International Journal of Mechanical and Industrial Technology ISSN 2348-7593 (Online)
Vol. 7, Issue 2, pp: (1-7), Month: October 2019 - March 2020, Available at: www.researchpublish.com

INVESTIGATION OF THE CONDITIONS THAT TRIGGER CAVITATION IN A PUMP

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Abstract: **This paper will consider cavitation, the mechanism that causes it, its damaging effect on mechanical components, cavitation mitigation and the practical applications of cavitation. Cavitation is a phenomenon that occurs when bubbles form in a liquid due to a pressure drop, then violently collapse. This is usually a consequence of fluids moving at high velocity when the local pressure falls below vapor pressure allowing small amounts of liquid to vaporize. When the bubble reenters a region of high pressure, the bubble then collapses violently with enough energy and force to erode metal. Damage from a single bubble collapse is almost immeasurable; it is the constant accumulation of damage over long periods of time that causes significant removal of material, hence "cavitation erosion". The highly focused jets of liquid from the collapsing bubbles blast away micro-amounts of material which eventually gives the surface a pitted appearance. This is commonly a problem for mechanical components such as hydrofoils, propellers, automobile engines and centrifugal pumps in working environments of in the marine, automotive and industrial applications where liquid velocity is high and pressure head is low.**

Keywords: **Pump Head, Erosion, Cavitation Phenomenon, Fluid Pressure.**

1. INTRODUCTION

Cavitation is defined as the process of formation of the vapor phase of a liquid when it is subjected to reduced pressures at constant ambient temperature. Although other factors such as changes in temperature, turbulence and velocity play a role, the change of liquid to vapor is the same. When bubbles then enter a region of higher pressure or lower temperature, they collapse violently producing a jet of liquid that creates shockwave upon impact with a surface enough force to erode metal. Although the collapse is generally a low-energy event, it is highly localized. The figure below illustrates the collapsing phase and resulting jet, referred to as the re-entrant micro jet:

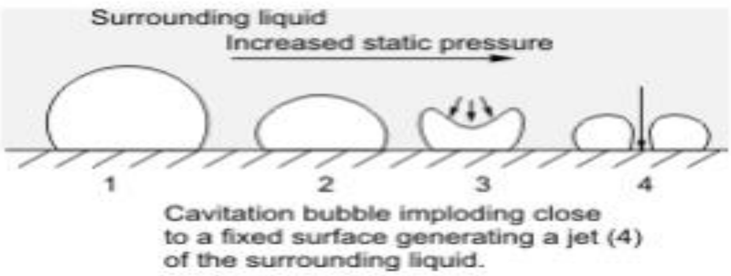

Figure 1: Collapsing Phase of Vapor Bubble

As previously mentioned the mechanism responsible for initiating cavitation is a pressure drop causing the water to undergo a phase change from liquid to vapor. However, this is unlike a boiling pot of water that is common to most of us. When water boils under normal conditions, say 212°F at 1 atmosphere, it undergoes a phase change from liquid to vapor and increases in volume over 1000x. The vapor bubble rises to the surface and bursts. The pressure in the bubble is low (approx. 1 atm) and the circular area is relatively large. Now if water was to change from liquid to vapor due to a pressure drop at an ambient temperature such as 68°F it increases to over 50,000x its original volume. Almost the exact opposite happens to a collapsing bubble due to cavitation compared to a bubble bursting at the surface of a pot of boiling water. When this bubble begins to collapse the pressure may be up to 10,000 atmospheres. Also, the bubble also tends not to collapse uniformly in all directions and as a result, a powerful jet of liquid is formed as it rushes in to fill the void once occupied by the bubble. Unfortunately, the direction of the jet is most likely to be directed at the surface of the device initiating the process, such as the blades of a pump.

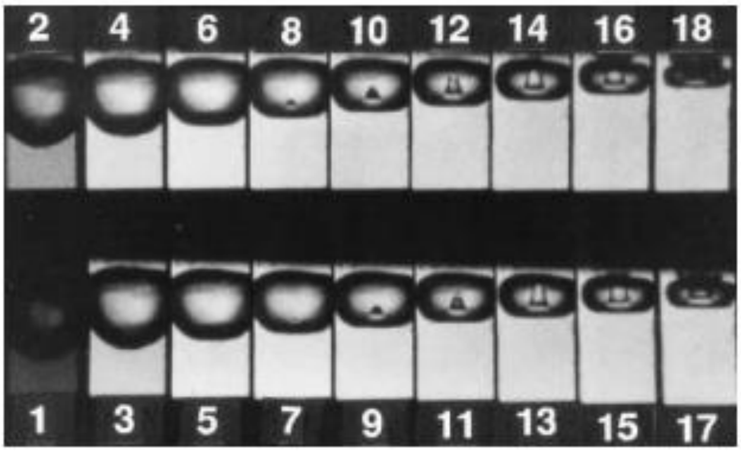

Figure 2: Actual stages of a collapsing vapor bubble. Note how the bubble collapses unevenly and the formation of the jet.

