Cavitation measurement of a pump

1. Introduction

The phenomenon of cavitation, when the local pressure decreases to the saturated vapor pressure, so steam is generated, can occur in various places in pipe systems that transport liquids. Cavitation happens typically at pumps or valves and could be harmful in many ways. The first aspect is the noise and vibration load on the environment, the second aspect is the physical damage of the equipment. Vibration can travel easily in lightweight buildings, so other machines and equipment may be damaged. The generated vibration can also damage the source machine or affect its operation negatively. Pumps are the critical points in a system from the perspective of cavitation, and the phenomena can be observed at the suction side of pumps.

2. The emergence of cavitation

If the absolute pressure during the transport of a liquid (mainly water) decreases below the saturated vapor pressure (this is typically at the leading edge of the impeller in case of pumps) the homogeneity of the liquid is ceased, and small steam bubbles are generated at the micro-cracks of the wall and small particles, so the liquid is boiling locally. This phenomenon is called cavitation, and it is considered the practical operational limit of pumps. Cavitation can be the source of significant vibration and noise. Moreover, the characteristics of the machinery can also change, and the damage cannot be avoided.

Figure 1. Signs of erosion because of cavitation on an impeller

Physical cavitation is when the appearing bubbles are unique and separate. The micro-cracks on the walls, solid particles, and gas bubbles are the core of the cavitation. In usual, everyday pipe systems, these cores can always be found in large numbers. The generated steam bubbles, which have a diameter in the range of hundred microns, do not affect the flow parameters of the fluid machinery.

When bubbles are joined together, and the bubble zone is well observable, the phenomenon is called technical cavitation. The cavitational zone is generated mainly at the boundary walls, then it detaches from the wall and drifts away, but on the wall, a new zone is created. The hydraulic characteristics of a pump (head, volume flow rate, etc.) are affected by the technical cavitation.

Supercavitation state happens after the technical cavitation when the pressure of the flow field is decreased further. During this phase, the generation of steam bubbles are not point-like, but larger steam bubble zones are emerging.

In case of physical or technical cavitation, the bubbles drift away with the flow and reach a place with higher absolute pressure, so condensation occurs in the steam bubbles, the bubbles collapse and get filled with liquid. This collapse generates measurable vibration in the machine, and can even grow enough to create an audible sizzling, crackling noise. If the collapse happens near the boundary walls of the liquid, the periodic mechanical impact can load the solid walls, which can result in the erosion seen in Figure 1.

If the cavitation bubble fills the whole cross-section before the impeller, the continuity of the liquid is broken, the pump drops the liquid, the transport of the medium ceases. The lowest pressure can be measured at the leading edge of the impeller, so cavitation occurs first at this place. In Fig. 1. it can be observed where the leading edge of the impeller was since the erosion is the greatest.

3. Suction head, characteristic curves

The question arises, how can the cavitation be avoided. To answer this question, the following quantities have to be introduced: Net Positive Suction Head, which is available in the system $NPSH_a$, and the Net Positive Suction Head, which is required by the pump at a given flow rate $NPSH_r$. By definition:

$$NPSH_a = \frac{p_0 - p_g(t)}{\rho g} - H_{sg} - e_s - h'_s(Q), \tag{1}$$

where the pressure above the water level on the suction side is denoted by p_0, the saturated vapor pressure of the liquid as the function of the temperature is denoted by $p_g(t)$, the water level of the suction side from the center of the intake manifold is denoted by H_{sg}, the height difference of the center of the intake manifold and the rotational axis of the impeller is denoted by e_s (in our case it is zero, $e_s = 0$.), and last $h'_s(Q)$ denotes the head loss in the suction pipe with all of its valves. At the border of operation without technical cavitation, the required and available net positive suction head is equal, $NPSH_a = NPSH$. Operating problems are avoidable by keeping the following inequality:

$$NPSH_r < NPSH_a. \tag{2}$$

In high-pressure boilers, the normative is that $NPSH_a$ should be 1.5-2 times of the $NPSH_r$ value, so the effects of transients and malfunctions are fended off. These security reserves are needed because the physical and technical cavitation cannot be distinguished. Physical cavitation can occur during regular operation (because of the impurities of the liquid) without affecting the hydraulic characteristics of the machine. During technical cavitation, the drop in efficiency is observable, and the erosion is significant. However, the transition between the two states is continuous.

