

Cavitating Herschel Venturi nozzle test rig

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Abstract

Cavitation is a phenomenon, which is typically associated with negative effects, for example damage at propellers in water. However, there are various applications in which cavitation is exploited advantageously such as injection nozzles in diesel engines or cleaning with an ultrasonic bath. A new application is the deployment of cavitating nozzles in liquid flow measurements. The novelty of the application means from a metrological point of view the requirement to analyse potential influencing factors on the measurement quality in-depth. These comprise among others the installation conditions of the nozzles in a test rig or the additivity of flows when more than one nozzle is used. Furthermore, comprehensive insights into cavitation processes for different liquids are desirable with the view on a broad range of cavitation nozzle applications in liquid flow measurements.

First investigations are carried out for different fluids including liquid mixtures such as white spirits. A detailed analysis of the pressure measurement in front and at the back of the nozzles gives further information about how fast the flow rate changes and about the cavitation process itself. This is of relevance for a possible application, in which flow rate profiles are used to assess flow meter performance under dynamic loads. Such load profiles e.g. serve as input for a test rig with cavitation nozzles to assess the performance of domestic water meters.

1. Introduction

Cavitation occurs if a liquid pressure is lower than the local vapour pressure and a gaseous saturated steam volume is formed. The appearance of this cavitation ranges from single bubbles to stable cavitation layers. In case of a nozzle throat, the cavitation layer is a cylindrical skirt around the liquid flow. On the one hand this cavitation is a disadvantage in applications, where the gas bubbles collapse and cause damage to structural components for instance at propellers. On the other hand, cavitation is exploited in ultrasonic cleaning baths, wastewater treatment and to homogenize suspended particles in colloidal liquids. Another application of cavitation is the use in flow metrology. Known from gas flow measurements with critical flow venturi nozzles (CFVN) the concept of a stable and reproducible mass flow is transferred to liquid flows deploying cavitation nozzles.

In first experiments nozzles are installed in a test rig with water as liquid. The measurements proves the feasibility of using nozzles as liquid flow controlling device [2],[3]. The experiments are performed with toroidal gas nozzles

referred to ISO: 9300 [1]. Furthermore, numerical investigations by Brinkhorst [4] show that the deployment of Herschel Venturi nozzles instead of toroidal Venturi nozzles leads to an improved flow stability. The difference between the nozzle typ is a cylindrical throat in the Herschel Venturi nozzle and the difference of stability is on the order of one magnitude.

Another aspect affecting flow stability is related to the ratio of upstream and downstream pressure. To ensure that cavitation occurs, the ratio of downstream to upstream pressure needs to be below 0.75 [3]. For all measurements presented in the paper the ratio is less than 0.6. This is well below the critical value of 0.75. Above this value cavitation inception, and thereby the flow, becomes unstable [3]. The basics can be described by Bernoulli's principle. If the pressure of the liquid drops below the local vapour pressure, cavitation begins in the nozzle throat and a further decrease of the liquid pressure is not possible. In this case the flow is regulated by the absolute upstream pressure and depends on that stability. Thus, it became clear that monitoring the pressure at temporally higher resolution and more precise as previously, would provide a deeper insight into the

performance of the cavitating nozzles. Therefore, four pressure sensors are installed as shown in Figure 1, with two sensors measuring the upstream pressure and two the downstream pressure. The time resolution of the pressure sensor with temporally higher resolution is about 100 ms and the resolution of the precise pressure sensor in amplitude is on the order of 1 mbar.

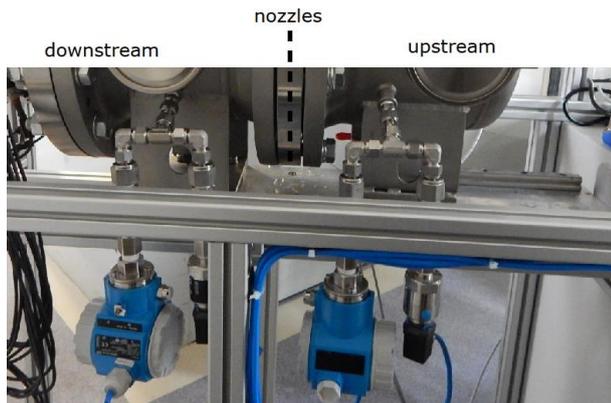


Figure 1: Pressure sensors upstream and downstream of the cavitating nozzles.

