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6 - 8 May 1986 , Cairo

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SCALE EFFECTS ON LIMITED CAVITATION PRODUCED BY VIBRATION OF THE WETTED SURFACE OF CYLINDER LINERS

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ABSTRACT

The processes of cavitation erosion in the space within the cylinder jacket of Diesel engines, which is the principal cause of failure of the outer wetted surface of cylinder liners, can be suppressed by avoiding the appearance of cavitation. This can be achieved if reliable information existed about the scale effects on the inception of cavitation which are an important consideration in the prediction of inception in a design process. Unfortunately there is insufficient information available at present to help the engine designer.

Therefore, the purpose of this paper is two-fold. First, new experimental data are presented which show the effects of the vibration frequency, water distance, and water temperature and pressure on the inception of cavitation. Second, a model for the inception of cavitation is presented.

Cavitation inception data are presented and discussed for a vibratory setup . The vibratory setup was designed to simulate the flow on the wetted surface of a liner. Measurements of inception were obtained visually through a transparent beaker containing tap water. The effects of vibration frequency, water depth , static pressure of water and water temperature on the inception of cavitation were investigated.

The results showed that the cavitation inception vibration amplitude decreased with increasing the vibration frequency and the temperature of water. In addition, the cavitation inception vibration amplitude increased as the depth of water increased.

The results were compared with the model and a good agreement was observed.

In the light of these results the designer should design his engine with cylinder liner vibration amplitude less than the inception vibration amplitude to operate his engine free of cavitation and therefore to avoid damage due to cavitation.

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1. INTRODUCTION

Cavitation is the rupture of a liquid caused by reduction of local static pressure. A rupture is the formation of a macroscopic or visible bubble. Liquids contain many macroscopic and submacroscopic voids which act as nuclei for cavitation. However, cavitation said to occur when these voids grow to significant size.

Cavitation occurs in many ways, produces light as well as noise. It also causes damage in bearings erosion damage to pipes, valves, pumps, turbines and propellers. It contributes to erosion of diesel-engine cylinder liners and limits the output of sonar transducers. Therefore, most interest in cavitation is in avoiding its undesired effects.

Cavitation is an especially important noise source in underwater acoustics. Since it involves volume changes. In marine vehicles, cavitation usually occurs most seriously on the propulsor. While submarines and torpedoes can often avoid cavitation by operating at deep depths, surface ships cannot avoid it.

Cavitation is described by the cause of the static pressure drop, the location of the rupture and the contents of the bubble. One cause of cavitation is the pressure drop occurring in the negative half cycle of a sound wave. A second cause of pressure drop is flow of liquids in hydraulic systems, called hydraulic cavitation. A third type is associated with the motion of bodies in a liquid, or the equivalent motion of liquids past stationary bodies. This is termed body cavitation for three-dimensional bodies and hydrofoil cavitation for flows past two-dimensional shapes.

Increasing velocity or power of diesel engines has resulted in unexpected cavitation erosion of cylinder liners. This erosion is caused by the collapse of cavitation bubbles produced in the cooling water as a result of cylinder liners vibration. The vibration of the cylinder is mainly due to the impact of piston against cylinder wall as a result of sidewise motion of the piston across the cylinder clearance space due to reversal of the direction of the crossforce component of connecting-rod force, i.e., piston slap. Piston slap exists in most, though not all, reciporcating machines. Pitting erosion of cylinder liners has been reported by many researches [1,2,3]. Speller and La Que[4] was the First to realise that the damage of cylinder liner is entirely due to the collapse of cavitation bubbles.

Joyner[1] concluded that the pitting erosion of cylinder liners was due to the collapse of vacuum bubbles created at the surface of liner when the pressure dropped below the vapour pressure. Clegg[2] and Thornycroft [5] reported that cavitation damage was found both on the cylinder liner and on the jacket. They concluded that the cavitation attack can be eliminated by reducing cylinder liner vibration.