If we do the measurement of the characteristic curve of a pump, we experience that increasing the volume flow rate, the curve parts from the theoretical one (dashed line), as it is seen in Figure 2.a. At the bifurcation point is the emerging point of the technical cavitation. Measuring the suction curve can be done at a given constant volume flow rate, so the value of the required net positive suction head, $NPSH_r$ can be obtained. The volume flow rate Q value should be kept constant. The value of the $NPSH_a$ can be changed, for example, by a choke on the suction side. To keep the volume flow rate constant, we also have to intervene after the pump. If the water level (H_{sg}) or the head loss (h'_s) on the suction side increases, or the pressure (p_0) at the suction side, the valve on the pressure side should be opened. If the value of the $NPSH_a$ is decreased and the head of the pump H is measured at every point, after a critical $NPSH_a$ value, the head will drop significantly. This is illustrated in Fig 2.b. At the corner point of the curve will be the $NPSH_r$ value for the given Q volume flow rate.

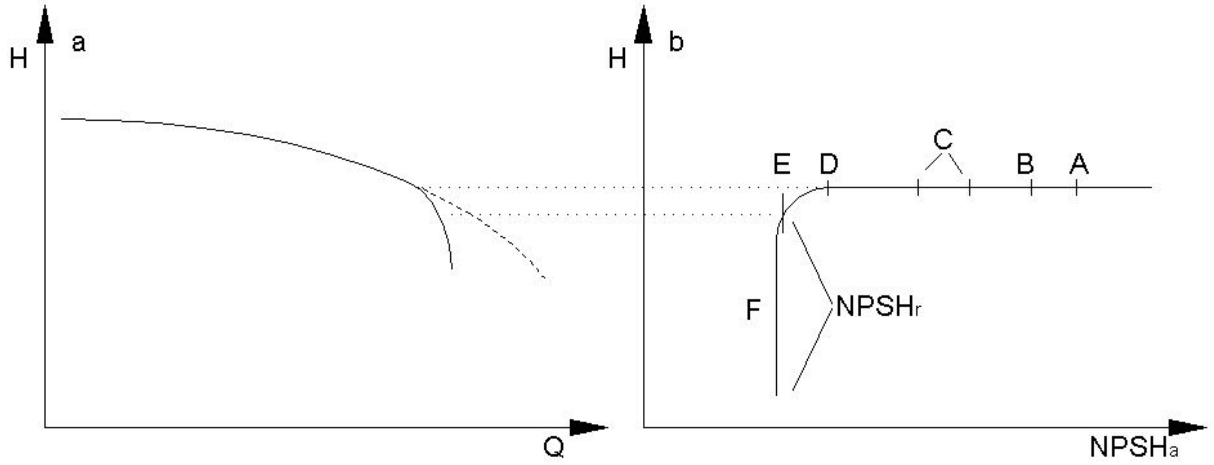

Figure 2. a, Characteristic curve and b, suction curve

The slight crunching, crackling noise appears at Point **A** of the $NPSH_a - H$ in Fig 2.b. Small bubble zones appear at the leading edge of the impeller at Point **B**. The erosion of the impeller blades along the intensifying noise starts at Point **C**. As can be seen in Fig. 2.a, the characteristic curve of the pump remains unchanged, although the machine is damaged. Point **D** is the limit, so after the $NPSH_a$ is decreased further, the characteristic curve starts to drop (Fig. 2.a). Even though a significant drop is present in the characteristic curve (3-5%), Point **E** is the limit of the acceptable cavitational operation. Near Point **F**, the impeller is mainly surrounded by a bubble cloud. The noises of the pump fade, its head drops, its efficiency worsens, though its power intake decreases as well. The damaging erosion also disappears. The operation of the pump is not reliable, since it may drop the liquid at any moment.

