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CAVITATION IN RECIPROCATING POSITIVE DISPLACEMENT PUMPS

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ABSTRACT

Owing to their impressive properties reciprocating positive displacement pumps are used in many applications. Pumping fluids at high delivery pressures and metering are the areas of frequent use. The design of reciprocating pumps requires an exact knowledge of the appearing phenomena such as unacceptable pipeline pulsation and harmful cavitation. But cavitation in reciprocating positive displacement pumps is still an insufficiently understood problem.

For a better understanding of the effects of incipient, partial and full cavitation in reciprocating positive displacement pumps high-speed camera measurements were done under real operating conditions using a horizontal single-acting plunger pump. Inspection windows were placed to capture all cavitation phenomena. Exemplarily the cavitation phenomena and their erosive potential are to be described on the basis of high-speed sequences for selected cavitation conditions. Also the mechanism of the incipient cavitation and the opening of the self acting valves could be clearly investigated with this experimental setup.

Standards and guidelines were discussed concerning the economical operating of reciprocating positive displacement pumps.

INTRODUCTION

Even though cavitation in positive displacement pumps is a well-known and very formidable phenomenon, the erosive potential and the risk of malfunction is not sufficiently clarified. On the one hand, fatigue tests with lacquer superimposed plungers have revealed that cavitation is not harmful in many cases. While on the other hand, manufacturers report damage due to cavitation. Because of this uncertainty, standards like API 674 and DIN EN ISO 13710 require operation of this pump type with high suction side pressure to ensure a certain safety margin to cavitation. Many pumps are required to operate with a certain amount of cavitation without any damage and also without any loss in flow, because as long as the point of backformation of the bubbles occurs before the end of the suction stroke, the working chamber is completely filled. A special example for such a machine is the type running with 1000 rpm and more, especially used for water jet cleaning or the like.

However according to API and ISO this is often an uneconomical way of operating pumps. But the question therefore is: how critical is cavitation in reciprocating positive displacement pumps? To clear this question and to eliminate this uncertainty the detailed mechanism of cavitation in positive displacement pumps has been investigated with high - speed camera technique under real operating conditions. Hence the cavitation mechanism in the working chamber as well as in the valve area can be visualized.

BACKGROUND – PRELIMINARY WORK

Although many researchers have published experimental results of cavitation in reciprocating positive displacement pumps the detailed understanding of the entire mechanism is rather limited.

Vetter et al. (1968) studied the operational behaviour of a piston pump with an acrylic glass casing. The effects of certain types of cavitation on the performance of reciprocating pumps were discussed and measures were taken to avoid the significant effects of cavitation. Defining cavitation criteria and establishing which type of cavitation is harmful was the aim of this observation. The experiments revealed a rather wide range of cavitation under real operating conditions yet the pump was still worked properly. Due to this fact, the extent of harmful cavitation could hardly be estimated.

Also the flow visualization study of cavitation in a mock reciprocating pump cylinder published by Edge et al. (1994) showed no evidence of erosion caused by collapsing cavities. Edge investigated the nature of formation and collapse of vapor cavities within the camber. The results revealed that no cavities were obviously collapsing near boundaries. Edge intended that visualization of cavitation in a real reciprocating pump has to be undertaken.

This gap has might been closed by the work of Schade et al. (2008). According to the investigations of Schlücker and Klapp (2002) a common plunger pump housing was equipped with pressure resistant inspection windows. The very fast generation and collapsing of vapor bubbles are not visible to the naked eye. Therefore the detection of appearing cavitation phenomena needs to be optically observed by a high-speed camera. Additionally the pump was equipped with several pressure sensors to get detailed knowledge of the pressure evolution.

Blendinger et al. (2008) proved that computational fluid dynamics (CFD) is becoming more and more of an efficient means of research and development of reciprocating positive displacement pumps. In his work Blendinger also visualized cavitation phenomena at a standard plate valve.

EXPERIMENTAL SETUP

The experimental investigations of the appearing cavitation phenomena were performed using a horizontal single-acting plunger pump. To observe the generation and the backformation of cavitation in the working chamber and at the suction side valve the pump was equipped with several pressure resistant inspection windows.

