EXPERIMENTAL AND NUMERICAL RESEARCH OF THE FLOW INSIDE THE CONTROL VALVES TRIM

by

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In this paper are presented desing, testing and numerical analysis for two manufactured control valve trims. Valve trim is consisted of cage or dick stack, plug, stem and seat. Size from app. 15.88 mm (0.625 in) up to 101.6 mm (4 in) is suitable for 3-D metal and plastic print, what is presented in this paper. Selective laser melting 3-D metal printing is applied on the disc presented in this paper. Even better material properties from rest of the valve parts could be obtained. This is of great importance for valve retrofitting. In this paper is presented, also, new developed channel geometry, what is followed by various fluid-flow phenomena. Measurement results for second prototype manufactured by 3-D printing using plastics are presented in details. Here is shown, in short, procedure for determination of K_V values of the test valves according to the EN 60534-2-3, Industrial-process control valves – Part 2-3: Flow capacity – Test procedures. In addition, some aspects of CFD calculations are presented.

Key words*: control valve, trim design, standardized test procedure, 3-D modelling, 3-D metal and plastic printing, CFD*

Introduction

Control valves have numerous applications like in natural gas control and transport (as anti-surge and recycle valves, hot/cold bypass valves, throttling valves, degasser flow/level control valves), natural gas treatment for dehydration and desulphuring (TEG injection, flashing drum pressure control, amine pump re-circulation control valves), LNG processing (gas/steam to vent valves, blowdown and depressing valves), refineries and petrochemical (charge pump recycle valves, blowdown control valves, emergency vent valves, amine pump recycle valves), ethylene plants (feed-pump recycle valve, blowdown and gas to vent/flare valves, steam conditioning and desuperheating, compressor recycle) and*, etc.*

One of the most successful technology proven on the field is the multi-stage and multi path technology. It utilizes turns in the flow channels of various geometries (mostly used are 90° angle turns) with the aim to reduce the fluid's energy. Constant design and production modifications of the existing trim design are ongoing [1, 2]. Main components of the control valve are presented in fig. 1.

In this paper is discussed the trim, its design, numerical results and testings. The modified design of a multi-stage continuous-resistance trim is presented in [1]. The trim geom-

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etry should ensure sufficient energy dissipation and control the speed of the fluid-flow, but it directly affects the production process, because the limits of the modern metal printing method should not be exceeded.

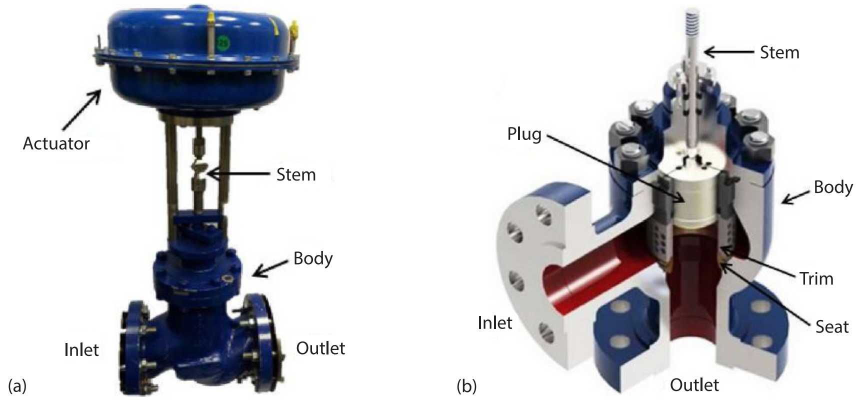

Figure 1. Components of the control valve; (a) valve with the actuator and (b) valve body with the trim [1]

The sizing of the valve regulating element, according to the [3, 4], as well as some aspects of the trim manufacturing and CFD results are discussed in [2]. The traditional manufacturing method has a *high risk potential for failure [2]. Processes like EDM (electric discharge manufacturing) for burning the flow paths into the disks, brazing (for joining the disks into a stack) and final machining of such and assemblies are not only related to very high cost, but limit also the design freedom significantly [2]*.

Savić *et al.* [2] and here is presented a new approach and application of additive manufacturing in materialization of the designed trim geometry. In addition, testing standard is here presented, as well as some comments on the obtained CFD results.