Fig 2.b shows the point where there is a significant change in the head of the pump as the function of the $NPSH_a$. At Point **F**, the relationship of (2) is not fulfilled, there is significant cavitation in the system. After appointing a critical ΔH drop of the head, which is usually the 2-3% of the head value, multiple suction curves at different Q=constant values can be measured, so we get the $NPSH_r - Q$ function curve of the pump, which is as significant characteristic of a pump as the $H - Q$ curve.

The gas content of the liquid can have a favourable effect on the noise and vibration of the cavitation. The gas in the quantity of some volume percent may decrease the generated noise, harmful vibration, and erosion effect during the collapse, as a cushing effect. However, this method cannot be used in some technological processes (for example, heating system, chemical processes). Moreover, because of the gas content, the mixture's density is smaller than the pure liquid's, at a given mass flow rate, the volume flow rate of the mixture will be higher. The higher volume flow rate increases the head loss of the suction side (h_s'), which decreases the $NPSH_a$ value based on equation (1). If we want to keep the cushing effect of gas bubbles without further decreasing the $NPSH_a$, air can be introduced just before the intake manifold of the pump. We just have to keep in mind that efficiency will decrease this way because of the increased volume flow rate.

Cavitation can be detected by the vibrations it generates. The advantage of this method is that slight, physical cavitation can also be detected, unlike with the detection from the hydraulic parameters, which can only show the technical cavitation. Both investigations should be done at a constant volume flow rate by increasing the head loss of the suction side – so decreasing the $NPSH_a$ value. Figure 3. shows the suction curve ($H - NPSH_a$ curve) and the measured acceleration at the housing of the pump. It can be seen that the level of the vibration (n_g) is increasing even before the drop of the head, which is related to the appearance and collapse of small cavitation bubbles, namely physical cavitation that has a strong erosive effect. This cannot be seen in the hydraulic parameters, that is why detecting the vibrations may be more advantageous.

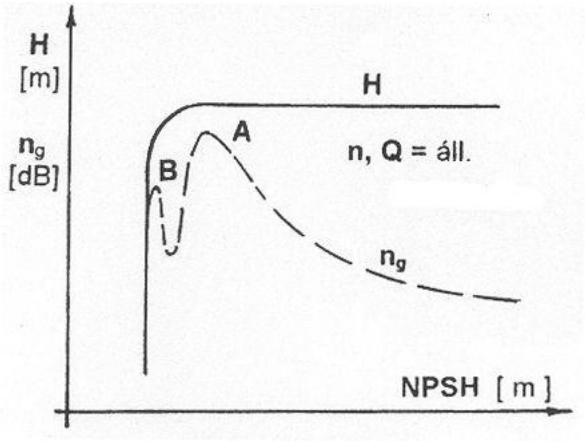

Figure 3. Relation of the suction curve and the levels of vibration

4. Measurement device

Figure 4. shows the measurement device, which uses a single-stage pump with a plexi side, so the generated cavitation can be observed visually. The pump denoted by **S** is delivering water from the tank **ST** through the valves **T1** and **T3**. These valves are suitable to increase the hydraulic loss on the suction side. The pressure on the suction and pressure sides are measured with a single-tube pressure gauge, which is filled with mercury. The volume flow rate is measured with an orifice plate **MP**, and a single-tube pressure gauge is connected to it. Through the plexi sidewall of the pump, the open impeller is illuminated with a stroboscope **Str.** The frequency of the stroboscope’s flashing is set in a way, that the impeller and the blades seem to stand still. Then the generated bubbles can be observed.

