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The cause of cavitation and prevention methods of this destructive phenomenon in pumps

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ABSTRACT: When fluid'slocal pressure reachesa level lower than the saturation vapor's pressure at environment temperature, cavitation bubbles begin to grow and together with fluid flow are driven to the points with high pressure where they are quickly collapsed. This collapse is due to the fluid pressure which is higher than the pressure inside the bubble. Studying behavior of the bubbles arising from cavitation phenomenonincluding their growth and collapse nearthe rigid wall has been for years of interest for researchers worldwide. The bubbles collapse near the rigid wall has been always accompanied with a very rapid fluid jet which starts from the bubble's farthest point to the rigid wall and passes through the bubble and brings a heavy strike on the rigid wall's surface. The heavy strike of fluid jet is the most important and the main factor causing erosion and serious damages to propeller (or vane) ships, turbines, pumps and other hydraulic installations.The main criteria in detection of cavitation phenomenon aredecrease in pump performance, and observation of erosion using laser systems. Usually, the point at which the pump's head drops for three percent is considered as the departure point for cavitation phenomenon. However, this phenomenon may occur at a stage earlier than the three percent performance drop. In a pump, using noise measurement techniques and observation of bubbles, starting point of cavitation phenomenon is empirically determined and compared with pump performance drop point.
Key words: fluid pressure, erosion, performance, rigid wall, pump head, cavitation phenomenon

INTRODUCTION

In the literature on cavitation, a lot has been said about the factors causing damage to materials. Cavitation is a phenomenon which at high speeds causes damage and cavity on rigid wall's surface. Sometimes, in a hydraulic system, due to increase of speed, local pressure drops and this pressure may decrease to the point equal to fluid vapor pressure[1]. As a result of these two fluid factors, in the part where it is in flow it immediately turns into boiling state and transforms into vapor and vapor bubbles are produced. These bubbles after traversing a short distance reache a region with higher pressure and after explosion while producing noise and waves strikes the boundary between the fluid and the structure and after a short while they cause erosionover the solid boundary.

Cavitation phenomenon can cause damage nearly all over the rigid wall. Various types of solid surfaces which are exposed to cavitation damageare with a variety of factors which have been investigated by researchers. For example, Futtinger put a glass venturi tube inside cold water and investigated its cavitation damage. Schroter studied cavitation damage inside a diffuser. For this purpose, he selected a matter which did not have much chemical and electrolytic change. Yet his used experimental matter was damaged at higher rate. Hence, he concluded that cavitation damage might appear by even much solider matterials such as stainless steel, tungsten, carbides, and quartz.

Scientific background and prior research on cavitation phenomenon

From among the studies and researches carried out in recent years it can be referred to the studies on bubbles collapse pressure, indicating the calculated pressure for bubbles collapse is high. It should be noted that in some cases, there is no correlation between four factors of bubble's initial size, flow rate, and bubbles collapse pressure changes on the one side, and magnitude of the resulted damage, on the other side. In addition, even when the collapse pressure is high, this collapse occurs in the region which is not sufficiently close to rigid wall surface and as a result has no detrimental effects. The figures regarding bubbles collapse inside static fluids represent a kind of difference relative to flowing fluids in the collapse action and indicate that in some jets if the bubbles collapse action is close enough to solid boundarylayer, it is regarded as damaging factor. It should be noted that the images of the static fluids have been prepared by Shutler and Mesler which are similar to Ellis and Naude. In addition, similar pictures for venturi tubes and water tunnels have been prepared by Ellis, Ivany, Hammitt, Mitchell and Kling.

In a separate research, Gibson continued researchworks of Ellis and Benjamin to investigate bubble collapse state near rigid wall and in 1966 in an article on cavitation phenomenon, he states that cavitation bubbles through collapse actionare opened in neighborhood ofthe rigid boundary in a state similar to a vortical mode (vortical ring)and transforms into toroidal form, and the rotatory movement developes from the continuous one-dimensional (singular) state towards continuous two-dimensional state. Researchers believe that presence of rotation or vortex in flow is necessary for the protection from damages arising from Kelvin Impulse and if there is no rotation in flow, Kelvin Impulse will cause lots of damages. Theoretical arguments of Benjamin and Ellis are based on laboratorial documentations and are obtained by instantphotography from collapse of cavitation bubbles near rigid surfaces. Principally it was assumed that the flow is non-rotatory and incompressible and the under study fluid is non-slimy, and upon this assumption,numerical studies have been carried out. It should be noted that the first important studies in this area were carried out by Chapman and Plasset in 1971. These researchers using a small battery investigated collapse of the first bubbles near rigid surface the results of which indicate this prediction method regarding bubbles jet development has been successful. Following these studies, Boundary Integral Method turned into a strong and desirable method for calculation of bubbles movement. Guerri (1981) and Blake (1986, 1987) used this method, and in 1991, this method was employed by Lundgren and Mansour for calculation of bubbles movement with fixed volume and rotating movement. These calculations advanced only to the stage where the eruptive attack occurs on the far most point from the bubble. On the other hand, studies indicate that the jet's fluid dynamic is associated tofluid superficial slimy compressibility and the size of the above quantities varies in different physical regimes and should be given more importance in future works.

Definition of Cavitation Phenomenon

Cavitation phenomenon is formation of gas bubbles in suction segment (as a result of pressure drop), entrance of bubbles into propeller and crust, bubbles explosion as a result of pressure increase, energy release and occurrence of failure or break-down in pumps' parts. Numerous mathematical and computer methods have been proposed regarding bubble's behavior as a consequence of cavitation phenomenon. In majority of these methods, water vapor pressure inside the bubble is assumed to be constant and the development of distillation and evaporation inside the bubble is ignored.

