CAVITATION – MEASUREMENTS FOR INDUSTRIAL VALVES

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Abstract: *The paper treats the cavitation process, which refers to the formation of spaces filled with vapour and gases in the liquid. During flow of technical liquids – especially water – such processes occur when, instead of high velocity, the absolute static pressure reduces and comes down to vapour pressure and the liquid evaporates locally. When the pressure rises again with further flow, the vapour condenses and the cavities disintegrate, which usually generates a strong, buzzing sound. Cavitation not only causes a great noise emission, but also mechanical damage caused by extremely high pressure points. Knowing the data about the procedure, the occurrence of cavitation can be estimated quite accurately by the factor Z_y . The cavitation intensity increases with the increasing pressure. The results of the study and the findings are obtained on the basis of experiments, measurements and calculations.*

Key words: *Measurement, Cavitation, Industrial valves, Noise emission.*

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1. Introduction

Cavitation is a significant cause of wear in engineering contexts. Collapsing voids that implode near to a metal surface cause cyclic stress through repeated implosion. This results in surface fatigue of the metal causing a type of wear also called cavitation. The most common examples of this kind of wear are to pump impellers, and bends where a sudden change in the direction of liquid occurs. Inertial cavitation occurs in control valves, pumps, propellers and impellers. Non-inertial cavitation is the process in which a bubble in a fluid is forced to oscillate in size or shape due to some form of energy input, such as an acoustic field (Wang et al., 2018). In order to study the bubble morphology, they analysed a transparent valve and used camera for valve optimization.

A common problem encountered in hydraulic valves is a progressing deterioration of tightness of their water flow cutting-off seats. The seats are provided usually with a copper-alloy insert joined mechanically with cast-iron valve housing. The problem of unreliability of such joints can be solved by providing surface of the seat with a coating. Researcher carried out different tests for reducing cavitation wear (Orlowicz et al., 2018; Tan & Yeo, 2016). Cavitation craters on the material used typically for valve seats to date were more distinctly outlined and deeper compared to craters observed on the coating. Various studies had been carried out on cavitation erosion in the presence of abrasive particles.

Cavitation is a phenomenon in which rapid changes of pressure in a liquid lead to the formation of small vapour-filled cavities in places where the pressure is relatively low. In order to avoid the damage from cavitation, regardless of the intensity of cavitation (Franc & Michel, 2005), the following measures can be used:

- In operating conditions when $p_1 < 10$ bar and $\Delta p < 3$ bar, cavitation in non-corrosive media does not cause material damage. Small adjustable valves (Samson, 2011) with one bearing up to DN 25, can also reach an acceptable service life in difficult operating conditions.
- If the pressure difference $Z_y + 0,1$ still does not cause cavitation and the pressure difference $p_2 - p_v$ is lower than 10 bar, then the reduction of the bearing's diameter is sufficient. A large drainage volume reduces the erosion of the shell. The pre-pressures p_1 exceeding 28 bar cause damage to the interior. The guide with a bracket has a priority compared to the guide with a spindle. The flow velocity at the inlet should not exceed 5 m/s, otherwise the conical guides may be damaged.
- For the coefficients of the pressure difference up to $Z_y + 0.15$, the contour must be additionally protected. At an operating temperature above 300 °C, the service life can be extended by using the sharpened cones and guides.
- The difficult operating conditions can be controlled with a conical opening during flow in the direction of closure. The larger cavitation space behind the cone in the four-flange housing further reduces the erosion of the housing. The conical opening must not be combined with any of the guides below.
- If the single-stage pressure expansion results in large cavitation intensities, they can be controlled with a multi-stage expansion, such as an RLS internal set. The internal unit RLS must be placed so that cavitation in middle stages cannot occur. The

cavitation intensity can also be reduced by increasing the additional pressure by means of a shock absorber or a damper at the valve's outlet.

- In extreme cases, it is necessary to use an angular valve with a side flow and characteristic of the bearing (small to middle diameter), a conical opening or an internal set RLS. In order to avoid damage of the pipeline, an extension behind the valve should be provided (Kiesbauer, 2000).

Usually we use valves with a double bearing.

The problem with built-in valves is volume, wear, turbulent flow, speed ... – in short, cavitation. How to deal with the problem is indicated in this chapter. We used measurements on the valves-prototype, the correct design of the seats, the appropriate size-speed relation, and the elimination of turbulent flow. In this way we also reduced the volume in the valves.