Designed trims

First approach was to develop and test the limits of the manufacturing technology by applying the selective laser melting (SLM) 3-D metal printing process. The nickel steel alloy 718 was used. Flow channels of various complex geometries are made by the SLM method, which acts as optimal, because it enables, after thermal treatment, regulation at high pressures. The first prototype utilised narrow channels with different geometries (1×1 mm, ∅1 mm; squared, circle and elliptical). These two, in combination with the mechanical properties of alloy steel used, were very challenging for this production process. However, the prototype final dimensions were ∅25.4 × ∅67 × 38 mm and flow passages utilising the multiple 90° angle turns (elliptical/circle 12 and squared 18) were calculated and designed after the procedures presented in [3, 4]. This is presented in [2]. The developed trim design is presented in fig. 2(a). In fig. 2(b) is presented the fluid-flow filled space, 3-D model prepared for CFD.

The developed and manufactured second trim design prototype, by using the 3-D printing with plastic materials (PLA, a biopolymer), is presented in fig. 3(a). The prototype final dimensions were ∅24.9 × ∅66.5 × 33 mm. In fig. 3(b) is presented the fluid-flow filled space, geometry prepared for the CFD.

The second trim has different channel geometries comparing to the first one, also calculated after the procedures presented in [3, 4]. This production procedure was, also, successfully implemented on these complex channels.

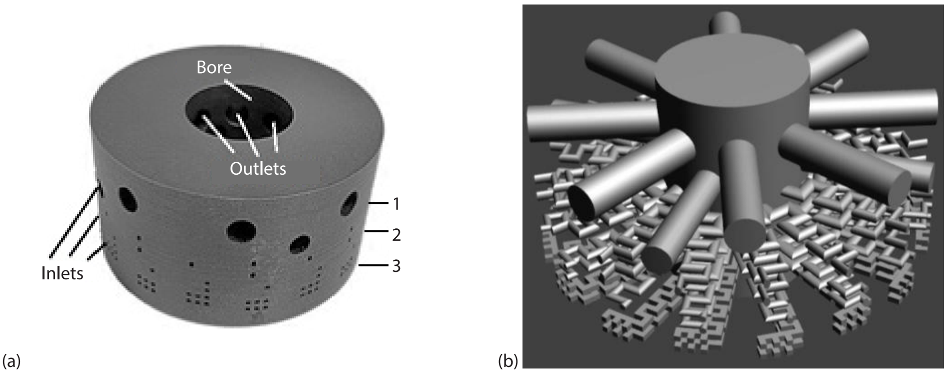

Figure 2. (a) Manufactured first prototype by the SLM 3-D metal printing process and (b) trim space filled with fluid – geometry prepared for CFD

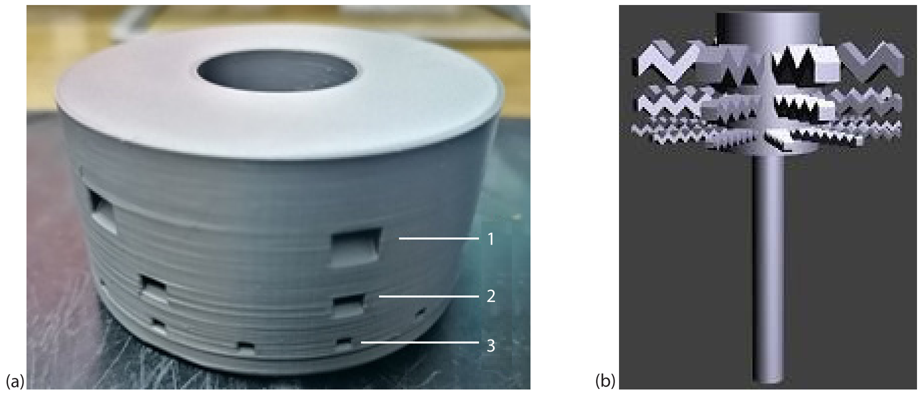

Figure 3. (a) Manufactured second prototype by 3-D printing using plastics and (b) trim space filled with fluid – geometry prepared for CFD

Trim testing

The first trim design was tested in the Dr. Ing. T. Baumer GmbH, Pruflabor-Ingenieurburo, Herford, Germany (in the following text: Test Laboratory). The tests were following the ANSI/ISA-75.02.01-2008 (IEC 60534-2-3 Mod) *Control Valve Capacity Test Procedures* [5], *i.e.* DIN EN 60534-2-3. *Industrial-process control valves – Part 2-3: Flow capacity - Test procedures (IEC 65B/865/CD:2013)*. [6], with the support of the company VLL solutions, Vienna, Austria. A basic flow test system is presented in fig. 4.