The test loop consists of a 10 kW plunger pump operating with variable speed control up to 400 rpm. The piping setup is a closed loop which is fitted with a storage tank, several check valves and a heat exchanger to ensure constant fluid temperature. To operate the plunger pump under usual industrial conditions (Edge, 1994) the storage tank can be pressurized up to 8 MPa. The volume flow up to 70 l/min is detected by an inductive flow meter.

Because of the inspection windows it is possible to capture the cavitation phenomena by means of a high-speed camera with a frame rate up to 100,000 frames per second. The measurements of the pressure history were triggered with the recording at same rate and hence every single high-speed camera frame is corresponding to an accurate measured pressure. If necessary, two pulsation dampers are available one on the suction side and the other on the discharge side. The experimental investigations were performed using different valve designs such as a plate valve, a cone valve and a ball valve as shown in Figure 1. Therefore different cavitation phenomena can be detected due to the valve construction while operating the reciprocating pump.

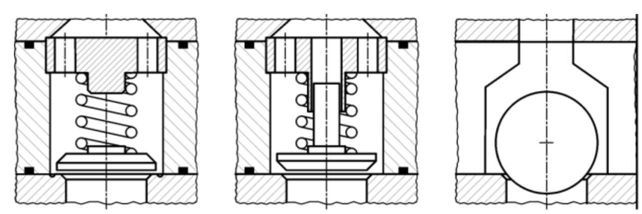

Figure 1: Valve designs: left, plate valve; middle, cone valve; right, ball valve.

EFFECT OF CAVITATON ON PUMPS

In pump technology cavitation is generally feared and therefore following a basic rule has to be avoided. Vibrations, noise development and losses in efficiency are effects of cavitation, which do not directly lead to a malfunction or breakdown. If cavitation phenomena are connected with high pressure surges or material removal respectively cavitation erosion then undisturbed operation of hydraulic machinery is endangered. In each case cavitation must be controlled or prevented. The levels of safety and the acceptable limits are fixed in the guidelines.

If a hydraulic machinery, e. g. a centrifugal pump experiences a 3% reduction in its total head while operating at a constant speed and flow-rate the criterion is fulfilled. In contrast cavitation in reciprocating positive displacement pumps has to be completely avoided.

CAVITATION TYPES

Generally the origin of cavitation in reciprocating positive displacement pumps lies at the beginning of the suction stroke because of the highest mass acceleration and the under pressure spike. As the opening of the suction valve is influenced by inertia, it takes place with a certain time delay. Therefore right at the beginning of the suction stroke the flow rate equivalent caused by the movement of the displacement body is higher than the flow rate from the suction side. This results in expansion, pressure decrease and finally leads to cavitation in the working chamber at that point in time when the vapor pressure is reached. This so called cavitation due to expansion leads to formation of several cavities close to a rigid surface, e.g. the plunger. Once you have vapor pressure in the working chamber, the suction side fluid flow is no more linked to the motion of the displacement body. The liquid in the suction piping is decoupled and obeys other physical laws. The liquid column between suction vessel and pump is influenced by a constant differential pressure depending on the difference between the vapor pressure and the head in the suction vessel until all cavities were collapsed. Therefore Schlücker et al. (1997) developed a mathematical method for calculating the progress of flow during cavitation.

Cavitation due to pseudo-adhesion in the valve gap

After the expansion of the fluid the opening of the fluid controlled suction valve begins. The valve body begins to loosen itself from the valve seat due to the increasing differential pressure. Thereby the initially very small valve gap cannot be completely filled fast enough by the flowing fluid, as shown in Figure 2. Subsequently an area of low pressure in the valve gap will be formed.

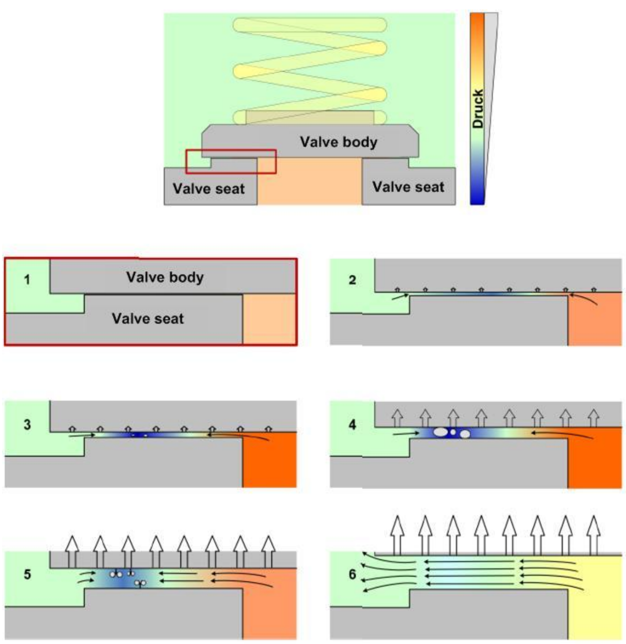

Figure 2: Process in the gap during opening of the valve (Blendinger, 2010).