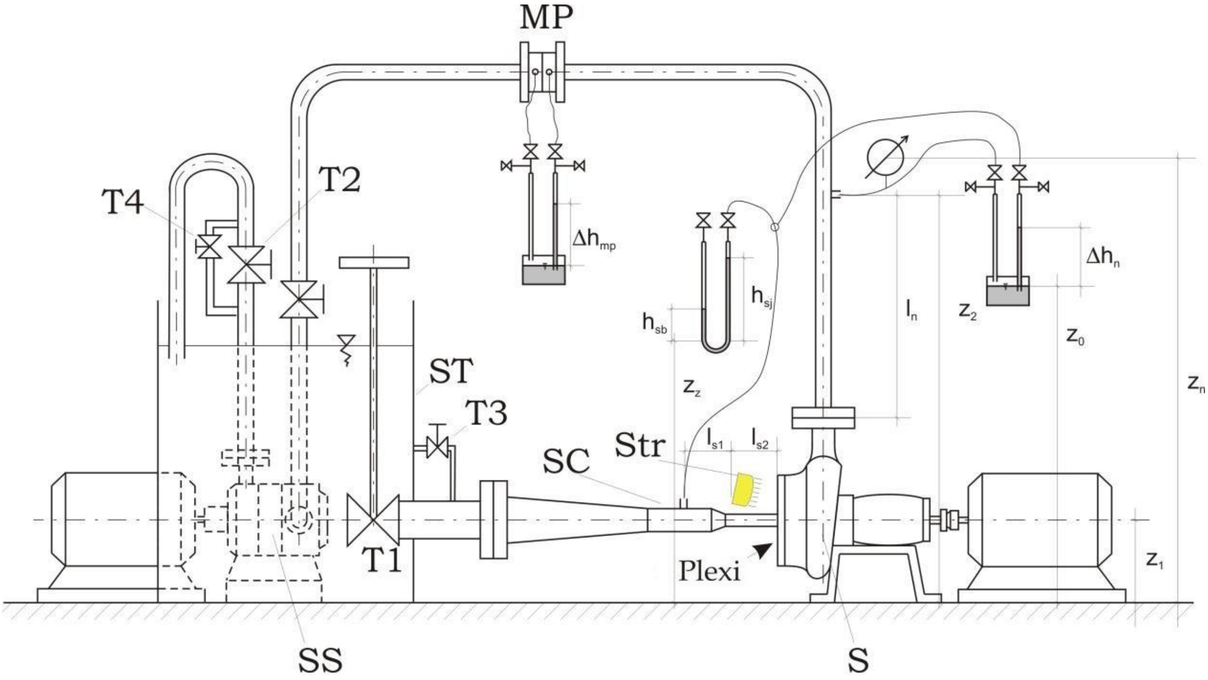

Figure 4. Measurement device

With the help of the notation from Fig. 4., the head *H* and the volume flow rate *Q* are calculated with the following formulae:

$$Q = \alpha(D,d,Q)\cdot\frac{d^2\pi}{4}\sqrt{\frac{2\cdot\Delta p_{mp}}{\rho_{viz}}} = \alpha(D,d,Q)\cdot\frac{d^2\pi}{4}\sqrt{\frac{2\cdot g\left(\rho_{Hg}-\rho_{viz}\right)\Delta h_{mp}}{\rho_{viz}}} \tag{3}$$

$$H = \frac{\rho_{Hg}-\rho_v}{\rho_v}\Delta h_n - \left(z_2 - z_1 - l_n\right) + \frac{Q^2}{2g}\left[\lambda\left(\frac{l_{s1}}{d_{s1}A_{s1}^2} + \frac{l_{s2}}{d_{s2}A_{s2}^2} + \frac{l_n}{d_n A_n^2}\right) + \frac{1}{A_n^2} - \frac{1}{A_{s2}^2}\right] \tag{4}$$

The narrowed pipe on the suction side (**SC**) and the **T1, T3** valves are a significant resistance on the suction side, so the at larger volume flow rate values, cavitation occurs, and the characteristic curve drops (Figure 5.).