A single cavitation event produces little if any noticeable damage. It is the accumulation of damage from multiple events (thousands, millions, billions…) over time that causes noticeable damage known as pitting, hence the phrase "cavitation erosion". It is sometimes referred to as cavitation corrosion, but this is inaccurate. Corrosion is due to chemical reactions and erosion is the physical removal of material by an external force, but cavitation can help initiate corrosion by exposing surfaces. Therefore, corrosion due to cavitation is a secondary mechanism. The chances of cavitation occurring can be calculated based on the ambient pressure (Pa), cavity pressure (Pc), mass density (ρ) and velocity (U) of the liquid. Similar to the Euler equation, the equation for cavitation number is:

$$\sigma = \frac{p_{a-P_c}}{{}^1/_2\rho U^2}$$

Equation for cavitation number

For a specific liquid, the value calculated by the cavitation number at which cavitation occurs is called the critical cavitation number. Above this value cavitation does not occur.

2. TYPES OF CAVITATION

There are mainly four types or stages of cavitation:

1. Incipient Stage

In this stage bubbles formed are very small. It is easily detected. Zone in which it takes place is limited. Any change in parameter will change in vaporization rate. All other stages after this stage is referred as developed stages.

2. Traveling Cavitation

At this location bubble nuclei are formed. Growth of bubble takes place. They expand shrink and collapse. Generally these bubbles are formed at low pressure side of solid boundary or high shear region of turbulence flow or low pressure vortex side.

3. Fixed Cavitation

In this type of cavitation, liquid flow near the solid boundary separates from solid surface and bubble formed in cavitation zone sticks to surface forming cavity in quasi-static sense. It is appeared in high boiling region of turbulent zone. This stage can be detected after inception has occurred.

4. Vortex Cavitation

As stated above, this cavitation is formed in cores of vortex flow. It is found in either in fixed or in moving stage. Sometimes it is called as tip cavitation .open type of propeller and ducted propeller face such problem.

Pump and its Practical Application

Pump is a mechanical tool which increases fluid pressure and makes the effects arising from the system's friction, gravity and functional pressures possible. By means of this tool, the fluid is transferred from one place to another, and based on the various fluids which may be transferred to the pump, the following functions can be defined:

- Hydrocarbons
- Chemical materials
- Whitewashes
- Water and similar fluids

Technically, pumps are of dynamic and displacement nature, and based on their way of functioning, they are divided into three following groups:

- Axial flow pumps
- Radial flow centrifugal pumps
- Mixed flow pumps

Investigating the methods of cavitation effects on pumps

There are three general methods for study of cavitation phenomenon as follows:

- Indirect observation by determining cavitation effect on pump's efficiency based on head or performance drop
- Direct observation using visual and photography (imaging) equipment (in this method, sophisticated photographic equipment is required)
- Indirect observation through measurement of the produced noise by cavitation (studies indicate that upon intensification of cavitation, noises with high frequency are produced, therefore, presence of cavitation is detectable by measuring such noises).

3. METHODOLOGY

The simplest way to limit cavitation phenomenon is increase of pressure inside the pump relative to liquid vapor pressure and the possible solutions considered for control of this phenomenon are as follows:

- Reduction of suction height
- Reduction in suction drop
- Replacement of pump or propeller
- Increasing pump's booster
- Bringing changes in the pumps design to minimize hydrodynamic pressure difference in the course of flow
- Use of stronger alloy in construction of the pumps
- Creating smooth surface on propellers (smooth surfaces are not suitable for bubbles germination)
- Covering of metallic parts with soft coatings such as plastic

– Cathodic protection (in this method, the formed hydrogen bubbles over metal's surface like air cushion adsorb the shock waves)

Measurement of drop arising from cavitation phenomenon

Different experiments indicate that pump as a result of cavitation phenomenon will face 1% drop in efficiency and 3% decrease in head performance. Of course, measurement of these two quantities requires accurate devices and continuous and regular calibration and internal calibration standards, and laboratorial services should be employed. In cavitation phenomenon, materials' approximate amount of damage is obtained from the following formula:

$$\Delta G = \Delta T V^n$$

In the above formula, ΔG is amount of decrease in weight of pump's materials, T time duration of pumping in hour, V fluid velocity inside the system, and n is a number between 6 and 8 which is determined based on the pump's working condition. In addition to the above formula, also a table is prepared to show relative resistance of some metals against cavitation phenomenon which is referred to in the following of the paper.