The sum of the resulting forces acting at the inlet valve body is degraded thereby leading - metaphorically spoken - to certain persistence. This phenomenon is called pseudo-adhesion. The pressure in the gap can drop maximally down to the vapor pressure of the liquid. If the vapor pressure is reached cavitation will occur whereby the period of pseudo-adhesion is terminated. This process repeats itself with each opening of the valve and can lead to damage of the valve sealing surfaces.

Since the collapse of the cavities takes place in the area of the valve gap, it can result in erosion of the functional surfaces of the valve seat as shown in Figure 3. But also very often, the damage had not really influenced the functionality of the machine, because the backformation of the cavities had happened away from the functional sealing area. Therefore it is still an open question: how should a valve be designed?

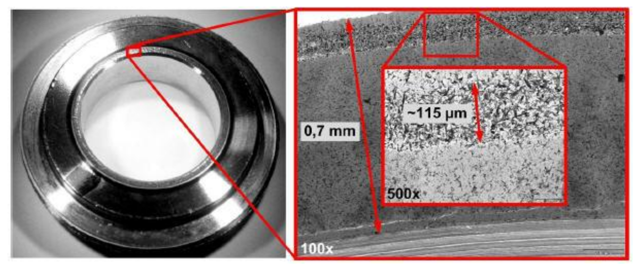

Figure 3: Cavitation erosion valve seat

In high-speed films of the suction valve during opening Blendinger (2010) was able to verify remaining cavities in the valve gap. In Figure 4 a sequence of pictures is shown. The time interval between the frames is 0.033 msec. As illustrated in this figure the generation and the collapse between the valve body and the seat becomes visible. By means of the yardstick it is getting obvious under which extreme optical conditions the process of the cavitation was documented.

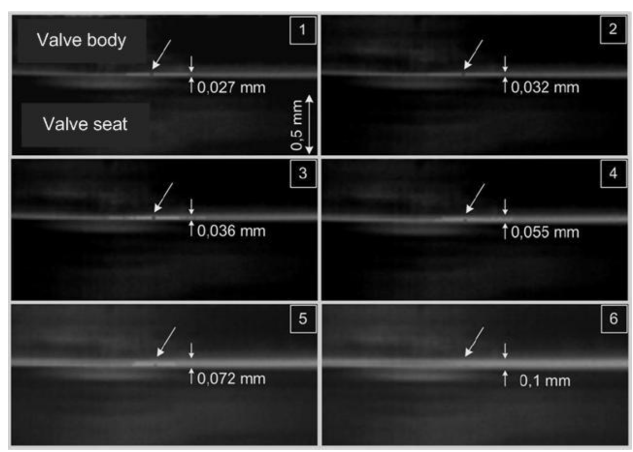

Figure 4: Vapor cavities due to pseudo-adhesion (Blendinger, 2010): 1. Bubble generation; 2-4, Growing of the bubble, 5-6, Backformation

Due to the suction side pressure different types of cavitation occurring in reciprocating positive displacement pumps during suction could be classified by the indicator diagram, as illustrated in Figure 5. An indicator diagram is generally seen as a pressure diagram and it indicates particularly the pressure pattern over the plunger stroke - thus for the discharge and the suction stroke - according to kind of a cyclic process:

1 – 2 compression of the fluid
2 – 3 discharge phase
3 – 4 expansion of the fluid
4 – 1 suction phase

Basically the cavitation types will be categorized into three cavitation conditions.

Incipient cavitation

At the very first beginning of the suction stroke the working chamber pressure-time plot exceeds the vapor pressure for a very short time (Figure 5 b). This form is called incipient cavitation. The reason for this is the under pressure spike during the opening of the suction side valve. Generally, it can be said that the bubbles in the working chamber are strictly caused by volume expansion and are randomly distributed in the working camber without any contact to the walls. This type of cavitation seems harmless.