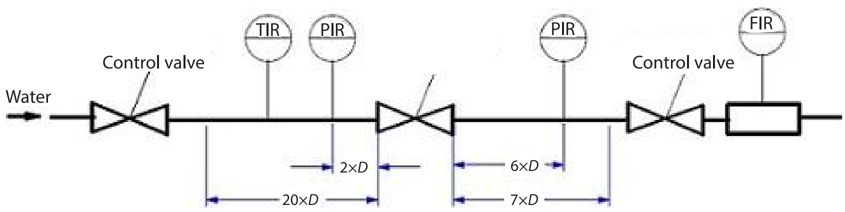

Figure 4. Water test section for the determination of K_V values of test valves according to [6]

The test specimen is any valve or combination of valve, pipe reducer, and expander or other devices attached to the valve body for which test data are required [6]. In the case when the first trim design was tested, the flow test system presented in fig. 5. was used, where Control valve is the throttling valve, FIR is the flow measurement device, TIR is temperature measurement, while PIR are pressure measurement devices. Test valve is the tested trim design.

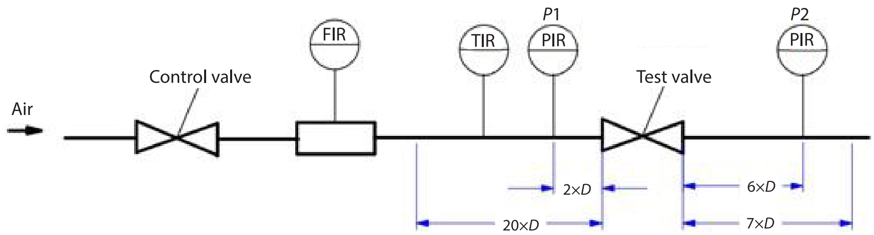

Figure 5. Air test section for the determination of K_V values of test valves according to [6]

Air was used for valve testing and it was incompressible case. Trim was positioned in the cylindrical box, *i.e.* in the valve gallery, and its top was blocked. It was tested with the fully open inlets, and closed the first and the second row, fig. 2. These tests have proven that first trim design specimen survived tests.

Principially, test bench is according to DIN EN ISO 60534. Temperature was approximately 20 °C, while outlet pressure 1.0 barg. The mass-flow rate corresponds to K_V. According to the ANSI/ISA-75.01.01-2012 (60534-2-1 MOD), C_V or K_V is valve flow coefficient, where C_V is based in imperial units system, while K_V is based in SI units system. Measurements were performed with air-flow for maximum 50 mbar. Effects of laminar flow in disc stack should be minimal. Results are reported in the officially issued report [7].

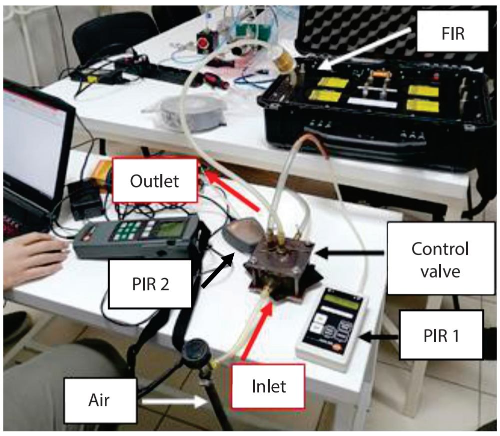

Figure 6. Air test section in laboratory

Tests for the second trim size are performed in the Laboratory of the Department for hydraulic machinery and energy systems and accredited Laboratory for fluid mechanics, both at the Faculty of Mechanical Engineering University of Belgrade. The flow test system, presented in fig. 6, was used, where the trim was positioned in the cylindrical box. FIR is the flow measurement device, while PIR1 and PIR2 are pressure measurement devices. Test valve is the tested trim design. Flow measurement was performed by a master flow meter with accuracy 0.25%.

Measurements were made for three plug positions in the trim, fig. 1(b), by closing certain openings by level, fig. 3(a): completely open, fig. 3(a), positions 1-3, the upper row closed, fig. 3(a), position 1, and the upper two rows closed, fig. 3(a), positions 1 and 2. Measurement results for: inlet gauge pressure, p_{1g}, outlet gauge pressure, p_{2g}, volumetric, Q, and mass-flow rate, q_m, are presented in tab. 1.

