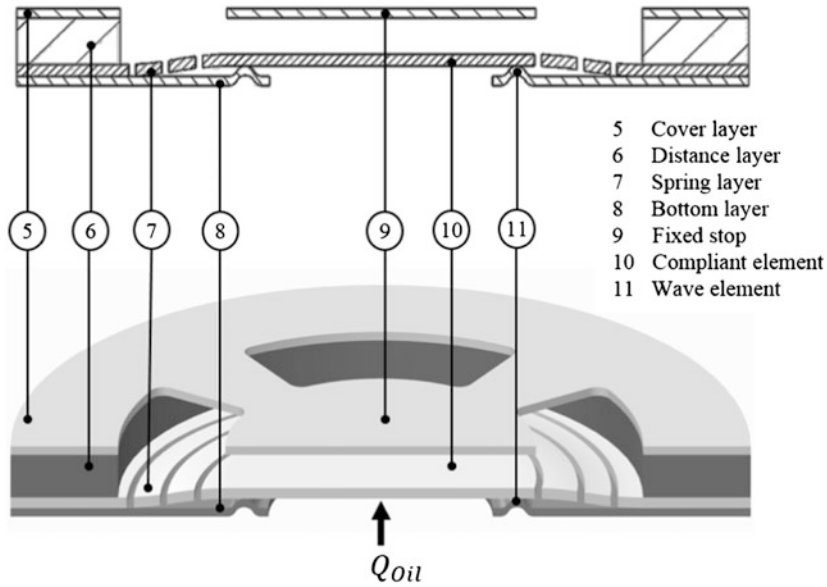
- required volume should be reduced by at least 50 %
- maximum outer diameter  $d_V \leq 14$  mm should not be exceeded
- inlet diameter of  $D_i = 4.6$  mm as in the BCV should remain
- formation of the valve should be done with metallic layers
- the spring and sealing element should be generated using a single component
- the spring deflection should be limited by a mechanical stop
- the sealing surface should be continuous and line-shaped
- the valve geometry should not protrude beyond the metallic layers
- the opening pressure  $p_{open}$  must be 0.025 MPa
- the pressure drop should be smaller than 10 % of the system pressure  $p = 8$  MPa.

## 4 Development of a New Compliant Valve

The method of achieving a significant reduction of the mounting volume is the development of a valve system formed from individual metallic layers with a compliant valve element (10) called plate check valve (PCV), while still fulfilling the basic functions of a check valve.

As shown in Fig. 4 symbolically with an arrow, the oil flow  $Q_{oil}$  must be allowed in indicated direction and blocked in the other direction. By forming a fine-toleranced ( $\pm 10$   $\mu$ m) wave element (11) in the bottom layer (8), it is possible to adjust the spring preload force  $F_{PCV}$  of the compliant element (10). It is formed with bridges out of the spring layer (7). The wave element (11) serves as the valve seal. The oil pressure supports the sealing function of the closed valve to prevent an oil flow  $Q_{oil}$  in the opposite direction (Fig. 4). Here the parallelism between the wave element (11) and the compliant element (10) is given to reduce the hydraulic pressure drop of the valve.

In order for oil to be able to flow from one side of the valve to the other, the distance layer (6) is left open at the location of the compliant element (10), generating an opening valve path. This, in turn, is limited by the cover layer (5), while still offering the oil a flow path through the openings lateral.



**Fig. 4** *Top* section drawing of the valve with layer descriptions; *bottom* 3D section view

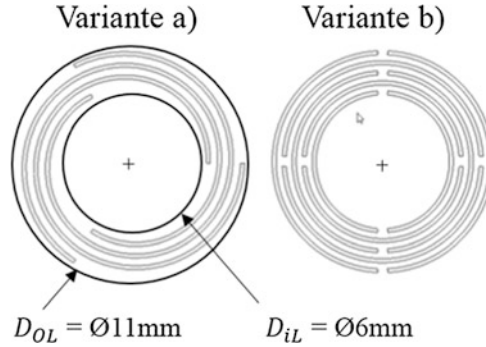
#### 4.1 Design Variants of the Spring Layer

A compliant element (10) is provided for within the spring layer (7). The element combines the functions of the helical spring (4) and the steel ball (2) from the BCV (Fig. 1) and is made of spring steel in order to achieve the best possible properties. Two different variants were analyzed. These own the same compliant properties by adapted spring curves. Both variants were produced using the laser cutting process with a laser spot width of 150  $\mu\text{m}$ .