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Leith[6]stated that the worst pitted area is located on the water side of the liner exactly where the "side slap" of the piston takes place during the power stroke, which is 90 deg. from the crankshaft axis, causing a maximum vibration amplitude at the middle of water Jacket. Tests conducted by Leith [7] and Hobbs[8]showed that cavitation attack may be reduced using commerical additives and thus lengthening the periods between replacements and maintenance.

In spite of widespread support for cavitation damage of cylinder liners, Hanson[9]reported that corrosion can produce complete engine failure, and Collins[10]believed that attack may be reduced by using corrosion inhibitors and attack is entirely dependent on chemical action. Nevertheless, in 1978 Associated Engineering Group's technical symposium[11]has come to the conclusion that the major problem of wet liners is water side cavitation damage and the best solution is to eliminat by piston design modification the source of liner vibration excitation. All of the previous investigations indicate that pitting of cylinder liners is undoubtedly due to cavition attack accelerated by corrosion.

A compormise design solution could be established if reliable information existed about cavitation inception scale effects on diesel engines. Scale effects is defined as all those phenomena which result in a change in the state of cavitation in a given flow regime which occur as a result of changes in operating conditions such as pressure, velocity, machine-size, fluid and fluid condition (temperature etc) with geometric and gross dynamic similarity maintained. Unfortunately there is insufficient information available at present to help the diesel engine designer. This is because most of previous studies dealt with purely metallurgical aspects of the problem, i.e., the relative resistance of cylinder liners materials to erosion. In addition, previous work showed that the effect of the flow parameters of cooling water on the cavitation inception has not been adequately described either theoretically or experimentaly.

Because of this situation the work, reported here in brief, is intended to study the effects of vibration frequency depth between the liner and the water jacket, static pressure of cooling water and temperature of cooling water on the inceplion vibration amplitude of cavitation.

2. THEORETICAL MODEL FOR CAVITATION INCEPTION

Cavitation inception is the beginning of cavitation. It is well known that cavitation inception occurs as a consequence of the rapid growth of small nuclei that have become unstable due to a change in ambient pressure. These nuclei can be either presented in the flow or find their origins in small cracks or crevices at the boundary surface of the flow [12].

The sound field generated in a liquid by vibrations of a solid boundary normal to its surface may at sufficiently large amplitude and frequency lead to cavitation. This vibratory cavitation is essentially, independent of flow, and cavities are produced and collapsed repeatedly within the same liquid volume. This is because the velocity of cooling water is so low.

Normally, gaseous nuclei in an undisturbed liquid shrink due to diffusion of gas into liquid, but if a sound field of sufficient amplitude is imposed, the bubbles perform radial oscillation, and they grow slowly by rectified diffusion. During the expansion phase the gas pressure is reduced sufficiently to cause diffusion of gas from the liquid into the bubbles through the expanded bubble surface , while during compression the reversed diffusion into the liquid takes place through a reduced surface only, resulting in a net transport of gas into the bubbles. The bubbles may drift away from the zone of sound, or they may reach their, critical size and grow by vaporous cavitation and collapse as transient cavities. It is possible to distinguish between gaseous and vaporous vibratory cavitation, the former referring to bubbles containing noncondensible gas and the latter to pure vapour bubbles.

Most of the progress in understanding the details of the inception process has been made through the consideration of the dynamic equilibrium of a spherical bubble containing vapour and non-condensible gas. The Rayleigh-plesset [13] equation describes this equilibrium :

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho}\left[P_v + P_g - P - \frac{2S}{R} - 4\mu\frac{\dot{R}}{R}\right] \quad \text{..........(1)}$$

wherein R is the bubble radius, p_v the vapour pressure p_g the partial pressure of noncondensable gases, P the external pressure, S the surface tension, μ the dynamic viscosity, ρ the liquid density. The dote denote differentiation with respect to time. It is generally agreed that dynamic effects can be important when the time available for growth i.e., exposure time is shorter than about 1 milliseconds. Dynamic effects are especially important in ultrasonics, where exposure time per cycle is less than 0.03 milliseconds[14]. Therefore, the dynamical terms in Rayleigh-plesset equation may be neglected in the present study.