Partial cavitation

If you lower the suction side pressure or increase the plunger speed you get from the cavitation condition of the incipient cavitation to the partial cavitation (Figure 5 c and d). After the under pressure spike during the opening of the valve the pressure in the working chamber remains nearly constant at the level of the vapor pressure until backformation occurs. Therefore cavitation bubbles will be generated at the beginning of the suction stroke and collapse due to certain pressure conditions similar to a water hammer. The partial cavitation is characterized by the complete bubble degeneration at the latest end of the suction stroke. Therefore the backformation of the vapor cavities goes along with pressure surges.

Considering the point of the water hammer the cavitation condition of the partial cavitation could also be classified into three categories (see Figure 5):

- Incipient partial cavitation
- Advanced partial cavitation
- Distinctive partial cavitation

The incipient and advanced partial cavitation is characterized by the impact within the first half of the suction stroke. High-speed camera investigations showed that the volume of vapor cavities increased in comparison to incipient cavitation. The bubbles are well distributed in the working chamber. Sometimes wall contact is given, but we could not find any hint for damages. Therefore this type of cavitation seems also harmless.

Distinctive partial cavitation is particularly marked by the backformation of volume expansion generated cavitation during the second half of the suction stroke. Independent from the suction side pressure the pressure surges could arise up to a multiple. In certain applications this is not always harmless anymore. Here further investigations are necessary.

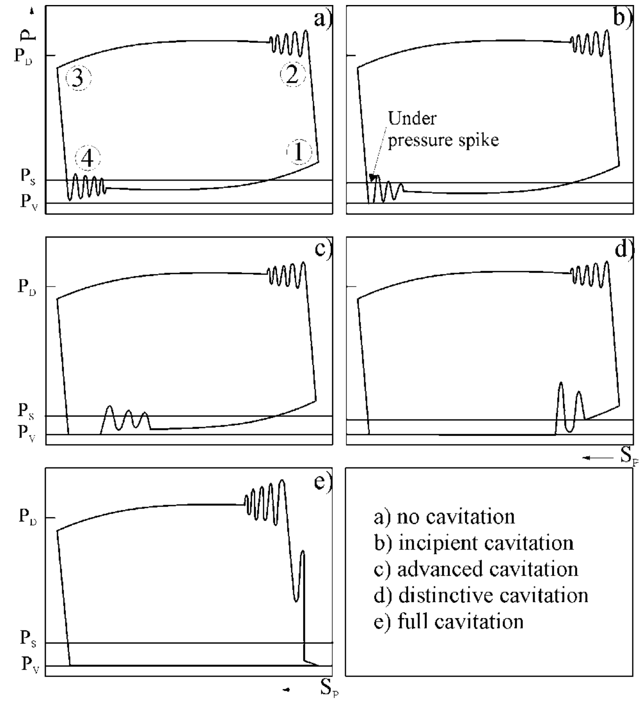

Figure 5: Principle indicator diagrams of a reciprocating positive displacement pump with different cavitation types (S: Stroke, PD: Discharge Pressure; PS: Suction pressure; PV: Vapor pressure

Full cavitation

If the vapor cavities were degenerated at the beginning of the discharge stroke this cavitation condition is called full cavitation. Very high pressure surges have to be expected and additionally a loss of flow and efficiency has to be suspected. Thus under normal circumstances in process technology this cavitation condition has to be avoided (Remark: The injection flow of gasoline in combustion engines in several car types is controlled by this phenomenon).

Visualization of cavitation phenomena

Inlet valve

The pictures in Figure 6 were obtained with a constant suction side pressure of 0.18 MPa and a variation of the stroke frequency from 240 rpm to 300 rpm. Due to the desired reproducibility of the measurements over the entire speed range a maximum delivery pressure was adjusted to 3 MPa. It is clearly recognizable that with increasing revolutions flow induced cavitation (marked area) occurs at the valve plate. With the flow passing the plate eddies are formed at the plate edge, which are responsible for an area of lower pressure. If the local pressure undercuts to the vapor pressure of water, the formation of steam bubbles will occur, which are dragged along at the lateral surface of the valve plate due to the flow. In areas of higher pressure it may collapse. Important in that case is, that the backformations of these bubbles are not occurring close to walls and therefore supposed to be harmless.