During the measurement, we want to obtain different points of the curve based on the measurement of the suction curve (*$H(NPSH_a)$*). We start from a point on the *$H(Q)$* curve, where no visible bubble generation is present. The **T1** (then **T3**) valves are gradually closed, and simultaneously open the **T2** and **T4** valves to keep the volume flow rate constant. The change of the head *H* is plotted as the function of the $NSPH_a$ (Figure 6.). The following formula is used to calculate the $NPSH_a$ value by using h_{sb} and h_{sj}:

$$NPSH_a = \frac{p_0 - p_g}{\rho_v \cdot g} - \left(h_{sj} - h_{sb}\right)\frac{\rho_{Hg}}{\rho_v} + h_{sj} + z_2 - z_1 + \frac{Q^2}{2g}\left[\frac{\lambda \cdot l_{s1}}{d_{s1}A_{s1}^{2}} + \frac{\lambda \cdot l_{s2}}{d_{s2}A_{s2}^{2}} + \frac{1}{A_{s1}^{2}} - \frac{1}{A_{s2}^{2}}\right] \qquad (5)$$

Based on the measured suction curve at a given volume flow rate Q, the $NPSH_r$ value is the point where the head drops around 3% (Point B on Fig. 6.). The occurring cavitation can be followed up visually because of the plexi side.