The flow coefficient K_V [m^3 per hour] for water is calculated:

$$K_V = \frac{Q}{N_1}\sqrt{\frac{\frac{\rho_1}{\rho_0}}{\Delta p}} \tag{1}$$

where Q [m^3 per hour] is volumetric flow rate, Δp [bar] – pressure drop, ρ_1/ρ_0 is relative density (equals 1.0 for water at 15 °C), N_1 – the constant and depends on the units used in the general sizing equation and the type of flow coefficient: K_V or C_V. According to ANSI/ISA-75.01.01-2012 (60534-2-1 MOD) $N_1 = 1$.

Table 1 shows the K_V value obtained for the assumption that the air-flow is incompressible, where the air density ρ_1 is calculated for the test temperature of 22 °C and the absolute pressure value p_1, while ρ_0 is the standard density at 101325 kPa and 273 K.

The true value of K_V will be obtained by testing the trim incorporated in the control valve body. The effect of fittings on the nominal flow coefficient of the valve, which are attached to the valves, can be significant.

Table 1. Measuring series for three plug positions in the trim

Completely open						
p_{1g}	p_{2g}	Δp	ρ_1	Q	q_m	K_V
[hPa]	[mbar]	[Pa]	[kgm^{-3}]	[m^3 per hour]	[kg per hour]	[m^3 per hour]
204.8	201.00	380.0	1.42	5.1024	7.2560	86.80
174.3	171.00	330.0	1.39	4.6520	6.4479	83.84
125.8	123.00	280.0	1.33	3.9027	5.1858	74.77
93.0	91.00	200.0	1.29	3.3135	4.2745	74.01
104.8	103.60	120.0	1.30	2.5797	3.3638	74.78
52.6	52.00	60.0	1.24	1.7748	2.2048	71.02
27.7	27.48	22.0	1.21	1.0428	1.2648	68.09

The upper row closed						
p_{1g}	p_{2g}	Δp	ρ_1	Q	q_m	K_V
[hPa]	[mbar]	[Pa]	[kgm^{-3}]	[m^3 per hour]	[kg per hour]	[m^3 per hour]
235.1	196.89	3821.0	1.46	5.1758	7.5457	28.12
176.0	146.70	2930.0	1.39	4.3910	6.0949	26.58
102.8	85.73	1707.0	1.30	3.2756	4.2635	25.15
94.7	86.05	865.0	1.29	2.3581	3.0468	25.35
68.3	61.93	637.0	1.26	1.9727	2.4873	24.41
42.2	38.17	403.0	1.23	1.5365	1.8900	23.61
20.3	18.42	188.0	1.20	1.0100	1.2162	22.48

The upper two rows closed						
p_{1g}	p_{2g}	Δp	ρ_1	Q	q_m	K_V
[hPa]	[mbar]	[Pa]	[kgm^{-3}]	[m3 per hour]	[kg per hour]	[m^3 per hour]
980.4	106.32	87408.0	2.34	2.5311	5.9181	3.64
857.2	85.19	77201.0	2.19	2.2477	4.9283	3.33
762.5	67.14	69536.0	2.08	1.9725	4.1044	3.00
633.8	49.32	58448.0	1.93	1.6677	3.2166	2.66
526.8	34.95	49185.0	1.80	1.3953	2.5149	2.35
380.8	21.41	35939.0	1.63	1.0581	1.7247	1.98
265.6	13.14	25246.0	1.49	0.8125	1.2137	1.74
188.8	8.75	18005.0	1.40	0.6461	0.9066	1.59
170.8	65.71	10509.0	1.38	0.4812	0.6650	1.53
86.8	30.28	5652.0	1.28	0.3223	0.4134	1.35
47.1	15.66	3144.0	1.24	0.2274	0.2810	1.25
27.7	9.44	1826.0	1.21	0.1751	0.2124	1.25

Dependence of the volume flow rate, Q, of the pressure drop Δp, for three plug positions in the second trim, is presented in fig. 7.

Dependence of the flow coefficient K_V of the volume flow rate, Q, for three plug positions in the second trim, is presented in fig. 8.