The released energy as a result of bubbles explosion is the very hidden energy of liquid evaporation given by the liquid at the time of vaporization. Literally, cavitation phenomenonis equivalent to "cavity – creation", because as a result of liquid boiling, vapor bubbles are produced and simultaneously the dissolved gases inside liquid are released and inside the liquid some cavities are formed which are filled with gas and vapor bubbles. These bubbles explode in the high pressure region and are transformed from gas into liquid and following it, the bubbles disappear. Of course, in the vicinity of surfaces, the cavities are in contact with them. This is a hydrodynamic process and for this reason, the above process is called cavity – creation or simply cavitation.

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

Investigation 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 equipments are required)
- Indirect observation through measurement of the produced noise by cavitation[2] (studies indicate that upon intensification of cavitation, noises with high frequency are produced, therefore, presence of cavitation is detectable by measuring such noises).

Cavitation and bubbles collapse phases
Cavitation bubbles collapse may create a pressure to a magnitude of 100atm. A force to this magnitude may cause plastic transformation in many kinds of metals. The bubble damage is a result of simultaneous effect of erosion and mechanical stresses so as collapse of vapor bubbles destroys superficial crusts (outer layers). Actualization process of this phenomenon is as follows:

- The bubble is formed over the protection layer.
- Bubble explodes and damages the crust.
- The metal's new surface is exposed to corrosive environment and protective crust is reformed.
- On the same spot, another bubble is formed.
- Bubble explodes and crust is destroyed.
- The metal's new surface is exposed to corrosive environment and protective crust is reformed.[3]

Schematic representation of bubble-caused corrosive phases (cavitation phenomenon)
Since contact point of these bubbles is with very small rigid surfaces, it applies an extraordinary force on the surfaces as a result of these explosions. This action in a short period of time and with high frequency gives rise to corrosion of surfaces and gradually these erosions turn into large cavities.
Every kind of aperture, projection or sudden replacement of cross section may cause separation of flow lines, and the flow with high rate prepares the ground for cavitation phenomenon.
σ is Toma Coefficient, cavitation number or index, and cavitation capability, and according to the following formula, it is a dimension-less quantity and a form of pressure coefficient which characterizes pump's maximal suction capacity on the utilization point.

$$\sigma = (P_a - P_b)/(1/2\rho V^2)$$

In the above formula, P_a is absolute pressure, P_b liquid vapor pressure, ρ liquid density, and V is reference velocity or non-homogeneous velocity. Liquid vaporization process or solution gases emission in it or simultaneous emergence of the two phenomena, their development, density and loss occur within a very short time duration (about one hundredth or one thousandth of a second), as a result, the bubbles life is very short and cavitation phenomenon state is very instable.The bubbles are displaced along with liquid flow in high pressure area and are congested in contact areas with parts' solid wall (propeller or crust). Liquid particles, in search of filling such local cavities, collide with the center of these cavities at high velocity and by crushing and exploding them theydeliver local strikes on rigid surfaces. By application of heavy force with high frequency to parts and causing erosion and damage to them as a result of this phenomenon which is known as fluid jet microscopic effect, increase of local pressure occurs at high speed with intensity up to 100atm.

Factors associated to cavitation phenomenon

Cavitation phenomenon is caused by a set of factors and conditions. Usually, one factor alone is not enough for occurrence of cavitation issue and a combination of geometrical and hydrodynamic factors and other associated factors are required. Among these factors, it can be referred to the following ones:

- Pump's high velocity
- Limitation in suction head or performance
- High temperature of fluid in flow
- Pump-specific high rotation rate
- Geometrical factors (including superficial unevenness, particularly local elevations and depressions, slide and basic valves fissures of sectoral valves, columns separating flow and deflectors, change in the form of flow course and curvature and deflection in the flow course)
- Hydrodynamic factors (including specific discharge, flow rate, valve performance, and expansion of boundary layer)
- Miscellaneous factors (heat transfer during collapse, water temperature degree, number and size of the bubbles inside water and their distribution)

Measurement of drop arising from cavitation phenomenon

Different experiments indicate that pump as a result of cavitation phenomenon will face one percent drop in efficiency and three percents 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, ΔT 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.ai,mn)	forged	60-70	-	20-30	-	-	-	-	-	-	19.2	19.9
Burns(cu,zn,pe,mn)	melting	58	-	40	-	-	-	1	-	-	53	55.4

Axial and Centrifugal pumps and effect of cavitation phenomenon on their performance

Axial pumps are the pumps which transfer high flow rateat 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 sever 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.

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 pumpswhere 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. MovafaghZaherti 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. MovafaghZaher 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 ad 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 RotatoryVelocity. 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:

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

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' maximumrotatory 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 $_c\sigma$. $_c\sigma$, 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 criticalToma Coefficient, thus, control of this phenomenon can take place by this parameter. It should be noticed that between $_c\sigma$ 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.

Analysis 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.

Methods for prevention and confrontation with bubble damage (cavitation phenomenon) in pumps

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)

CONCLUSION

- 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 1 percent drop in efficiency occur.
- Cavitiation phenomenon can be controlled by Toma Coefficient, because cavitation occurs when $\sigma$is smaller than $_{c}\sigma$.
- 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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FOOTNOTES

1. Fluid vapor pressure is a pressure at which the liquid starts boiling and with its vapor reaches equilibrium.
2. In a pump, noise nature is derived from static pressure on one point.
3. Iteration of this action leads to creation of deep cavities and for this reason, cavitation amount increases.
4. The noise is caused by the bubbles explosion when entering the high-pressure region and the vibrations occur because of the imbalance, and the created waves occur at the time of cavitation.