Hence,Rayleigh-Plesset equation (1) reduces to

$$P = P_v + P_g - \frac{2S}{R} \quad \text{........(2)}$$

Clearly, such a bubble may begin to grow if

$$P < P_v + P_g - \frac{2S}{R}$$

Now, if it is assumed that the temperature and mass of the gas in the bubble remains constant as the external pressure is reduced, then the pressure, P_g, for a given mass of gass will vary inversely with the volume of gas bubble(i.e. the gas is free to expand isothermally, $P \cdot V = C$) that is ,

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$P_g \propto 1/R^3$. Thus the gas pressure can be represented as :

$$P_g = (P_o - P_v + \frac{2S}{R_o}) \frac{R_o^3}{R^3} \qquad ...(3)$$

where the subscript "O" refers to the initial value of the appropriate quantity.

Substituting (2) into (3), an expression for the external pressure is obtained ; thus corresponds to the static equilibrium of bubbles differing in radius,

$$P = P_v + (P_o - P_v + \frac{2S}{R_o}) \frac{R_o^3}{R^3} - \frac{2S}{R} \qquad ...(4)$$

A bubble, whose radius is R_o at the initial ambient pressure P_o, explodes at the critical ambient pressure P_c. The pressure P_c can be obtained by differentiating equation (4) with respect to R, and setting the derivative equal to zero and is expressed by the following equation.

$$P_c = P_v - \left[\frac{2\sqrt{3}}{9} \left(\frac{2S}{R_o}\right)^{\frac{3}{2}} / (P_o - P_v + \frac{2S}{R_o})^{1/2} \right] \qquad .... (5)$$

Equation (5), shows that a large tensile strength is required to explode a small bubble. The minimum radius of the nucleus, where explosion may start, can be estimated from the observed minimum pressure using equation (5).

The theoretical determination of the external pressure (P) as a function of vibration amplitude and frequency is extremely complex. In principle, a knowledge of the factors affecting the external pressure is necessary to determine the inception of cavitation. This point was considered by recent work of Moustafa [15], which indicated that the external pressure is highly correlated with the vibration amplitude and frequency and water depth. Moustafa appear to be the first investigator to conduct an extensive experimental study of driving pressure using magnetostriction vibratory. His experiments showed that the driving pressure is proportional to water depth to the power - ½, that is,

$$P \propto t^{-0.5} \qquad ...(6)$$

When a cylindrical piston vibrates with its circular face inside the liquid, the acoustic pressure amplitude at the radiating surface is approximately given by

$$P = \rho C A \omega \qquad ...(7)$$

where A is the amplitude of the vibratory end, ω is the circular frequency ($\omega = 2\pi f$), f is the vibration frequency, C is the sound speed in liquid, and ρ is the density of liquid.

By combining (6) and (7) P_c can be given as follows

$$P_c \propto 2\pi C.\ A_c f.t^{-0.5} \qquad ...(8)$$

where A_c is the cavitation inception vibration amplitude.

Substituting (8) into (5), a new scaling law for inception of vibratory cavitation is given by,

$$K.A_c.f.t^{-0.5} = \left\{ P_v - \left[\frac{2\sqrt{3}}{g} \left(\frac{2\ S}{R_o} \right)^{3/2} \left(P_o - P_v + \frac{2S}{R_o} \right)^{1/2} \right] \right\} \qquad ...(9)$$

where K is constant ($K = 2\pi\rho C.K_1$). K_1 is constant of the proportionality in equation (6). In equation (9) K and R_o can be estimated from relevant test results. The units are Kg/m for S, Kg/m^2 abs. for P_v and P_o, m for R_o, mm for A, Hz for f and cm for t.

Equation (9) gives the cavitation inception vibration amplitude (A_c) as a function of vibration frequency, water depth between liner and water Jacket surfaces vapour pressure, surface tension, initial pressure of the liquid, initial raduis of bubble, and the constant K which includes liquid density and speed of sound in the liquid. This equation is valid for vibratory cavitation. It can be used to predicte the inception bivration amplitude of cavitation at a given operating condition.