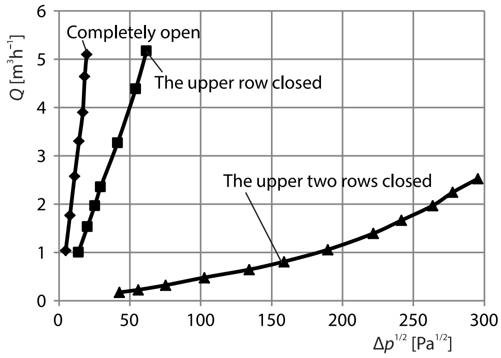

Figure 7. Dependence of the volume flow rate, Q, of the pressure drop Δp

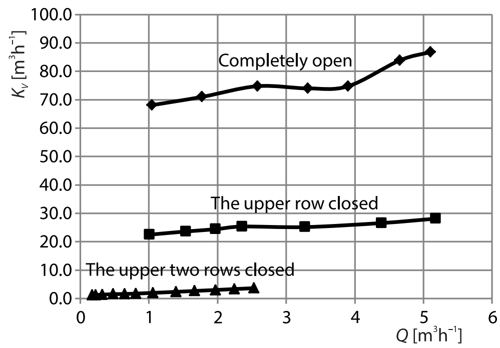

Figure 8. Dependence of the flow coefficient, K_V,of the volume flow rate, Q

As expected, the K_V has the highest values in the case *completely open* (open all three levels), and, respectively, lowest values when the upper two rows are closed. Flow rate in the case when the upper two rows are closed is about 50 times lower than the first case when the trim is completely open, fig. 8. Here are presented experimental results which testify good trim functionality.

Figure 9. Unstructured mesh for CFD calculations on the first trim design

The CFD calculations

The CFD calculations for the higher pressures have been performed on the first trim design, fig. 2. Water was considered as the working fluid. Unstructured mesh with 5.8 milion elements was used, fig. 9. Twenty layers within boundary-layer were considered.

Designed regulative element, *i.e.* the first trim design, has various levels of opening. In

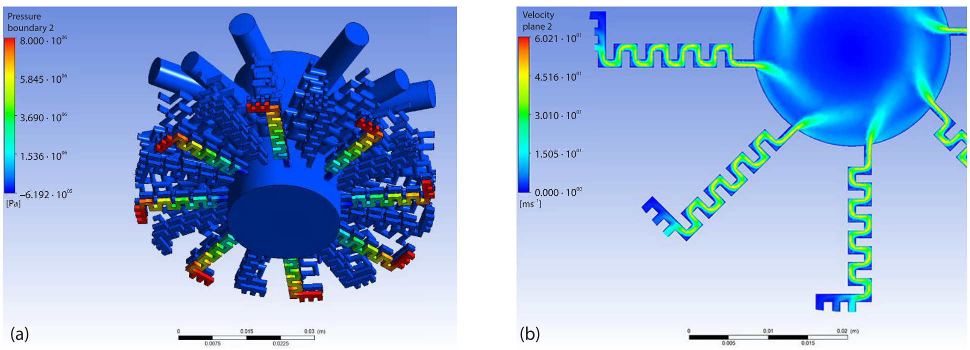

Figure 10. The first trim design for the lowest flow rate; (a) pressure distribution and (b) velocity distribution