Main problems:

- how to reduce erosion,
- how to eliminate turbulent flow,
- how to reduce the volume of the valves,
- how to reduce costs in solving the problem.

Proposals of our solutions:

- erosion is reduced by appropriate design of the valve flow channels,
- turbulence is reduced by appropriate speeds-design of valve seats,
- reduction of the volume in the valves with the appropriate speed, elimination of the turbulence, and the appropriate size of the valve seats,
- production costs are reduced by appropriate finishing of models for casting valve housings.

2. Shape of Control Valves at Evaporation

2.1 Saturated Water

A seat characteristic or a conical opening have been foreseen as a damper. Flow in blocked direction. For large bearing diameters, a conical opening is preferred, while for small ones, a seat characteristic is preferred.

The diameter of the bearing must be reduced several times (at least for two nominal diameters).

At large pressure differences, erosion of the housing occurs, which can be avoided with an angular housing. If the use of an angular housing is not possible, at least four flanges need to be used due to the larger flow volume. In such case, the lower cover is a consumable part.

The calibration line behind the valve has to be 10 times longer than the pipe's diameter or at least 1 meter.

2.2 Slightly Cooled Liquid

Medium cavitation occurs ($p_v \geq p_1 / 3$). Therefore, the cavitation guidelines need to be followed (Sirok et al., 2006; Blatnik, 2017). In addition, the nominal diameter has to be reduced several times (for at least two nominal diameters).

2.3 Cooled Liquid

Medium cavitation occurs ($p_v < p_1 / 3$). Therefore, the cavitation guidelines apply.

3. Erosion

Under cavitating flow conditions, the wear rate can be many times greater than that caused by erosion and corrosion alone. Cavitation wear can destroy the strongest of materials – tool steels, stellites, etc. Such damage can occur rapidly and extensively.

Particles loaded by solid parts or high flow rates cause surface erosion (Kiesbauer et al., 2006). In case of austenitic steels, the permanent destruction of the passivation layer results in wear and tear and corrosion (Fig. 1). The erosion resistance (Lohrberg et al., 1999) is higher in austenitic steels than non-alloy steels and low-alloy steels.

Fig. 1. Cavitation: a) at a housing's cover, b) at a valve closure.

The service life can be extended with solid materials (Eisenhauer, 1995) resistant to wear and tear such as stellite, solid carbide or ceramic (Iwai & Li, 2003).

Valve type	Valve factor		
	F_1	Z_y	XT
Standard valves	0,84 - 0,97	0,30 - 0,50	0,55 - 0,75
Silent valves	0,88 - 0,98	0,60 - 0,90	0,72 - 0,75
Regulating valve	0,55 - 0,78	0,15 - 0,25	0,20 - 0,38
Ball taps	- 0,55	0,1 - 0,2	0,15 - 0,25

Tab. 1. Orientation values for the valve factors F_1 , Z_y and XT at load $y = 75$ %.

The valve factor Z_y depends on the shape and load. The fittings with high back pressure suppression have low Z_y factors. At a small load, the values are usually higher (Tab. 1).

The factor of the valve's shape F_d considers the geometrical shape of the damper.

The curve provided in Fig. 2 relate the valve Reynolds number (Re) to the Reynolds number factor (F_R) for viscous fluid.

Fig. 2. Reynolds number factor F_R for viscous fluid.

Equations for viscous liquids, gas and vapour follow.

3.1 Newtonian fluids

$$\Delta p = p_1 - p_2 \quad (1)$$

$$\Delta p > Z\gamma * (p_1 - p_v) \quad \text{Partial cavitation} \quad (2)$$

$$\Delta p > F_L^2 * (p_1 - p_v) \quad \text{Maximum cavitation} \quad (3)$$

$$F_F = 0,96 - 0,28 * \sqrt{\frac{p_v}{p_c}} \quad (4)$$

$$\Delta p_{\max} = F_L^2 * (p_1 - F_F * p_v) \quad (5)$$

If $\Delta p > \Delta p_{\max}$, the flow will be limited.