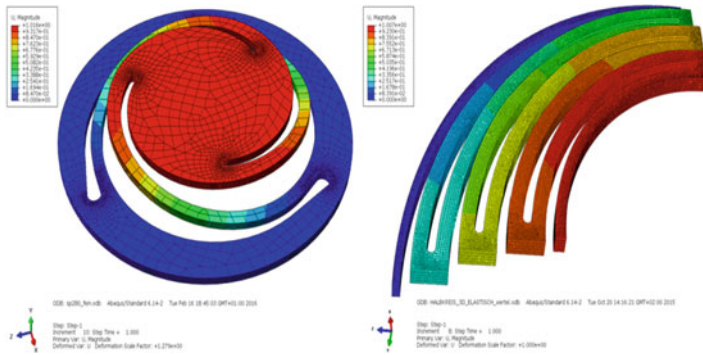
The compliance of variant (a) is achieved by cutting three recesses around the center and offset by  $120^\circ$ . This spiral, known as an Archimedean spiral, arises from a circular motion which increases the radius in proportion to the rotation angle. In this variant, the flow surface affected by the pressure drop  $\Delta p$  has an area of  $A_{(a)} = 10.8 \text{ mm}^2$ .

Variant (b) possesses 10 circular segments cut out using a laser. They are arranged such that two segments are located at each radius, forming two bridges with a width of 0.3 mm. The radius values are set linearly and the segments at each radius are rotated  $90^\circ$  about the center with respect to the radii above and below. The flow surface here is  $A_{(b)} = 27.7 \text{ mm}^2$  (Fig. 5).

Both variants (a) and (b) form a compliant element out of a flat metallic material. The outer diameter  $D_{OL}$  of both contours is 11 mm, fulfilling the requirements. The inner area with the contour diameter  $D_{IL}$  forms a spring plate, which provides for sealing of the wave element (11) (Fig. 6).



**Fig. 5** Design variants for the valve compliant element; **a** spiral contour made of bridges rotated 120°; **b** 10 circular-segment contours with different radius

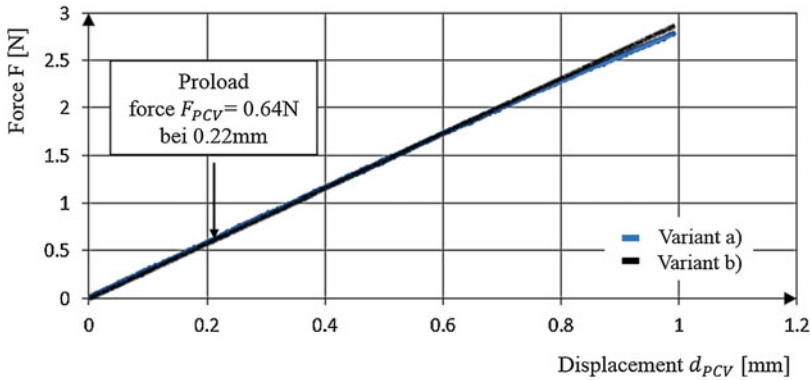


**Fig. 6** Displacement simulation of variant (a) (left) and (b) (right)

In order to limit the number of variables, the protrusion of the wave element (11) above the bottom layer (8) will be set at 0.22 mm. Based on the spring parameters of the ball check valve from Sect. 2, the opening pressure  $p_{open}$  of the compliant valve is been determined at 0.025 MPa. Assuming a wave element (11) diameter of 5.7 mm, the spring preloading force  $F_{PCV}$  is 0.64 N. Variant (a) as well as variant (b) should have that value and they are shown in Fig. 7.

The characteristic curve of Fig. 7 is reached by variation the length of variant (a) and the number of variant (b) of the bridges in the compliant element (10) and thus the gradient of the spring curve is been influenced (Table 1).

With the help of FEM and the program Abaqus/CAE, the geometry is connected using primarily C3D8R elements and the calculations run. The resulting functionality corresponds to that of the ball check valve.



**Fig. 7** force-displacement curve of variants (a) and (b) of the compliant element

**Table 1** Parameter of the FEM models

	Variant (a)	Variant (b)
Type/number	C3D6/8070 C3D8R/83200	C3D6/3835 C3D8R/75985
Element size	0.025 mm (10 elements)	0.05 mm (5 elements)
• Thickness	Critical Sects. 0.011–0.5 mm	0.015–0.05
• Surface		
Symmetry	Not possible	XY- and ZY-plane
Boundary C	Fixed at outer diameter	Fixed at outer diameter
Deflection	Contour diameter displaced Path-controlled to 1 mm	Coupling inner elements on reference point Path-controlled to 1 mm