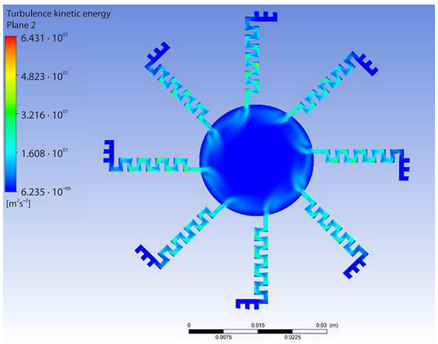

Figure 11. Turbulence kinetic energy for the first trim design

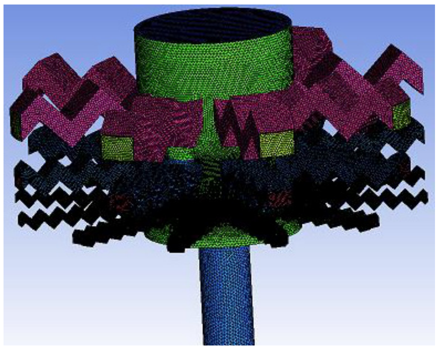

Figure 12. Unstructured mesh for CFD calculations on the second trim design

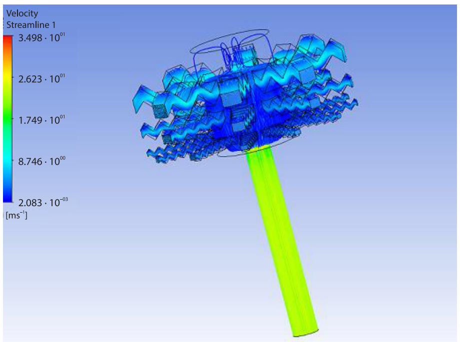

Figure 13. Velocity distribution for the second trim design

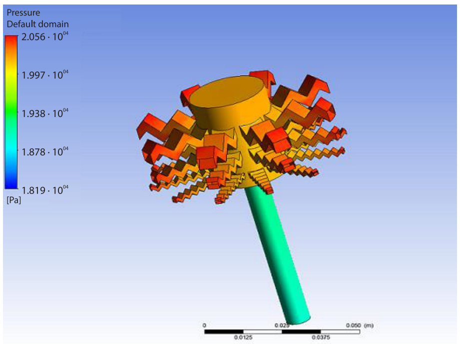

Figure 14. Pressure distribution for the second trim design

fig. 10(a). is presented pressure distribution for the lowest flow rate. In this case, only the lowest level of channels is open. Velocity distribution for the same case is presented in the fig. 10(b). Dead flow zones are obvious in the channels' corners.

The designed first trim geometry at the lowest level (studied case) has eight channels with three inlets each with the same outlet. Boundary conditions are here defined on the channels' inlets, while outlet at the exit of the cylindrical chamber.

Turbulence kinetic energy distribution in trim geometry for the lowest flow rate is presented in the fig. 11. These results are presented with the aim to show turbulence character in theses trim patterns. For CFD calculations k-ε model was used.

The CFD calculations have been performed, also, for the second trim design, fig. 3. Air was considered as the working fluid. Unstructured mesh with 12135543 elements was used, fig. 12. Five layers within boundary-layer were considered.

Boundary conditions for both trims are presented in tab. 2. Other surfaces were set as a wall boundary condition.

Table 2. Boundary conditions for both trims

Surface	Boundary conditions	Input
Channels' inlets	Pressure inlet	p_{1g} [Pa]
Channels' outlets	Mass-flow outlet	q_m [kg per hour]

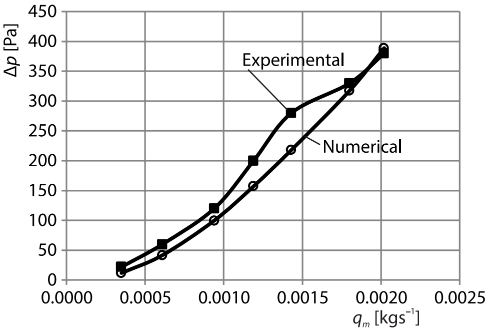

Figure 15. Static pressure drop distribution for the second trim design

In fig. 13. is presented velocity distribution for the first completely open case in the second trim design, fig. 1. In fig. 14 is presented pressure distribution for the same case.

In fig. 15. experimental and numerical simulation results for the second trim design with completely open all three level openings, are presented. Trendlines of the presented numerical and experimental results are very similar. There is a good agreement of the obtained CFD results in comparison with the experimental results.

Conclusions

Two trim designs for the regulating valves are developed and presented in this paper. The first regulative element geometry is manufactured by selective laser melting by using the alloy 718, while the second one with the additive manufacturing by using the printer and plastic materials. Channels of various sizes and geometries were used and they were properly manufactured in both cases. So, the conclusions are as follows.

- The optimal complex geometry of the control element of the control valves is defined.
- Elliptical, squared and round flow channels are successfully utilized within the regulative elements, *i.e.* in both trim geometries.
- The SLM 3-D metal print, by using the Alloy 718, is well suited as manufacturing method of regulative element.
- Experiments with the air performed for both trims, show that both trim designs specimens passed the structural tests.
- The CFD calculation for the first trim geometry gave the first approach in the study of the turbulence flow inside the trim geometry, which is correlated with the energy dissipation processes in these regulating elements.
- Experiments with air are performed for the second trim and the K_V value are calculated.
- The CFD calculations for the second trim geometry have good agreement with the obtained experimental results.

Acknowledgment

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Nomenclature

K_V – flow coefficient, [m^3 per hour]
N_1 – constant, [–]
Q – volumetric flow rate, [m^3 per hour]
q_m – mass-flow rate, [kg per hour]
p_{1g} – inlet pressure, [Pa]
p_{2g} – outlet pressure, [Pa]
Δp – static pressure drop, [Pa]

Greek symbols

ρ_0 – standard fluid density, [kgm^{-3}]
ρ_1 – fluid density at inlet, [kgm^{-3}]

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