Table1. Relative resistance against bubble erosion (cavitation phenomenon)

Non iron	form	copper	tin	zink	magnesium	sillica	nickel	iron	lead	aluminim	Fresh water	Sea water
Burns(cu,sn,zn)	melting	88	10	2	-	-	-	-	-	-	65.5	57.4
steal	roll	.25	-	-	-	-	.45	.67	-	-	24.2	29.6
steal	roll	.27	-	-	-	.4	.45	.48	-	-	68.3	77.8
steal	roll	.2	-	-	-	.03	.02	.5	-	-	78.2	82.4
steal	melting	.27	.31	-	-	.04	.04	1.1	-	-	44.8	52.6
steal	melting	.26	.32	-	-	.04	.04	.6	-	-	72.9	80.9
Steal(ni,cr)	melting	.24	.2	-	-	.03	.02	.52	.6	1.18	20	22
Steal(ni)	-	.19	-	-	-	.02	.02	.6	-	2.2	61.3	64
Stainless steal(cr)	roll	.08	.57	-	-	.02	.03	.47	17.2	.24	11.8	10.8
Stainless steal(cr)	roll	.09	.28	-	-	.02	.02	.43	12.2	.32	20.6	22
Stainless steal(cr,ni)	melting	.015	.5	-	-	-	-	.5	16-20	8-12	13.5	12.4
Stainless steal(cr,ni)	roll	.07	.37	-	-	.14	.19	.48	18.4	8.7	16.1	15.3
Nickel(cu,fe,si)	melting	22-32	-	-	-	4	62-63	2	-	-	20	21.4
Nickel(cu,fe,mn)	roll	29	-	-	1	-	68	1	-	-	53.3	53.2
Nickel(cu)	drown	70	-	-	-	-	20	-	-	-	86.2	87.6

ferrous	form	carbon	sillica	copper	iron	sulfur	phosphorus	magnesium	cream	nickel	Fresh water	Sea water
iron	melting	2.1	2.2	-	-	.12	.07	.75	-	-	50.1	80.9
iron	melting	2.4	1.3	-	-	.08	.25	.75	-	-	69.8	115.3
iron	melting	2.4	2.3	-	-	-	-	.59	-	-	89.7	1000.2
Iron(cu,ni,cr,si)	melting	3	1.9	6	-	-	-	-	4	14.4	41.6	51.4
Iron(no)	melting	2.3	1.3	-	.4	-	-	.51	-	-	54.1	63.9
Iron(mn,cu,ni,cr)	melting	2	1-2	60	-	.1	.04	1	1-3	12-15	85.3	95.3
Burns(cu,zn,sn)	roll	60	1	39	-	-	-	-	-	-	69.5	65.2
Brass(cu,z	roll	60	-	40	-	-	-	-	-	-	77.	68.

n)											8	7
Brass(cu,zn)		85	-	15	-	-	-	-	-	-	115.2	101.3
Brass(cu,zn)	roll	90	-	10	-	-	-	-	-	-	124.9	122.8
Burns(cu,ai)	melting	89	-	-	-	-	-	-	-	10	15.3	14.5
Burns(cu,sn,ni)	melting	87.5	11	-	-	-	1.5	-	-	-	54.6	62.4
Burns(cu,sn,pb)	melting	88	10	-	-	-	-	-	2	-	60.4	48.5
Burns(cu,si)	melting	92.94	-	-	-	2.4	-	-	-	-	42.6	40.4
Burns(cu,si,mn)	melting	94	-	-	1	5	-	-	-	-	52.4	54.4
Burns(cu,zn,al,mn)	forged	60-70	-	20-30	-	-	-	-	-	-	19.2	19.9
Burns(cu,zn,pe,mn)	melting	58	-	40	-	-	-	1	-	-	53	55.4

4. RESULTS AND DISCUSSION

Centrifugal Pumps and Net Positive Suction Head (NPSH)