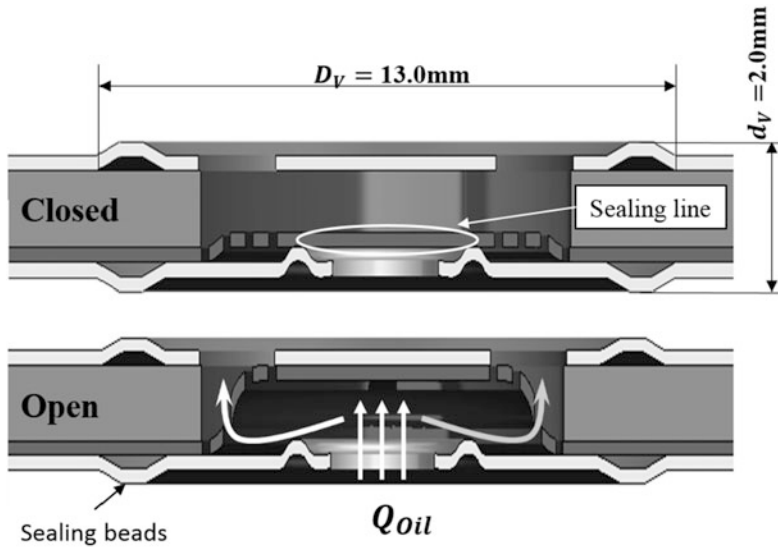
## 4.2 Comparison of Mounting Volumes

A comparison of the mounting volumes of the conventional BCV and the newly developed compliant valve PCV requires an explanation of the dimensions shown in Fig. 8, which are used to calculate the mounting volume  $V_{PCV}$ .

The diameter  $D_V$  arises due to trapezoid-shaped raised areas formed within the cover and bottom layers (5/8), which increase the diameter. These areas can be found around the valve recesses and are called “sealing beads”. The beads represent the valve system connection points with the surrounding parts and maintain an appropriate seal.

The total height  $d_V$  of 2.0 mm arises through the material thickness of the individual layers comprising the valve. The cover and bottom layers (5/8) contain the sealing beads, increasing the total height  $d_V$  by 0.4 mm. In contrast to the BCV, this setup does not require additional volume (base) to mount the valve. This yields





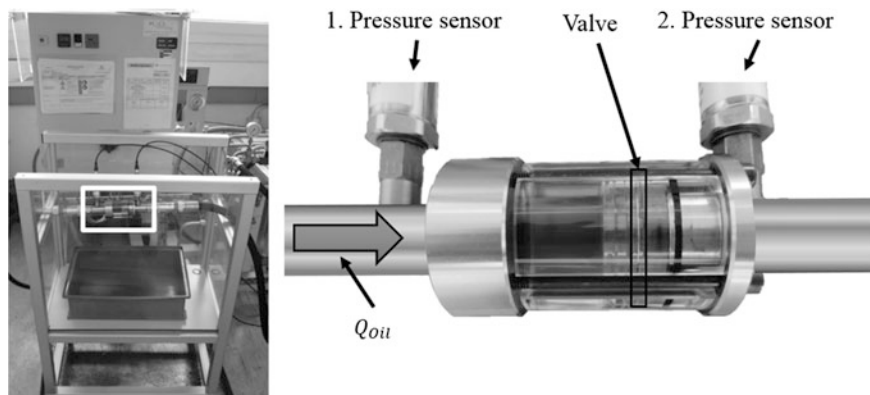
**Fig. 8** *Top* closed compliant valve with dimensions; *bottom* open compliant valve with flow process  $Q_{Oil}$

a mounting volume  $V_{PCV} = 265.5 \text{ mm}^3$  for the compliant valve system. Here, the mounting volume of the BCV is  $V_{BCV} = 5026.5 \text{ mm}^3$ . This means that the necessary mounting volume has been reduced by 95 %.