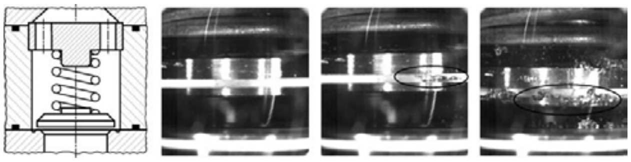

Figure 6: Cavitation at the inlet valve of the plunger pump with different stroke frequencies – 0.18 MPa suction pressure and 3 MPa delivery pressure at 240, 270 and 300 rpm

Working Chamber

In addition to the high-speed camera sequences at the suction valve the recording of the working chamber for the respective operating points are shown in Figure 7. Up to a stroke frequency of 210 rpm no cavitation occurs in the working chamber. If the number of revolutions is increased, the incipient cavitation during the expansion phase is recognized clearly. When raising the speed further the cavitation is constantly increases in intensity, until the complete working chamber is filled with vapor bubbles.

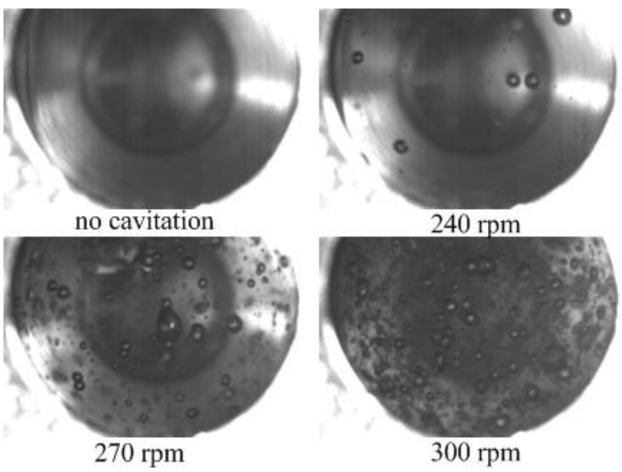

Figure 7: Cavitation phenomena in the working chamber of the plunger pump at different stroke frequencies – 0.18 MPa suction pressure and 3 MPa delivery pressure

The cavities will not collapse until the fluid flow commences after the opening of the suction side valve. Respectively the fluid column in the suction pipeline is coupled again to the pump kinematics. According to the cavitation phenomena at the suction valve the bubbles here were not forced to wall, too.

Summarizing the results of a huge sum of visual observations, it seems that cavitation effects in the valve area and working chamber are basically not harmful and in many cases harmless. This is, because as long as the pressure surge due to the water hammer effect is smaller than the discharge pressure, the pump will not experience damage due to over pressure. Also it can be stated, that the bubble distribution always covers the whole pump chamber. No explicit contact to the walls could be monitored. Because damage due to cavitation could only occur when a huge sum of bubbles will collapse exactly at the same position of the wall. The probability for this is fairly small. Therefore we state, that cavitation must not be harmful in reciprocating positive displacement pumps and is mostly harmless. The cases of a clear harmfulness could not be proved till now.

The only sensitive area is the suction valve. Here slight damages can occur when pseudo-adhesion occurs. But the probability for really harmful damages is fairly small. More important in our opinion is that the suction valve during severe cavitation closes faster than without. Additionally there is not a closed liquid film at the sealing surface. So the closing is harder and is not supported by a good fluid lubrication. Therefore it seems to us, that most damages are damages in the valve area. But mostly not caused by cavitation, but by a not perfect valve design. How the perfect valve design looks like is still in the focus of our investigations.

NPSH – VALUES VS. API STANDARD 674

With the help of usual NPSH (see Figure 8) values for pumps the pressure in the suction side vessel which leads to cavitation phenomena has to be determined with respect to the displacement motion. With the general computation method a forecast is not possible because the mechanism, which leads to flow induced cavitation, is not reflected properly by the NPSH values. Therefore wrong results were attained. Based on the conducted investigations it became clear that before and during the flow induced cavitation which has its origin preferably within the valve area cavitation due to volume expansion in the working chamber takes place.