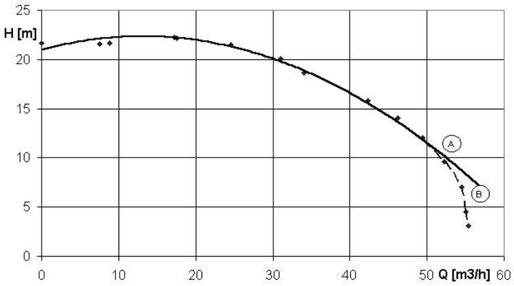

Figure 5. Characteristic curve of a pump

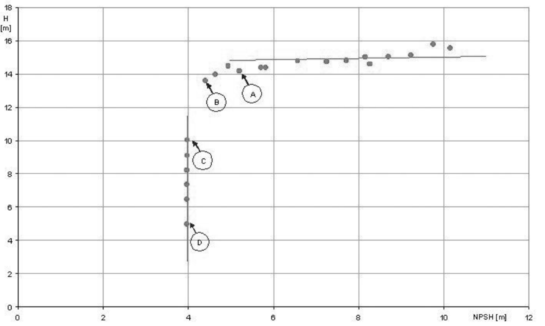

Figure 7. Suction curve of a pump

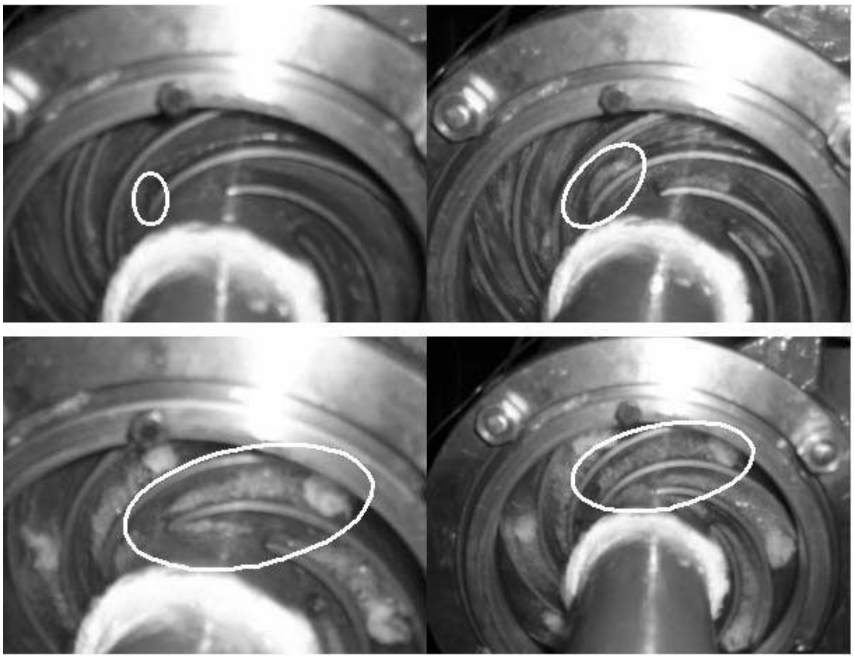

Figure 7. Photos of the cavitation zone at the points A, B, C, D from Fig 6.

5. Measurement

The aim of the measurement is to measure and plot a suction curve at a constant volume flow rate given by the supervisor. The supervisor starts the device after completing the necessary checklist. The measurement should start with fully open **T1** and **T3** valves, and the valves **T2** and **T4** on the pressure side of the supporting pump are used to set the required volume flow rate. The set volume flow rate can be calculated based on the parameters of the orifice plate and the pressure gauge connected to it. The following formula can be used (which can also be seen in Figure 8.):

$$Q\left[{}^{m^3}\!/_{h}\right] = 3.2472\left(\Delta h_{mp}[mm]\right)^{0.5} \tag{6}$$

The measurement starts with a fully open **T1** valve while setting the required volume flow rate with the **T2** and **T4** valves. The suction side valves are closed gradually during the measurement, and the pressure side valves are opened to keep the constant flow rate. After fully closing **T1,** the other suction side valve can be used. Pressure gauges are read out at every measurement point, and the state of the cavitation in the pump is observed by measuring the bubble zone length. The measurement is continued until the head drops drastically. At every point the head *H* and the available net positive suction head *NPSH*$_a$ can be calculated with the following equations (these are equation (4) and (5) with the respective constants written into):

$$H[m] = \Delta h_n[mm]\cdot 12.6/1000 + 0.18 - 9781\cdot\left(Q\left[{}^{m^3}\!/_{h}\right]/3600\right)^2 \tag{7}$$

$$NPSH_a[m] = 11.13 + \frac{13.6}{1000}\cdot\left(h_{sb}[mm] - h_{sj}[mm]\right) + \frac{h_{sj}[mm]}{1000} - 10773\cdot\left(Q\left[{}^{m^3}\!/_{h}\right]/3600\right)^2 \tag{8}$$

The data should be written in a table of the following form, where the needed values can be calculated based on equations (6), (7), and (8):

#	n [1/min]	Δh_{mp} [mm]	Δh_n [mm]	h_{sb} [mm]	h_{sj} [mm]	Observation	Zone length [mm]	Q [m^3/h]	H [m]	NPSH$_a$ [m]
1.										
2.										
…										

Then the suction curve can be drawn, and the *NPSH*$_r$ value can be estimated for the measured volume flow rate.