3. EXPERIMENTAL DETAILS

3.1 Experimental Equipment

The basic idea of the equipment is to vibrate a circular face of cylindrical piston in a given liquid contained in a beaker at a given vibration amplitude and frequency. These vibrations generate an acoustic pressure wave in the liquid. The acoustic pressure wave generated resulted in the formation of a cavitation bubble field in the depth between the face of the vibratory and the beaker base. These vibrations are produced in most cases by the magnetostriction oscillators. Since 1935 several investigators [16,17,18] have conducted these tests for investigating the phenomenon of cavitation damage.

The apparatus used for the present study is a simple vibratory in which the vibration frequency and amplitude can be varied independently. Figure 1. illustrates diagramatically the experimental arrangement. The vibratory was drived by a 500 Watts variable speed universal motor. The face diameter of the vibratory end was 25 mm. The maximum

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vibration frequency is of the order of 450 Hz. The operation of the engine may cause the cylinder wall to vibrate either at the speed of the engine or at its own natural frequency. The amplitude of vibration could be varied from zero to 7 mm. The vibratory end was mounted by an O-ring arrangement into a sealing flange so that the air space between water surface and flange can be pressurized as desired. An electric heater was mounted into the water container to maintain the water at the required temperature.

3.2. Tests Performed and Procedures

The tests were divided into a constant temperature sets for varying depth, frequency, and amplitude, constant pressures sets for varying amplitude, frequency with constant water depth and temperature. Six temperatures, ranging from 40 to 115 c°, four pressures, ranging from 1.033 to 3 Kg/cm^2 abs. and four water depth values ranging from 2 to 8 cm. were used. Table (1) shows the conditions used. The expected errors in measuring frequency, amplitude, depth of water and temperature of water are ± 3%, ± 5% , ± 1.5% and ± 2%, respectively.

Table (1) : Test Conditions

Temperature T, C°	Vapour Press P_v, Kg/cm^2 abs	Vessel Pressure P_o, Kg/cm^2 abs.	Water depth t, cm
40	0.075	1.033 1.5 2 3	2, 4, 6 & 8 4 4 4
55 70 80 100 115	0.16 0.32 0.59 1.033 1.72	1.033 1.033 1.033 1.53 2.2	2, 4, 6 & 8

Inception of cavitation refers to the first appearance of a cavitation zone and desinent the disappearance of cavitation. The conditions under which inception takes place are determined by vibration frequency and amplitude, water depth, physical properties of the liquid and temperature of liquid.

The temperature of the water in the vessel was maintained at the desired temperature by the electric heater. The vibration frequency was adjusted manually until the required frequency was reached. Visual observations using stroboscopic light through the transparent vessel started from an arbitrary vibration amplitude. The vibration amplitude then increased step by step until inception of cavitation occurred. As the vibration amplitude is increased cavitation occurs during a decreasing portion of the negative pressure part of the sine wave. The measurments of vibration amplitude and frequency and water temperature and depth corresponding to the inception were noted. These visual observations were repeated for many other frequencies, temperatures, water depths and pressures and the corresponding readings were determined. Tap water from laboratory of faculty of engineering, Menoufia University was used.

3.3 Pattern of Vibratory Cavitation

To the naked eye the cavitation produced by the vibratory apparatus is shown in Fig. 2 . These photographs show the commonly known cloud form of developed stage of cavitation at different operation conditions. Direct observations indicated that a mass of bubbles (i.e. cloud) appeared to radiate outwards. The cavitation bubbles believed to be produced radially are actually born with a vertically scattered distribution within a semi-spherical space. In the case of 2cm. water depth, Fig. 2, a cluster of bubbles appears on the center of the vessel bottom, which sometimes disappears again but mostly stays during the whole period of existence of the cloud.