$$K_v = \frac{Q}{31,6 * F_R} \sqrt{\frac{\rho_1}{\Delta p}} \quad \text{Without flow limitation} \quad (6)$$

$$K_v = \frac{Q_{\max}}{31,6 * F_L * F_R} \sqrt{\frac{\rho_1}{p_1 - F_F * p_v}} \quad \text{With flow limitation} \quad (7)$$

3.2 Viscous liquids

$$Re_v = \frac{707 * 10^4 * F_d * Q}{\lambda * (F_L * K_v)^{0,5}} \quad (8)$$

3.3 Gases and vapours

$$\Delta p = p_1 - p_2 \quad (9)$$

$$x = \frac{\Delta p}{p_1} \quad (10)$$

If $x \geq F_k * x_r$, the flow becomes critical and instead of x the product $F_k * x_r$ is used.

$$F_k = \frac{\kappa}{14} \quad (11)$$

$$y = 1 - \frac{x}{3 * F_k * x_r} \quad (12)$$

$$K_v = \frac{Q_N}{519 * p_1 * y} \sqrt{\frac{\rho_N * T_1 * Z}{x}} \quad \text{Gases} \quad (13)$$

$$K_v = \frac{W}{31,6 * Y} \sqrt{\frac{v_1}{p_1 * x}} \quad \text{Vapours} \quad (14)$$

$$K_v = \frac{W}{22,8 * p_1 * Y * \sqrt{x}} \quad \text{Saturated water vapour} \quad (15)$$

$$K_v = \frac{W * (1 + 0,00126 * \Delta t)}{22,8 * p_1 * Y * \sqrt{x}} \quad \text{Overheated water vapour } (\Delta t = t_1 - t_2) \quad (16)$$

The equations for incompressible fluids do not apply to Newtonian fluids, fluid mixtures, slurry or transport systems for fluids and solids (Brennen, 2013; Lavigne et al., 1995). The Reynolds number is the most important among the dimensionless parameters in forced flows. The Reynolds number is the ratio of inertial forces to viscous forces and is a convenient parameter for predicting if a flow condition will be laminar or turbulent. It is a dimensionless number comprised of the physical characteristics of the flow. The Reynolds number Re_v is an approximate formula, however it is accurate enough for control valves. The equations do not consider the geometry factor for the F_p pipelines, since the flow has no decisive influence on the fittings with low back pressure. Cavitation and evaporation are considered with the critical pressure ratio of F_F .

For compressible fluids, the equations do not apply to multi-phase liquids, gaseous liquids, volatile liquids or mixtures of gases and solids.

For media with a viscosity greater than 20 cSt, the value of K_v must be corrected by the Reynolds factor F_R (Fig. 3).

Fig. 3. Correction of K_v based on the Reynolds factor F_R .

If the fluid expansion in the contraction exceeds the vapour pressure, the fluid starts to evaporate (SIST EN 60534-8-2, 2012). Due to pressure recuperation, the vapour penetrates behind the damper and cavitation occurs (Sirok et al., 2002). The vapour formation causes volume increase which leads to flow limitation (Fig. 4 a). If the initial pressure is below the pressure of the medium's vapour, evaporation occurs (Fig. 4 b).

Fig. 4. An example of liquid expansion (a) and vaporization (b).

For gases and vapours, difference is made between the processes of subcritical and supercritical flow. When pressure drops from p_2 to $p_1/2$, a critical pressure ratio is reached. Acoustic velocity occurs in the contraction, thereby limiting the flow.

4. Calculation of the value K_v

DIN / EN 60534-2 specifies the equations for the size of incompressible and compressible fluids. The method of calculation is related to the behaviour of pressure to various types of fittings. One must consider cavitation, viscosity, natural gases and installation conditions.

Conversion of kinematic viscosity to dynamic viscosity. For kinematic viscosity, the unit cSt is often used.

4.1 General calculation

Mach number at the outlet side of the fitting is:

$$M_a = \frac{v_2}{C_2} \quad C_2 = 316,2 \sqrt{K \frac{p_2}{\rho_2}} \quad (17)$$

Efficiency loss in fittings is:

$$P \cong \frac{W \cdot \Delta p}{36 \cdot \rho_1} \quad \Delta p < \Delta P_c \quad \text{Fluids} \quad (18)$$

$$P \cong \frac{W \cdot p_1}{36 \cdot \rho_1} * \ln \left(\frac{1}{1-x} \right) \quad x = \frac{\Delta p}{p_1} \quad \text{Gases and vapours} \quad (19)$$

4.2 Flow rate in an adjustable valve

The depreciation process regulates the flow, the pressure or the temperature in the adjustable parts of the setting (Fig. 5). The pressure flow significantly affects the selection and shape of valves for a particular field of application.