When σ (Toma Coefficient) is zero, liquid pressure reaches vapor pressure and boiling occurs. Cavitation phenomenon occurs in centrifugal pumps where net positive head in the pump's suction is less (smaller) than what the manufacturing firm has recommended. Given numerous existing writings it might be assumed that relationship of NPSH and cavitation phenomenon is now full understood, but NPSH has not yet been understood and applied well and this fact has given rise to incurring heavy costs for installation of new systems and insecure functioning of installations equipped with the pump. Recently, an ideal solution in the inventive system has been designed by Dr. Movafagh Zaherti resolve this problem and to transfer the energy pressure from fluid carrying pipe to the suction pipe. This system functions as the inductor or similar means. Application of this de-airing system facilitates transfer of pressure energy from drift (running) tube to suction tube through a number of nozzles. Using this system when sufficient head is provided for the pump's propeller, the pump is able to continue its work under slight cavitation condition. Results of experiments carried out by Dr. Movafagh Zaher suggest that in case of optimum de-airing (depending on difference of water level) and application of new combination in the pump's geometrical and physical structure, its head increases up to 7 to 20 percent compared to final (marginal) head of a similar pump which lacks de-airing system. In addition, in this method, the pump's final (marginal) efficiency increases about 8 to 15% and average saving in electricity power reaches 16%. σ denotes maximum suction capacity on utilization point. Toma Coefficient (σ) is also expressed as follows:

$$\sigma=(H_s-H_v)/H=[(H_a-H_1)-H_v]/H=NPSH/H$$

The above formula is the analytic result of Bernoulli Equation (energy equation) and the factor

$[(H_a - H_1) - H_v]$ is NPSH. In this formula, NPSH is Net Positive Suction Head, H represents security head which corresponds to total energy absorbed by the pump from outside, H_v fluid vapor pressure in mw, H_1 relative suction pressure in mw, H_a air pressure in mw, H_s absolute pressure in the pump's suction segment in mw.

Form and dimensions of pumps' propeller changes proportional to a dimensionless design index called Specific Rotatory Velocity. Specific rotatory Velocity is an index for prediction of pump's specifications and is defined based on rotation velocity of pump's propeller per minute; the propeller with similar geometrical specifications which in each minute is able to put in flow a Gallon water by one foot head. The experiments indicate that ration of the pump's propeller main dimensions uniformly change proportional to the amount of Specific Rotatory Velocity. In calculation of specific velocity, all values regarding the pump's performance on optimum yield point with the pump's maximum nominal diameter and velocity should be taken into consideration. Pump designers use N_s as a valuable tool for improvement and development of propellers. The specific rotatory velocity (N_s) is used be pump designers as one the indices for description of propellers' geometrical features and their classification based on the type of their design and applications. It should be noted that assessment of dimensional ratios of a pump's propeller and comparison of various propellers with each other can be done by the below formula:

$Ns = (N\sqrt{Q})/H^{3/4}$

In the above formula, N_s is the pump's specific rotatory velocity (dimensionless number), N pump's propeller's rotation velocity per minute, Q flow rate in Gallon/min, and H pump's head in foot. It should be noted that pumps' maximum rotatory velocity is determined by NPSH. σ is Toma Coefficient (cavitation number) is a function of specific rotatory velocity, performance and number of pump's propellers, and specific rotatory velocity is defined so in which all geometrical dimensions of the imaginary turbo-wheel are similar to the assumed pump.

However, σ has also a critical measure which is denoted by cσ. cσ, the critical Toma Coefficient is obtained when cavitation is almost started and this value is obtained through actual experiments. Cavitation occur when Toma Coefficient is smaller than critical Toma Coefficient, thus, control of this phenomenon can take place by this parameter. It should be noticed that between σc and specific rotatory velocity the following mathematical relation holds:

$\sigma c=1.042\times10^{-3}(N_s)^{4/3}$

Considering the above matter, it can be concluded that σ (cavitation number) is in direct relation with 1.33 power of Specific Rotatory Velocity.

Axial and Centrifugal Pumps and Effect of Cavitation Phenomenon on their Performance

Axial pumps are the pumps which transfer high flow rate at low head (performance), i.e. they have a high specific rotating velocity and it is suggested that cavitation risk and cavitation number in such pumps to be greater relative to other types of pumps. Occurrence of cavitation phenomenon in centrifugal pumps in critical and instable state may cause disorder in the respective systems.