2. Single and multiple nozzle flows

In a first step the individual Herschel Venturi nozzles are characterised in a single holder by water flow measurements on a known test rig with different upstream pressures from 2 bar to 5 bar. Afterwards the six nozzles are installed in a cavitation nozzle apparatus added to the test rig and the characterization repeated for the whole ensemble. Following this, the flow rate for cases with multiple nozzles open simultaneously is investigated.

For the experiments six nozzles with a nominal throat diameter of 0.74 mm, 1.4 mm and 2.6 mm are selected (Table 1) to enable the relevant flow rates of a load profile, discussed in section 4. With different nozzles of the same nominal diameter the reproducibility of the nozzle manufacture can be assessed by flow rate measurements. The flow rates for the individual nozzles cover a range from 37 l/h to 588 l/h and are measured at a liquid temperature near ambient temperature of 22 °C with a maximum deviation of 2 °C. The mean variation of the temperature within one flow rate measurement is ± 0.1 °C.

Table 1: Diameter d of the nozzle throats, flow rate Q at pressure p and the slope b of the flow against upstream pressure.

Nozzle nr. i	Diameter d mm $\pm 1 \mu\text{m}$	Upstream pressure p bar ± 0.01 bar	Flow Q l/h $\pm 0.1 \%$	Slope b l/h/bar
1	0.740	3.999	42.69	5.4 ± 0.2
2	0.738	3.996	42.65	5.4 ± 0.2
3	1.396	4.005	151.80	19.2 ± 0.4
4	1.397	4.005	152.40	19.5 ± 0.5
5	1.393	4.004	154.50	19.5 ± 0.5
6	2.601	4.013	527.80	71.0 ± 1.4

The function of the cavitating nozzle apparatus is the simultaneous use of multiple nozzles to extend the range of generated flow rates up to the combined flow of six nozzles. The complete experimental setup is shown schematically in Figure 2. It consists of a conventional mass flow test rig in which a cavitation nozzle apparatus is integrated. As consumption is typically determined as volume flow, mass flow is converted to volume flow using the current medium's density and then considered in these investigations.

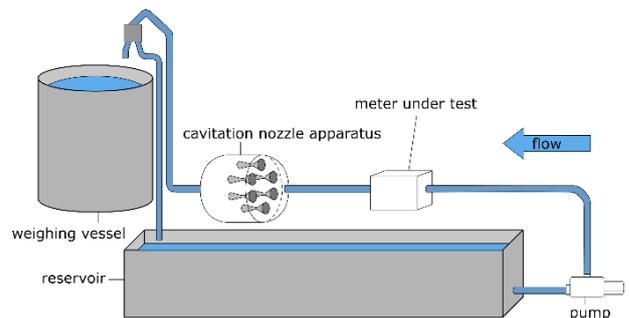


Figure 2: Schematic drawing of the test rig in the set-up.

2.1 Flow generated by individual Herschel Venturi nozzles

The correlation between flow rate and upstream pressure for each nozzle is important to know for an estimate of the flow generated by multiple nozzles, as higher flow rates (e.g. 1000 l/h) cause a relevant decrease (0.06 bar) in pressure. To describe the relation between flow rate and upstream pressure a regression line is fitted to the measurement data. An example for the regression is shown for nozzle 6 (Table 1) in Figure 3 at the top and is summarised for the other nozzles at the bottom. The expanded measurement uncertainty of the test rig is 0.1 % and the standard deviation for most flow rate measurements is less than 0.1 %. An exception are the two measurements with an upstream pressure below 3 bar, when nozzle 6 is characterised. The error bars for the measurement with these nozzles are shown in Figure 3 (top).