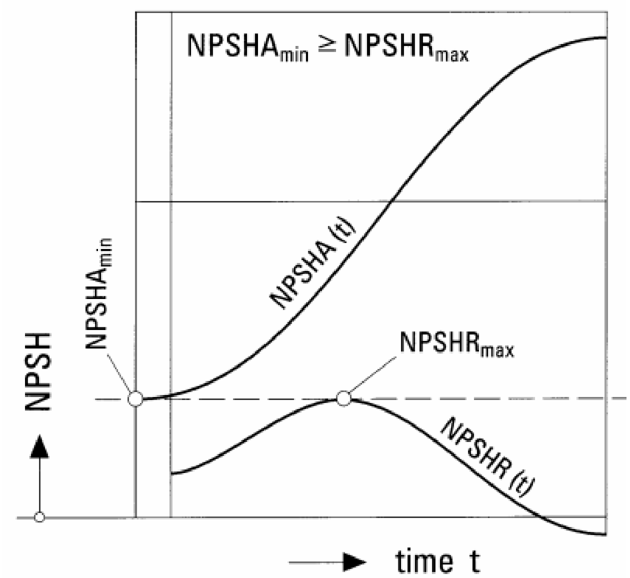

Figure 8: Usual NPSH situation of a system with reciprocating positive displacement pumps with $NPSHA_{min}$ = $NPSHR_{max}$.

Thus the fluid flow in the suction piping and at the suction flange is decoupled from the displacement motion and obeys other physical laws. Whether it comes to flow induced cavitation or not primarily could not directly determined by the displacement motion but by the course of the suction side flow during cavitation due to expansion in the working chamber. Beyond that the cavitation due to expansion is not considered in the NPSH guideline and especially a forecast of the occurring incipient cavitation phenomena during the opening of the valve is not possible. Due to the investigations it must be mentioned that the NPSH values are not suitable to determine cavitation in reciprocating positive displacement pumps surely.

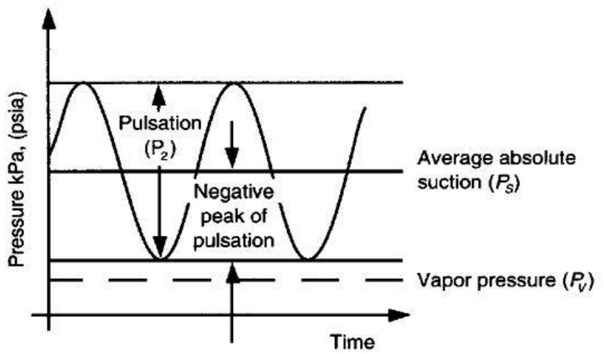

Figure 9: Maximum suction complex pressure wave amplitude

Referring to the API Standard 674 cavitation in reciprocating positive displacement pumps has to avoided at any times. Beyond this if not otherwise specified the minimum value of the suction side pressure shall not exceed the value shown in Figure 9. In addition to that the European Standard DIN EN ISO 13710 demands the minimum value to be at least 10 percent higher than the highest liquid vapor pressure of the fluid.

A closely look in the pressure history of a reciprocating positive displacement pump during suction reveals the occurring time-dependant cavitation phenomena as shown in Figure 10. As already mentioned the origin of cavitation lies at the beginning of the suction stroke. Due the expansion of the fluid in the working chamber the pressure reaches the vapor pressure of the fluid and cavities are arising. The fluid in the suction pipeline commences to flow and the flow velocity is increasing. Therefore, due to Bernoulli's law, flow-induced cavitation occurs at the valve plate. These phenomena delineated in Figure 10 coincide completely with the high-speed recordings. When the flow from the suction side exceeds the flow by the plunger motion, the degeneration of all vapor cavities commences and the working chamber is free of any bubbles. As shown in the pressure history, the pressure surges increase several-fold independent of the suction side pressure.

If the cavities were degenerated in the second half of the suction stroke unacceptable high pressure surges have to be expected and so there is a high potential of malfunction. But if the backformation takes place in the first half of the suction stroke the pressure spikes will not be as high as mentioned before and therefore the potential of malfunction is very low.