### 4.3 Functional Comparison of the Valve Types

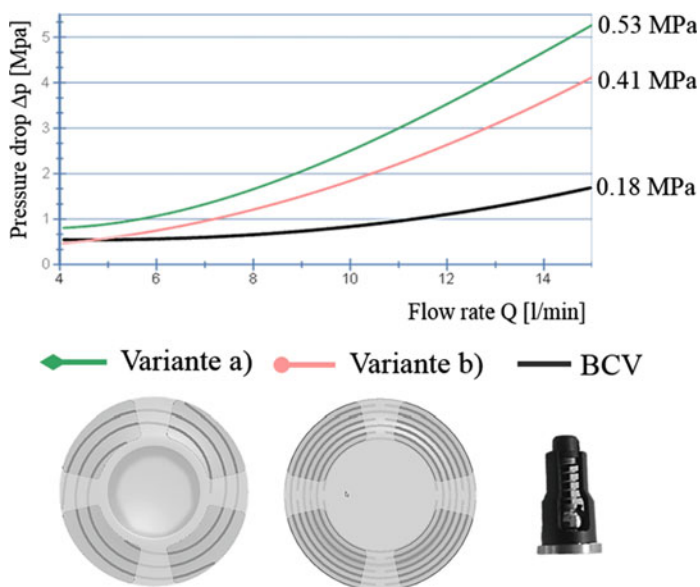
As previously described for the BCV in Sect. 2, the pressure-drop curve is a characteristic parameter for evaluating check valves. This curve is measured by hydraulic tests. These tests were carried out using a modified controllable hydraulic unit from the company NOLD Hydraulik + Pneumatik GmbH (Fig. 9 Left); the unit can generate a power output of 11 kW, a maximum pressure  $p = 21 \text{ MPa}$  and a volume flow rate of  $Q_{Oil} = 181 \text{ l/min}$ . Measurement data are captured by two pressure sensors, in front of and behind the object under test. The sensors can record a pressure drop with an accuracy of 0.1 % at a maximum pressure of 10 MPa [Fa. Tecsics GmbH (14.3.2016)]. The volume flow  $Q_{Oil}$  rate is measured with the same gear flow meter as the BCV.

Compliant valve variants (a) and (b) were tested along with the BCV. The pressure sensors record the absolute pressure at a constant temperature. The data was digitally captured and processed with the help of LabVIEW measurement software and DIAdem data processing software, both from National Instruments.



**Fig. 9** Left setup of the hydraulic unit; right test setup with measurement connectors and symbolic volume flow  $Q_{oil}$  direction

The results of the test stand experiments are shown in Fig. 10. Three measurement series were taken of each valve, the curves were averaged and smoothed. The pressure drop  $\Delta p$  can be calculated because the pressure  $p$  was measured both before and after the valves. The flow rate  $Q_{oil}$  remains the same at all locations along a closed conduit, so it only needed to be measured once.



**Fig. 10** Pressure-drop-flow-rate curve for variants (a)/(b) and the BCV, the images of the valve elements are not true to scale

Comparing the results of the individual measurement series with each other (see Fig. 10), it becomes evident that the geometry of the compliant element (10)—in particular the type of bridge connection used for the spring plate in variants (a) and (b)—has a significant influence on the pressure drop  $\Delta p$  of the check valve. Variant (a) causes a pressure drop  $\Delta p$  of 0.53 MPa at a flow rate  $Q_{Oil}$  of 15 l/min, whereas variant (b) generated a 23 % smaller drop. This can be traced back to the 256 % larger flow surface  $A$  in variant (a) compared to variant (b) as well as to the different overall forms.

Variant (b) also exhibits an advantageously smaller pressure drop  $\Delta p$  across the compliant valve at small flow rates  $Q_{Oil}$  between 0 l/min and 4 l/min even compared to the ball check valve.

However, both variants generate a larger pressure drop  $\Delta p$  in the range of flow above 4 l/min compared to the ball check valve tested, which generated a measured maximum value of 0.18 MPa at 15 l/min. This result was to be expected because the BCV uses a 2.3 times larger deflection  $d_{BCV}$  compared to the deflection  $d_{PCV}$  of the compliant valve. Nevertheless, the pressure drop  $\Delta p$  limit of 10 % of the system pressure ( $p = 8$  MPa) was not exceeded.

## 5 Conclusion and Outlook

The analysis of a ball check valve provided the basis for the development of a miniaturized check valve. The new development of the compliant valve system is based on the reduction of the mounting volume. This could be reduced by approximately 95 %. Geometric requirements have been met as well as the compliance with the material specifications. The spring characteristics of the compliant element could be set both in case of variant (a) and of variant (b) so that the hydraulic opening pressure corresponds to the default. It was possible to reduce the hydraulic pressure drop of the compliant valve system to approximately 49 % of the permissible limit. In partial areas of the pressure drop curve even an improvement compared to the ball check valve could be achieved.

The next step should be the optimization of the pressure drop at higher flow rates, so that the hydraulic resistance can be further reduced. In order to guarantee its long term function, the durability of the compliant element has to be analyzed. This includes both practice tests in the form of fatigue tests as well as analytical experiments with the finite element method. In addition, the opening movement of each of the variants to be investigated as a possible tipping behavior to prevent. In order to get from a development stage to a series product, it is not only required that the functional parameters fit, but that the most appropriate production method is established. Further investigation in this respect is required.

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