In some cases, determination of exact reason for the pump's instable performance (functioning) is not possible. Turbulent flow or flow's unusual conditions can cause severe vibrations in pump and may put it out of circuit. One of the primary reasons for vibrations of centrifugal pump is cavitation phenomenon. As a result of drop in fluid pressure, vaporization occurs, and bubble masses are produced on the side of propeller's suction and are forwarded to propeller's outlet for discharge and on their way as a result of pressure, bubbles are produced and compressed. The bubbles' compression is accompanied with noise (similar to noise of air bladder) and creation of vibration. Cavitation is a potential danger, particularly when the pump is working at high rotation velocity or at a capacity much more or much less than the best yield point. Cavitation phenomenon, in the long run, may cause quick damage to pump. Among other effects of cavitation phenomenon on pumps' performance, it can be referred to the following ones:

- Change in flow pattern with effective result in output (flow discharge) and pump's efficiency
- Fatigue in parts arising from cavitation phenomenon and probability of pump's propeller breaking
- Failure of flow passages as a result of cavitation damage and drop in pump's head
- Erosion and pitting of metal parts due to continuous abrasion resulting from bubbles collapse
- Creation of vibratory impulses and noise in parts of the pump's propeller (vane) when the applied hydrodynamic pressure on bubbles' surfaces changes. In addition to erosion and abrasion, cavitation causes vibration and noise.4 production of noise can be a result of changes in fluid hydrodynamic pressure. For example, the amount noise produced as a result of vapor bubbles explosion has been measured up to one megahertz.

The design for the best performance in a classification should be based on the studies on the curves of discharge relative to head, output capacity and efficiency. The curves which represent relationship of the pump's security head and its capacity and efficiency with flow rate are of high importance, because these curves provide useful information on the pump's optimum performance. Application of the pump's main parameters is important because maximum efficiency matters only when the parameters have their optimum value and the pump is able to work at design speed.

Analysis of Flow Rates Curves Relative to Head, Output Capacity and Performance

The best hydraulic efficiency is obtained at specific velocities and efficiency drop at these velocities is primarily caused in the pump's input sections. The pumps which transfer a large volume of outflow at low head (like axial pumps) will be with high specific rotator velocity. Hence, this type of pumps has a higher efficiency relative to other types of pump. The experiments in a specialized project indicate that there is always a type of pump for a specific rotatory velocity with the best efficiency. In other words, there is a certain flow rate on design condition line in order to have the best empirical features of the pump. Results obtained from these experiments carried out on axial pump suggest that with flow rate increase the pump's security head decreases, but increase or decrease of output capacity does not occur regularly and the optimum flow rate lies on design condition line. The studies indicate the optimum specific rotator velocity increases along with increase of the pump's propeller degree (for example, from 15º to 22-29º) and the optimum flow rate is obtained at high flow rates. The studies indicate that as a result of cavitation phenomenon, 3 percent drop in head (performance) and 1 percent drop in efficiency occur. With NPSH increase, NPSH-σ curve relapses to its descending state and its slope is somewhat steep but from a certain level on, the curve takes a gentle slope. In addition, with increase of NPSH, NPSH takes a steep slope but from a certain level of NPSH onward, the curve's slope significantly gets moderated.

5. CONCLUSION

The main Causes of pump cavitation are:

- Drop in pressure at the suction nozzle due to low NPSHA
- Increase of the temperature of the pumped liquid
- Increase in the fluid velocity at pump suction
- Reduction of the flow at pump suction
- Undesirable flow conditions caused by obstructions or sharp elbows in the suction piping
- The pump is not selected correctly

The main criteria in identification of cavitation phenomenon are pump's performance drop and observation of erosion using laser systems. Cavitation creation and bubbles explosion as a result of this phenomenon release a large amount of energy which gives rise to heat, negative energy and local pressure. The bubbles are very short live and cavitation phenomenon is a very unstable situation, but collapse of cavitation bubbles may create a pressure to the magnitude of 100atm and such a large force may cause change of plastic shape in many kinds of metals. Bubble damage arises from simultaneous effect of erosion and mechanical stresses. Hence, collapse of vapor bubbles destroys superficial protective crusts. As a result of cavitation phenomenon, 3 percent drop in head performance) and 1percent drop in efficiency occur. Cavitation phenomenon can be controlled by Toma Coefficient, because cavitation occurs when σ is smaller than σc. One factor in reduction of water supply and yield of pumps is cavitation phenomenon. This phenomenon in the long run may lead to their quick destruction. The studies indicate that jet fluid dynamism is associated to fluid superficial slimy compressibility and the amount of these quantities varies in different physical regimes.

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