In the inception stage where the cavitation bubbles just become visible to the naked eye, a few scattered bubbles are seen around the central region of the vibratory surface as shown in Figures 3 and 4.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The visual observations of cavitation inception were carried out for various operating conditions and are plotted against vibration frequency in Figures 5 to 11.

Figure 5 shows the effect of applied static pressure on the surface of water on the inception vibration amplitude at various vibration frequencies with a constant temperature of 40 C° and water depth of 4 cm. This figure shows that the inception vibration amplitude of cavitation is found to be strongly dependent on the vibration firequency and as the vibration frequency increases the vibration amplitude of cavitation inception decreases. It shows that for a given vibration frequency the inception vibration amplitude is indpendent of the static pressure acts on the surface of the water in the vessel. A possible explaniation for this trend is that the tensile strength of the water corresponding to inception of cavitation is independent of the static pressure to which the water is subjected and surface tension forces play great role on the tensile strength of water.

The variation of the cavitation inception amplitude with vibration frequency at fixed water depth is shown in figures 6 to 11 for temperature values ranging from 40 to 115 C°. In general, these figures show that the inception vibration amplitude of cavitation increases rapidly with decreasing the vibration frequency. This trend is reasonably confirmed by the acustic theory which indicates that the acustic pressure amplitude generated at the vibratory face is proportional to the vibration amplitude and the vibration frequency. Therefore, a certain level of vibration frequency and vibration amplitude is required to initate cavitation. The present trend is confirmed by previous published data[15, 18 , 20] . These previous published data showed that a certain value of pressure amplitude at the vibration frequency is necessary for the inception of cavitation.

The effect of temperature on the inception vibration amplitude of cavitation at fixed frequencies and constant water depth of 2 cm shown in figure 12 indicates quite clearly that the inception vibration amplitude of cavitation increases as the temperature of the water decreases. The consequences of increasing water temperature are to decrease the gas content, to increase the initial size of nuclei, to increase the vapour pressure and to change the speed of sound in the water. Previous researchers have predicted theoretically and shown experimentally that the critical pressure increases as the gas content decreases. For example Strasberg [21] showed that the threshold pressure for air-saturated water was about 2.5 atm rising to 6.5 atm in degassed water. Singer and Harvey[22] reported that the threshold pressnre for distilled water with a gas content of 19.5 ml^{-1} was 2.5 atm whilst a gas content of 6.1 ml^{-1} increased the threshold pressure to about 8 atm. When the attenuation of the acustic pressure wave is taken into account, it follows that for a law gas content, the region where the pressure amplitude is in excess of the threshold pressure is unlikely to extend to planes as distant from the radiating surface as would be the case for higher gas contents. With the increase in threshold pressure resulting from the reduction in gas content, cavitation occurs during a decreasing portion of the negative part of the pressure wave. It is evident that the threshold pressure increases with increasing the vapour pressure and with increasing the nuclei size which decreases the surface tension forces. Therefore, the increase in vapour and nuclei size with temperature and the gas content effects are all related to the decrease in the inception vibration amplitude with the increase in temperature at a given frequency and a given water depth.

Figure 13 indicates the variation of the cavitation inception vibration amplitude with water depth at fixed frequences and a constant temperature of 55 C°. This figure shows that the inception vibration amplitude of cavitation increases as the water depth increases. The reason for this is that the amplitude of the threshold pressure to initate cavitation is the sum of the amplitude of the acustic pressure wave and the amplitude of the reflected pressure wave from the vessel base. The factors affecting the amplitude of the reflected pressure wave at the vessel base are the water depth, the vibration amplitude and frequency, the attenuation of the acustic pressure wave and the physical properties of the water. Therefore, at a constant value of vibration frequency, the water depth has an effect on the cavitation inception vibration amplitude as a result of the wave reflections in the water.