Fig. 5. Pressure flow in an adjustable valve.

At the valve's inlet and outlet, the flow of matter and friction lead to a relatively small loss of pressure. In the narrowest part of the contraction there is an increase in velocity, which inevitably results in a pressure drop below the initial pressure. The decelerating velocity causes back pressure behind the damper.

4.3 Noise emission

Turbulences, especially compression shocks and gas and vapour jet bursts during supercritical pressure drop or cavitation in liquids, cause noise (Kiesbauer, 2001).

For fluids, there is no significant sound level in the laminar flow region. Laminar flow occurs at low differential pressures, very low K_v values and high viscosity. If a turbulent flow occurs behind the damper, the sound level increases significantly with the increased jet power (Fig. 6). From the difference in pressure $X_F > Z_y$, one can observe a significant increase in noise (cracking) caused by cavitation. The type of fitting and the load significantly affect noise.

Fig. 6. Gas noise at critical pressure drop.

Reynolds number for pipelines is calculated by:

$$Re = \frac{W * di}{\gamma} \quad (20)$$

The Reynold's critical number Re for pipelines is 2320. Below this value, the flow is always laminar. Within the range of 2320 to 8000, laminar flow can occur in the absence of disturbance. If the Reynolds number is greater than 8000, it is certainly a turbulent flow (Fig. 7).

Fig. 7. Turbulent flow.

For gases and vapours, the noise emission increases as the ratio of pressure differences increases as a result of turbulence, jet noise and in the supercritical region due to shock waves, stronger initially and gradual subsequently. There are no sudden changes in the sound level that are typical of fluids.

4.4 Calculation of a sound level

The permitted noise limits are usually established by regulations such as the workplace provisions and the accident prevention regulations. In order to avoid noise emissions that exceed the permitted values, when planning, it is necessary to already know the sound level that can be expected in certain parts of the device.

The methods for calculating the sound level of control and shutdown of valves for liquids, gases and vapours are described in VDMA 24 422 or in IEC 534, Chapter 8.

Formulas for calculating A-rated lateral sound level at 1 m laterally to the valve outlet are given below.

Fluids:

- area without cavitation ($X_F \leq Zy$)

$$LpA = 101gK_v + 181(p_1 - pv) - 51gp + 181g\left(\frac{x_F}{Zy}\right) + 40 \quad (21)$$

- cavitation area ($X_F > Zy$)

$$LpA = 101gK_v + 181(p_1 - pv) - 51gp + 292(x_F - Zy)^{0.75} - (268 + 38Zy)(x_F - Zy)^{0.935} + 40 + \Delta L_F \quad (22)$$

Gases and vapours:

$$L_{pA} = 141gK_v + 181gp_1 + 51g(273 + t_1) - 51gp + 201g\left(\frac{p_1}{p_2}\right) + 52 + \Delta L_G \quad (23)$$

Validity limits are:

$$1 < K_v < 6000; \quad 0,0001 < X_F \text{ or } X_G < 1,0 \text{ (evaporation has not been considered)}$$

$$L_A \geq 20; \quad W \leq 10 \text{ m/s (liquids) or } W \leq 0,3 \text{ Mach (gases and vapours)}$$

4.5 Mach number correction

The sound level largely depends on the conditions of gas and vapour outflow (Fig. 8). The calculation of the sound level VDMA 24422 assumes a velocity ratio of $Ma = 0.3$ on the flange for the fitting's outlet.

Fig. 8. Correction value of ΔL_G depending on the flow velocity.

Designations in the formulas:

- L_{pA} - A-rated sound pressure level (dB(A)),
- L_W - unrated sound efficiency level (dB),
- Re - Reynolds number (-),
- s - thickness of pipe walls (mm),
- X_F - pressure difference ratio for fluids (-),
- X_G - pressure difference for gases and vapours (-),
- ΔL_F - specific correction value for valves in liquid media (dB(A)),
- ΔL_G - specific correction value for valves in gas and vapour media (dB(A)),
- ΔR_m - correction factor for pipe wall thickness.