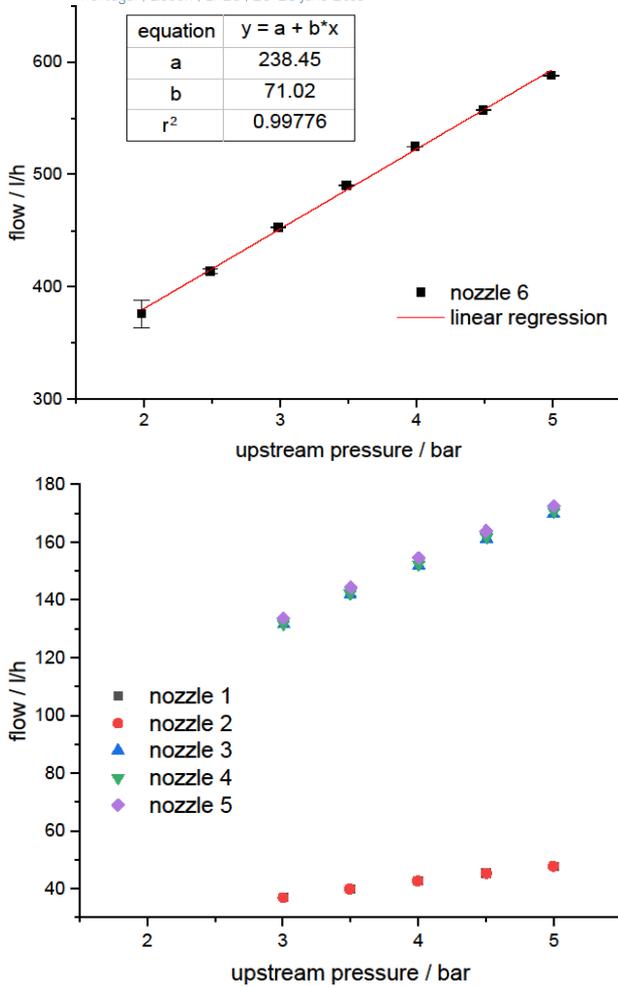


Figure 3: Flow rate against absolute upstream pressure, with different Y-axis. Top: Nozzle 6 and fitted regression line with correlation coefficient r^2 . Bottom: 5 different nozzles with a diameter of 0.74 mm and 1.4 mm, regression values in Table 1.

The slope b of the regression line is determined for each nozzle from the experimental data plotted in Figures 3. The values are summarised in the last column of Table 1 and quantify the above-mentioned flow rate dependency of the upstream pressure for the nozzles. With this relation a reduction of the upstream pressure mean variation directly leads to a more stable flow rate of the nozzle. There is no significant difference in the correlation between upstream pressure and flow rate for nozzles with the same diameter. A linear relationship exists between the flow rate of nozzles with different diameter and the slope b .

2.2 Multiple nozzle flow

After the characterisation of the individual nozzles these are set into the cavitation nozzle apparatus to generate multiple nozzle flows. As the pressure sensor in the single nozzle holder is mounted closer to the individual

measured nozzle than in the test rig, the correlation between upstream pressure and flow rate is investigated in the single nozzle holder. To take the different installation conditions into account, the characterization of the individual nozzles is repeated. Because the position of the pressure sensors is about 70 mm further upstream in the test rig than in the single nozzle holder the flow rates had a significant offset. With the flow rate determined in the test rig at an upstream pressure of 4 ± 0.01 bar the theoretical flow of two or more nozzles is calculated as the sum $Q_{theo,j}$ of the individual flow rates Q_i , corrected for the decrease in pressure due to higher flow rates, according to equation (1)

$$Q_{theo,j} = \sum_i (Q_i + (p_j - p_i) * b_i) \quad (1)$$

with:

b_i : calculated slope of each nozzle

p_i : upstream pressure of single nozzle flow

p_j : upstream pressure of multiple nozzle flow.

The relative deviation of the flow rate for the different nozzle combinations is calculated from equation (2) and given in Table 2

$$rel. dev. = \frac{Q_{exp} - Q_{theo}}{Q_{theo}} \quad (2)$$

Table 2: Nozzle addition, calculated and measured flows.