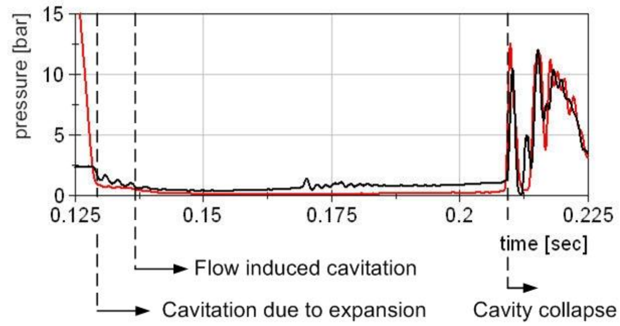

Figure 10: Pressure history during suction stroke at 270 rpm; 0.25 MPa suction pressure and 3.0 MPa delivery pressure

The time-dependant of the occurring cavitation phenomena in the working chamber and at the valve area as shown in Figure 10 indicates a discrepancy in the operation of reciprocating positive displacement pumps. If you operate on basis of the API Standard 674 you have to avoid cavitation at all times which is not economical. In comparison to this standard the NPSH value describes only flow-induced cavitation phenomena. The incipient cavitation especially at the beginning of the suction stroke is not considered in the guideline.

CONCLUSIONS

The analysis indicates that cavitation in reciprocating positive displacement pumps is not as harmful as expected up to now. The claim to largely avoid cavitation, as given in the NPSH - guidelines as well as in the API Standard 674, are therefore too strict and lead to an economic disadvantage compared to other types of pumps. In many cases a risk of unsafe operation of the pump is only given if the cavitation backformation takes place in the second half of the pump. But simultaneously it has to be ensured by a suitable design of the valve area and the working chamber that a permanent attack of cavitation is not likely if the cavitation backformation takes place in the first half of the suction stroke.

Therefore future research work should take the presented considerations as a fundament of the development of a new reliable cavitation criterion that allows the operation of pumps in a more economical way.

NOMENCLATURE

P	= Pressure	(MPa)
P_S	= Suction pressure	(MPa)
P_D	= Delivery pressure	(MPa)
P_V	= Vapor pressure	(MPa)
S_P	= Plunger stroke	(m)
rpm	= Revolutions per minute	(min^{-1})
NPSHA	= Net positive suction head available	(m)
NPSHR	= Net positive suction head required	(m)

REFERENCES

Anciger, D., Schilling, R., Opitz, K., Schlücker, E., 2009, "Numerical prediction of the piston driven valve motion in positive displacement pumps (PDPS)", *Proceedings of the 14th International Conference on Fluid Flow Technologies*, Budapest, Hungary.

Blendinger, S., (2010), "Strömungsinteraktionen, Kinematik und Verschleiß fluidgesteuerter Pumpenventile", Dissertation, University of Erlangen – Nuremberg.

Blendinger, S., Schlücker, E., Schade, O., 2008, "Computational Fluid Dynamics simulation of reciprocating pumps with respect to the fluid driven valve motion", Pump Users International Forum, pp. 186-195.

Edge, K. A., Xiao, X., Shu, J. J., Burrows, C. R., 1994, "Flow visualisation of cavitation in a mock-up of a single cylinder reciprocating plunger pump using high-speed cinematography." *Fourth Triennial International Symposium on Fluid Control, Fluid Measurement, Fluid Mechanics, Visualization, Fluidic*; Flucome, pp. 1101-1106.

Johnston, D. N., Edge, K. A., Vaughan, N. D., 1991, "Experimental investigation of flow and force characteristics of hydraulic poppet and disc valves", *Proceedings of the Institution of Mechanical Engineers Part A, Journal of Power and Energy*, 205, pp. 161-171.

Opitz, K. and Schlücker, E., 2010, "Detection of cavitation phenomena in reciprocating pumps using a high-speed camera", Chem. Eng. Technol., 33, No. 10, pp. 1610-1614

Schade, O., Schlücker, E., Blendinger, S., 2008, "Cavitation in reciprocating positive displacement pumps - not a mystery anymore", *Proceedings of the Pump Users International Forum*, pp. 81-90.

Schade, O., (2009), "Kavitation in oszillierenden Verdrängerpumpen", Dissertation, University of Erlangen – Nuremberg.

Schlücker, E. and Klapp, U., 2002, VDMA Fachverband Pumpen.

Schlücker, E., Fritsch, H., Stritzelberger, M., Schwarz, J., (1997), "A new evaluation method for estimating NPSH-Values of reciprocating positive displacement pumps", *ASME Fluids Engineering Division Summer Meeting*, FEDSM97-3363.

Vetter, G. and Fritsch, H., 1968, "Untersuchungen zur Kavitation bei oszillierenden Verdrängerpumpen", Chem. Ing. Tech, 41(5/6), pp. 271-278.

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