5. Measurement on industrial fittings – valves

The study results and the findings were obtained on the basis of tests, measurements and calculations on industrial valves. Applied test station is shown in Fig. 9. All measurements were made and tested in the INVENSYS laboratory (Young, 1999), Tab. 2 and Fig. 10. The accuracy and reliability of laboratory tests (Vasilnakova, 2018) play an important role in decision-making in the field of cavitation, especially for the design of valves' seats and housings (VDMA, 1981).

Size DN	Seat (mm)	Stroke (mm)	Kvs-value (mm)	Cv value	Zy factor					F _L factor					XT factor				
					10%	25%	50%	75%	100%	10%	25%	50%	75%	100%	10%	25%	50%	75%	100%
50 2"	42	20	40	46,2	0,63	0,53	0,43	0,36	0,30	0,95	0,93	0,92	0,91	0,90	0,83	0,78	0,73	0,7	0,67
	50	20	47,5	54,9	0,62	0,52	0,41	0,34	0,28	0,94	0,93	0,91	0,9	0,89	0,82	0,77	0,72	0,68	0,65
65	34	40	25	28,9	0,68	0,59	0,51	0,44	0,40	0,99	0,99	0,99	0,99	0,99	0,88	0,85	0,82	0,8	0,78
	42	40	40	46,2	0,65	0,56	0,47	0,40	0,35	0,96	0,95	0,94	0,93	0,92	0,84	0,8	0,76	0,73	0,71
	53	40	63	72,8	0,63	0,52	0,42	0,35	0,29	0,95	0,93	0,92	0,91	0,9	0,83	0,78	0,73	0,7	0,67
	67	40	80	92,5	0,61	0,51	0,40	0,33	0,27	0,94	0,93	0,91	0,9	0,89	0,82	0,77	0,72	0,68	0,65
80 3"	42	40	40	46,2	0,67	0,58	0,49	0,43	0,38	0,99	0,99	0,99	0,99	0,99	0,87	0,84	0,8	0,76	0,76
	53	40	63	72,8	0,64	0,55	0,45	0,38	0,33	0,95	0,94	0,93	0,92	0,91	0,83	0,79	0,74	0,71	0,68
	67	40	100	116	0,61	0,51	0,40	0,33	0,27	0,94	0,93	0,91	0,9	0,89	0,82	0,77	0,72	0,68	0,65
	80	40	125	145	0,60	0,49	0,39	0,31	0,25	0,94	0,92	0,9	0,89	0,88	0,81	0,76	0,71	0,67	0,64
100 4"	53	40	63	72,8	0,66	0,56	0,47	0,4	0,35	0,99	0,99	0,99	0,99	0,99	0,86	0,82	0,79	0,76	0,74
	67	40	100	116	0,63	0,53	0,43	0,36	0,30	0,97	0,96	0,95	0,94	0,94	0,84	0,79	0,75	0,71	0,59
	84	40	160	185	0,60	0,49	0,39	0,31	0,25	0,94	0,92	0,91	0,89	0,89	0,81	0,76	0,70	0,67	0,64
	100	40	180	208	0,60	0,49	0,38	0,3	0,24	0,93	0,91	0,9	0,88	0,87	0,80	0,75	0,69	0,65	0,62
125	53	60	63	72,8	0,66	0,57	0,48	0,42	0,37	0,99	0,99	0,99	0,99	0,99	0,88	0,84	0,81	0,78	0,76
	67	60	100	116	0,64	0,54	0,44	0,37	0,32	0,98	0,98	0,97	0,97	0,97	0,85	0,81	0,77	0,74	0,71
	84	60	160	185	0,61	0,51	0,4	0,32	0,27	0,95	0,94	0,93	0,92	0,91	0,82	0,77	0,72	0,69	0,66
	105	60	250	289	0,58	0,47	0,36	0,28	0,22	0,93	0,91	0,89	0,88	0,87	0,8	0,74	0,68	0,64	0,61
150 6"	67	60	100	116	0,65	0,56	0,46	0,39	0,34	0,99	0,99	0,99	0,99	0,99	0,86	0,83	0,79	0,76	0,74
	84	60	160	185	0,63	0,52	0,42	0,35	0,29	0,97	0,96	0,96	0,95	0,95	0,84	0,79	0,75	0,72	0,69
	105	60	250	289	0,60	0,49	0,38	0,31	0,24	0,95	0,93	0,92	0,91	0,90	0,81	0,76	0,71	0,67	0,64
	130	60	355	410	0,58	0,47	0,35	0,27	0,21	0,93	0,9	0,88	0,87	0,86	0,79	0,73	0,68	0,64	0,60
200 8"	100	80	200	231	0,64	0,54	0,44	0,37	0,31	0,97	0,96	0,95	0,94	0,93	0,82	0,77	0,72	0,69	0,66
	125	80	355	410	0,60	0,49	0,39	0,31	0,25	0,93	0,91	0,89	0,88	0,87	0,8	0,74	0,69	0,65	0,62
	150	80	450	520	0,59	0,47	0,20	0,28	0,22	0,91	0,89	0,87	0,85	0,84	0,78	0,72	0,66	0,62	0,59
250 10"	125	80	355	410	0,63	0,52	0,42	0,35	0,29	0,95	0,94	0,93	0,92	0,91	0,82	0,77	0,72	0,69	0,66
	150	80	450	520	0,61	0,50	0,40	0,32	0,26	0,94	0,92	0,9	0,89	0,88	0,8	0,75	0,70	0,66	0,63
	200	80	710	821	0,59	0,47	0,36	0,28	0,22	0,91	0,89	0,87	0,85	0,84	0,78	0,72	0,66	0,62	0,59
300 12"	150	80	450	520	0,63	0,52	0,42	0,25	0,29	0,95	0,94	0,93	0,92	0,91	0,82	0,77	0,72	0,69	0,66
	200	80	710	821	0,60	0,49	0,38	0,30	0,24	0,93	0,9	0,88	0,67	0,86	0,79	0,74	0,68	0,64	0,61
	250	80	1000	1156	0,58	0,47	0,35	0,27	0,21	0,91	0,88	0,86	0,84	0,83	0,78	0,71	0,65	0,61	0,58