Combined nozzles nr.	Calculated flow Q_{theo} l/h	Measured flow Q_{exp} l/h	Rel. dev. %
1+2	85.40	85.34	-0.071
1+3	194.57	194.51	-0.031
1+2+3	237.25	237.15	-0.040
3+4	303.48	303.49	0.004
1+3+4	346.16	346.15	-0.002
1+2+3+4	388.86	388.79	-0.018
3+4+5	456.54	456.56	0.005
1+3+4+5	498.89	498.88	-0.002
1+2+3+4+5	541.78	541.59	-0.037
1+6	570.59	570.29	-0.053
1+2+6	612.82	612.37	-0.074
3+6	679.11	678.69	-0.062
1+3+6	721.01	720.58	-0.060
1+2+3+6	763.03	762.45	-0.077
3+4+6	829.08	828.63	-0.055
1+3+4+6	870.89	870.48	-0.047
1+2+3+4+6	913.73	913.20	-0.058
3+4+5+6	980.32	979.99	-0.034
1+3+4+5+6	1022.94	1022.33	-0.060
1+2+3+4+5+6	1064.63	1063.74	-0.084

The results of the simultaneously cavitating nozzles are displayed in Figure 4 as relative deviation of the measured and the calculated flow rates. The error bars contain the overall uncertainty of the test rig (0.1 %) and the standard deviation of the measurements. The calculated flow rate based on the single nozzle measurements is accurate to 0.01 % in comparison with

the flow rate measurement at multiple nozzle operation. This result confirmed the assumption that the flow rate of multiple nozzles can be calculated using single nozzle flow rates, when the absolute upstream pressure and the correlation between upstream pressure and flow rate are known. Except for two measurements the deviation is negative but within the error. This could indicate a further upstream pressure loss between the pressure sensor and the nozzle holder, which is not included in the calculations. A comprehensive upstream pressure measurement would provide an insight into the pressure distribution that has a direct proportional influence on the flow rate of the nozzle.

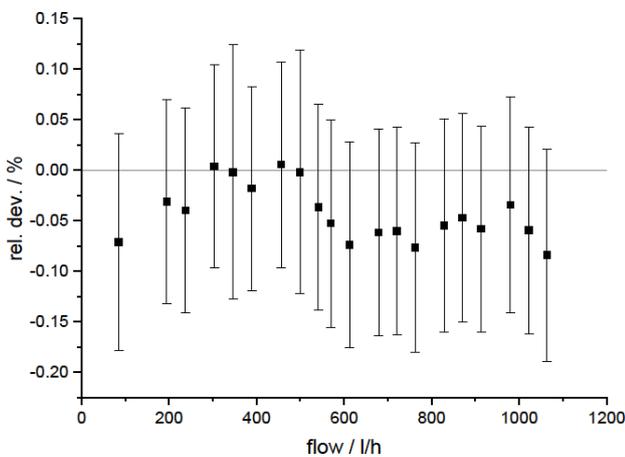


Figure 4: Relative deviation of calculated and measured nozzle flow rates against calculated flow rates. Ascending order as Table 2.

3. Different liquids

To understand the cavitation phenomenon in liquids it is necessary to investigate other liquids than water as well. One of the most frequently used liquids in flow applications is fuel. The typical substitute white spirit is used for the cavitation nozzle flow analysis. A second commonly used liquid in many applications is cleaner solvent. These two liquids are accessible easily and have different vapour pressure curves than water. This is expected to cause a different cavitation layer and flow rates. Furthermore, there is a potential for effects due to the different constituents that make up the liquid. As presented by Keller [6] the cavitation inception especially depends on the presence of nuclei and their size in a liquid.

For the investigations with different liquids nozzle 2 (Table 1) with a diameter of 0.74 mm is set in a second test rig for white spirits and the flow rate is measured against a gravimetric standard. Furthermore, the flow rate of nozzle 2 is measured in a third test rig operating with a cleaner solvent called Haku, which has a similar density to that of the white spirit (Table 3). The set-up of the two FLOMEKO 2019, Lisbon, Portugal

other test rigs is analogue to the first test rig run with water and single nozzle holder, described in Figure 2. The experiments are also done with the same temperature at $22\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$ and an opened downstream outlet. Due to the different densities of the liquids it is reasonable to compare the mass flow in this section.