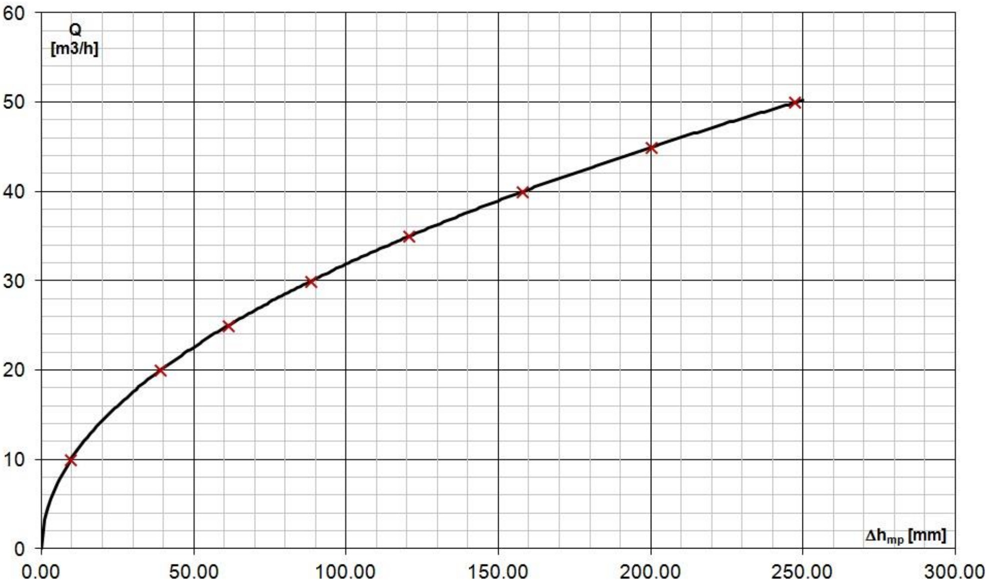

Figure 8. Measurement curve of the orifice plate

6. Preparation for the measurement

1. Prepare the table as mentioned earlier to collect the data.
2. Bring a graph (millimeter) paper.
3. Prepare from the lab description. An entrance test will be written at the beginning.

7. Data of the device

Motor type:	Mot 3 QU 160M4B-40 PTC
Motor serial number:	003896 DF
Pump type:	BMS 25/48
Pump serial number:	7012/4166

8. Entrance test questions

1. Explain the phenomenon of cavitation and its emergence!
2. Describe the difference between physical, technical, and supercavitation!
3. Write down and explain the formula of the $NPSH_a$!
4. Sketch the suction curve and describe its essential sections!
5. Demonstrate the main steps of the suction curve measurement!
6. Based on the suction curve, what criterium can you give for the $NPSH_a$ value? Justify your answer!
7. Explain the aim of the measurement and the quantities to be determined!
8. Sketch and explain the measurement device!

9. Measurement tasks

1) Calculate the useful power of the pump at a normal (without cavitation) operation and compare it with the useful power at an operation with
   a) technical cavitation!
   b) supercavitation!

2) Choose an electric motor to drive the pump, if the efficiency of the pump is
   a) 85%!
   b) 75%!

3) Calculate the absolute pressure at the intake manifold and compare it with the saturated vapor pressure at the ambient temperature at an operation with
   a) technical cavitation!
   b) supercavitation!

Technical information:

Checklist before starting the device (supervisor's task):

- *water level (should be higher than the T3 by-pass pipe)*
- *pressure side valves (T2 and T4) fully closed*
- *suction side valve (T1) at least half-open (indicator at the motor)*

If the electric valve (T1) won't move when the control buttons pressed, probably the plug is not connected.

Start of the device (supervisor's task):

1. *start the pump S, by turning switch next to the pressure gauges to position 1*
2. *start the auxiliary pump SS with the inverter (first power the cabinet, then press the green button then gently turn the potmeter)*
3. *open the pressure side valves T2 and T4 while checking the pressure gauge connected to the orifice plate*
4. *turn on the stroboscope (Str) after plugging it in*

Suggested measurement range at the given 1495 1/min revolution number is around 28-22 m3/h volume flow rate. This corresponds to 80-100 mmHg on the pressure gauge.

Measurement:

- *set the volume flow rate with T2 and T4*
- *set the choke with valve T1 until technical cavitation occurs, then use the by-pass valve T3*

Pay attention:

- *after the first point, the next should be measured if the available net positive suction head changed*
- *if the pressure gauge of the auxiliary pump displays 0 bar for a long time, then the seals of the pump may be burned. If smoke arises from the auxiliary pump, immediately close T2 and T4 to cool the seals down!*

Shut down:

- *just like the startup, but reverse*