Tab. 2. Results of the measurements of the cavitation factors K_v , C_v , Z_y , F_L , XT of the control valves for different diameters.

Fig. 9. Schematic representation of the test station.

Fig. 10. Example for measurement of cavitation of a control valve DN 100 mm, $P_n = 4$ bar with a single seat (in German).

6. Conclusion

The results are applicable to standard control valves, i.e. single control valves with a parabolic cone degree PN 40. The noise calculation considers only the noise generation due to hydraulic i.e. aerodynamic processes in the flow valves and the related pipelines. Noise generated by reflection and resonance of small internal parts is excluded.

During evaporation, the secondary pressure p_2 is lower than the p_v – the pressure that is reached during boiling, and results in constant evaporation. The frequency is higher, hence the depreciation of the housing and the pipelines within the range of $0.8 < XF < 2.0$ results in a decrease in the sound level as opposed to cavitation. In case of cavitation, the amplification calibration line should be 6 to 10 times DN, depending on the intensity, and at least 0.5 – 1 m. Where possible, cavitation should be prevented, because with appropriate countermeasures, the service life of the material can be extended, however we cannot prevent the damages to the material. When used in the field of stronger cavitation, the selection of appropriate reinforcement depends on many factors and for this reason the expert's decision should be a priority in relation to the general recommendation. The achievable precision has a tolerance range of up to 10 dB(A), whereby the achieved sound level is predominantly in the upper tolerance limit. If conditions deviate from the norm, a correction of the achieved value is required. This can be achieved with the values for noise correction ΔL_F for liquids and ΔL_G for gases and vapours for noise reduction installations. These correction values indicate the function of the ratio of the pressure difference X_F , i.e. X_G at a load of 75 %. Cavitation is avoided with larger valve seat surfaces, well-designed internal surfaces and proper valve flow channels.

The problem of volume, turbulence and consequent wear was solved with the correct design of the valve seat. The old models for casting the housings were repaired and finished, thus also saving costs, which has a positive effect on the price. Research is limited to measuring cavitation factors from which we conclude; we got other parameters for the correct design of valves.

In the future we will pay attention to the new optimal shape of flow channels, valve seats and (on the basis of new shapes and sizes) measure cavitation factors, which should be even more favourable.

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