Table 3: Liquids used for flow measurements with cavitating nozzles and the physical properties density, vapour pressure and kinematic viscosity measured at $20\text{ }^{\circ}\text{C}$.

Medium	Principal constituents	Density g/cm ³	Vapour pressure mbar	Viscosity mm ² /s
White spirit	Hydrocarbon, C10 – C13, n-Alkane, iso-Alkane, cyclic compound	0.785	0.5	1.2
Haku 1025-310	Hydrocarbon, C11 – C14, iso-Alkane, cyclic compound	0.761	0.6	1.3
Water	Tap water	0.998	23.4	1.0

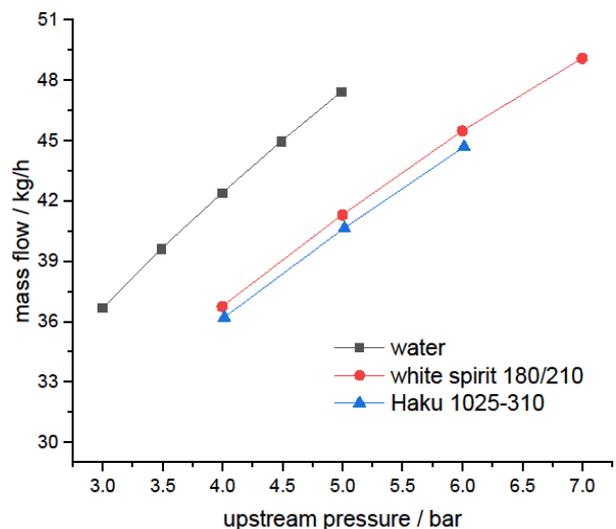


Figure 5: Nozzle diameter 0.74 mm; mass flow against upstream pressure for water, white spirit and a cleaner solvent, called Haku 1025-310.

The measurements for the different liquids water, white spirit and cleaner solvent are shown in Figure 5. The expanded measurement uncertainty ($k = 2$) of the test rig for white spirits is 0.05 % and 0.3 % for the cleaner solvent test rig. The standard deviation of the measurement carried out with water (about 0.01 kg/h) is the same as the standard deviation associated with the cleaner solvent (about 0.01 kg/h). The standard deviation of the measurement with white spirit is about 0.05 kg/h because of a lower number of measurement points, but in

the same order of magnitude. There is a significant difference between the flow rate measurements using water, white spirit and cleaner solvent. The white spirit and the cleaner solvent have a comparable mass flow and the same slope of 4.2 ± 0.2 l/h/bar, determined by linear regression. The difference in the flow measurements between water and white spirit is investigated for a second nozzle (2.6 mm in diameter as nozzle 6) and plotted in Figure 6. The flow rate of white spirit is about 13 % (0.74 mm diameter nozzle) less than the flow rate of water, 12 % less respectively for the nozzle with a 2.6 mm diameter.

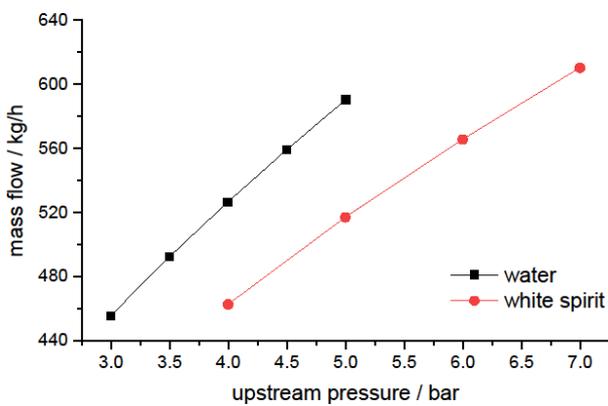


Figure 6: Nozzle diameter 2.6 mm; mass flow of water and white spirit.

For a nozzle diameter of 1.4 mm and two liquids the flow is shown against the upstream pressure in Figure 7. The offset between the two liquids is on the same order of magnitude as the flow difference of the nozzles with 0.74 mm and 2.6 mm and increases with the flow rate. Potential effects on this offset could have been caused by different vapour pressure curves or different suspended particle concentrations in the liquids. Thus, with cavitating nozzles, a stable flow rate could also be realised with the liquid mixtures in addition to water.

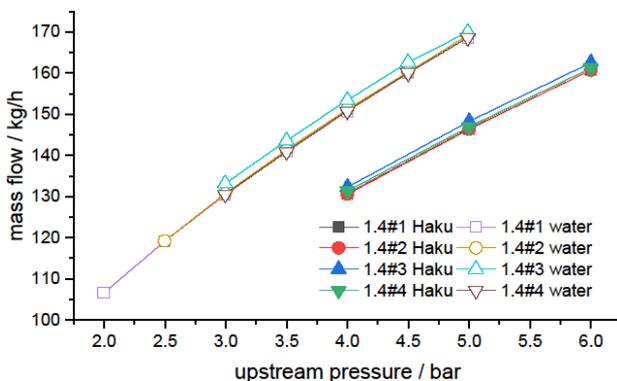


Figure 7: Flow measurement of four different nozzles, same nominal diameter 1.4 mm and two liquids (water and cleaner solvent Haku).

4. Generating load profiles

With the Herschel Venturi nozzles integrated in a water test rig fast flow rate changes (about 100 ms) and a wide range of flow rates (10 l/h - 10^4 l/h) could be realised, to generate load profiles close to actual consumption profiles [2]. These are current investigations about the water meter calibration procedure in which load profiles are needed. Based on a model profile load changes are generated with the test rig. The diagram in Figure 8 (top) shows the modelled profile in black as well as the generated flow rates in red. The profile in red considers the fact, that with the current setup 23 different flow rates can be generated. To verify the flow rates and the transitions, the weighing signal is recorded with a sampling rate of 2 Hz and a resolution of 1 g. The pressure variations are monitored with a sampling rate of 5 Hz and a resolution of 0.1 mbar. The third profile shown in blue in Figure 8 (top) is the flow rate calculated from the slope of the dynamic weighing values for each step of the load profile. The flow rate determined from the balance values in general fits with the generated flow rate, except for the time between about 90 s to 135 s. This discrepancy is caused by a controller failure, which results in one nozzle not opening as intended. Within the performance characteristics of the dynamic balance measurement technique there is no significant difference between the profile generated in the test rig and the balance measured profile.

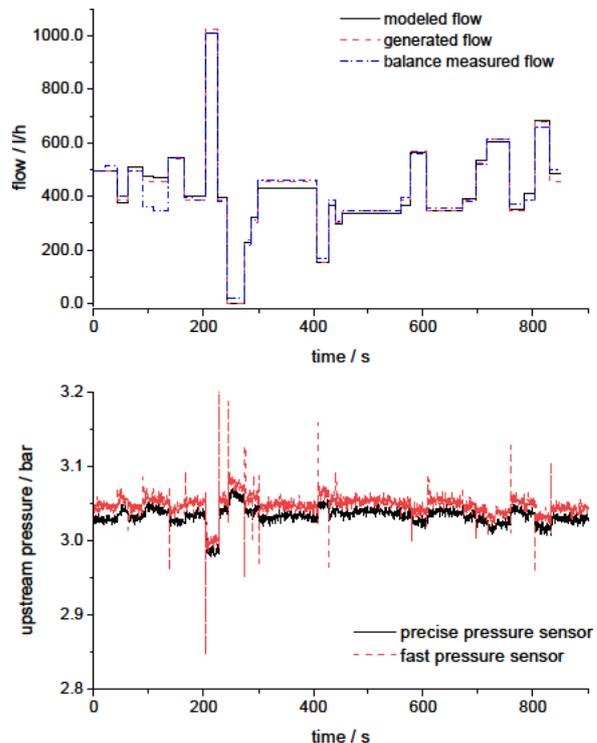


Figure 8: Top: model, generated and balance measured load profile; bottom: upstream pressure response of two different pressure sensors.

To investigate the quality of the flow rate change, the upstream pressure is measured with two different sensors as illustrated in Figure 8 (bottom). The offset between the two sensors before calibration is retained for better readability of the data. Both pressure sensors show peaks concurring with changes in the flow rate. In Figure 9 an enlarged section of the upstream pressure and the dynamic balance value is shown. The maximum amplitude measured with the fast pressure sensor is up to 7 % above the average pressure. The pressure excursion lasts about 1 s, but no influence on the balance signal and thereby the flow rate at the sampling rate of 500 ms is seen. Within the scope of the dynamic balance measurement technique there is no significant difference between the profile to be generated in the test rig and the profile measured by the balance. Consequentially, the dynamic balance signal can be used to verify the flow rates during a load profile generation

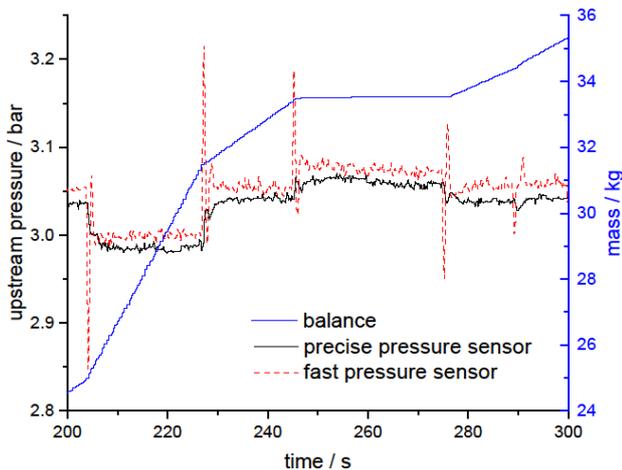


Figure 9: Upstream pressure peaks and mass measured by balance.

5. Conclusions

The experimental results presented in this paper show, that the flow rates of the individual nozzles simply sum up to the expected total flow rate, which is demonstrated based on the flow rates measured with six cavitating Herschel Venturi nozzles at the same time (Table 2). As expected, the flow rate decreases with upstream pressure loss. That could be corrected in case of a sufficiently known correlation between upstream pressure and flow rate.

Furthermore, a constant mass flow can be generated with different liquids, including liquid mixtures. The white spirit and the cleaner solvent in contrast to water have different flow rates for an identical upstream pressure (Figure 5). This difference is likely caused by different cavitation layer thicknesses in the nozzles. Apart from the vapour pressure other medium dependent properties

such as viscosity, density or compressibility could also affect the cavitation in the nozzle and thereby the flow measurement. This requires further investigations.

By an ensemble of Herschel Venturi nozzles load profiles can be generated. The values of the balance indicate an instantaneous flow rate change, whereas the upstream pressure sensors record a pressure pulse that takes about 1 s. This is caused by closing and opening the nozzles and could have an influence on the cavitation layer and thereby the flow rates at that time. The effect on the flow rate is temporally below the current detection limit of the balance. These experiments are a first step to understand the phenomenon of a stable flow in cavitating Herschel Venturi nozzles and their application in a test rig and could serve as basis for future research.

6. Acknowledgement

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References

- [1] ISO 9300: *Measurement of gas flow by means of critical flow Venturi nozzles*, 2005.
- [2] Schumann D, Wendt G, Tränckner J, “Development of a calibration process for water meters close to real word conditions”, in *FLOMEKO*, 2016.
- [3] Schumann D, Kroner C, “Using Cavitation Metrologically”, in *ISFFM Publications*, 2018.
- [4] Brinkhorst S, *Numerische und experimentelle Untersuchung zur metrologischen Nutzung von kavitierenden Venturi-Düsen*, dissertation, 2017.
- [5] Korth A, Martin T, (2016): “Aktualisierung von Verbrauchsganglinien für Haushalte, öffentliche Gebäude und Kleingewerbe sowie Entwicklung eines Modells zur Simulation des Wasserbedarfs”, DVGW-Forschungsvorhaben W-10-01-11, unpublished
- [6] Keller A, “cavitation scale effects – empirically found relations and the correlation of cavitation number and hydrodynamic coefficients“, in *CaltechCONF*, 2001