5. COMPARISON BETWEEN MODEL AND EXPERIMENTS

Figures 5 to 13 show that the calculated cavitation inception amplitudes using equation (9) agree well with those measured for all the present data. It is intersting to note that the calculated cavitation inception vibration amplitudes have been obtained using R_o = 50 μm and $K = 4.05 \times 10^{-7}\ T^{4.4}$ in equation (9). K and R_o were estimated from the results. The agreement between the model and expriments mean that the roles played by vibration amplitude, vibration frequency, water temperature and water depth are in consistent with the present analyses. However, the analyses presented here are only a step towards better understanding the factors controlling the cavitation inception in vibratory system. These analyses showed that the phenomenon of cavitation inception is very complex and therefore several simplifying assumptions have been made according to the physics of the processes as currently understood. This is reflected in the derivation of the relationship (9). Therefore, the present model represent an addition, to knowledge in this aspect which could help the diesel engine designer to avoid cavitation in his engine provided that the operating conditions is similar to that reported herein.

6. CONCLUSIONS

The important conclusions which can be drawn from the basis of the foregoing study are :

1) The cavitation inception vibration amplitude was found to be independent of the static pressure of the water.
2) At certain value of water temperature and water depths, the cavitation inception amplitude was found to be strongly dependent on the vibration frequency. The general trend was that the cavitation inception vibration amplitude increased as the vibration frequency decreased.
3) At certain vibration frequency and water depth, the cavtation inception vibration amplitude increased as the temperature of water decreased.
4) The cavitation inception vibration amplitude increased as the water depth increased.
5) A theoretical model has been presented for the variation of cavitation inception vibration amplitude with vibration frequency, water depth and water temperature. The prediced cavitation inception vibration amplitude was in good agreement with the present expriments.
6) The results obtained have certainly raised some recommendations to help the designer of diesel engines for avoiding cavitation. These recommendations are :
   a- The vibration amplitude resulting from the piston slap should be kept below the cavitation inception vibration amplitude to prevent the appearance of cavitation.

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b- The cooling water temperature should be kept as low as possible.

c- The water depth between the liner and the water jacket surfaces should be increased to obtain an actual vibration amplitede below the cavitation inception amplitude.

d- A cooling liquid with a certain physical properties should be used (i.e., high viscosity, high impurties, low gas content).

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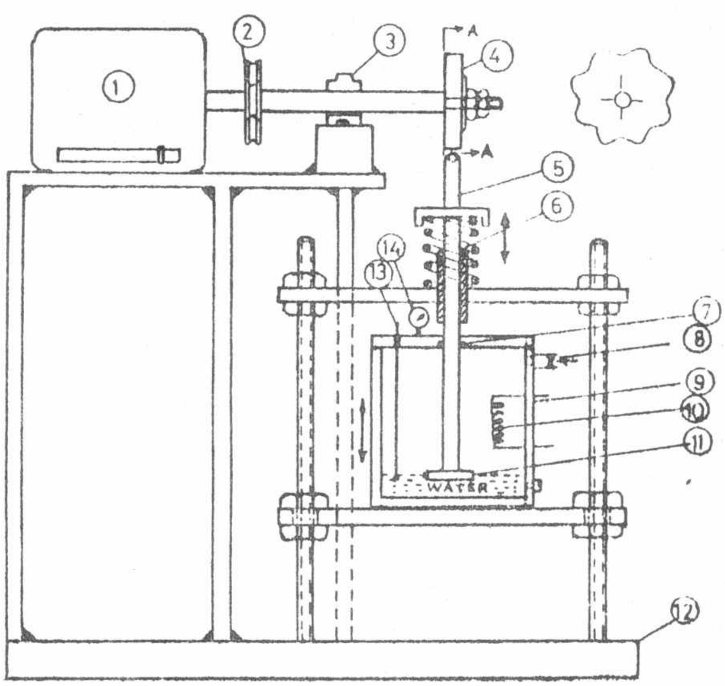


1. Electric motor
2. Pully (2.8 : 1)
3. Bearing
4. Cam
5. Vibratory
6. Spring
7. O- ring
8. Compressed air supply
9. Transparent vessel
10. Electric heater
11. Vibratory end
12. Frame
13. Thermocouple
14. Pressure gauge

Fig. 1. Diagrammatic arrangement of experimental vibratory apparatus.

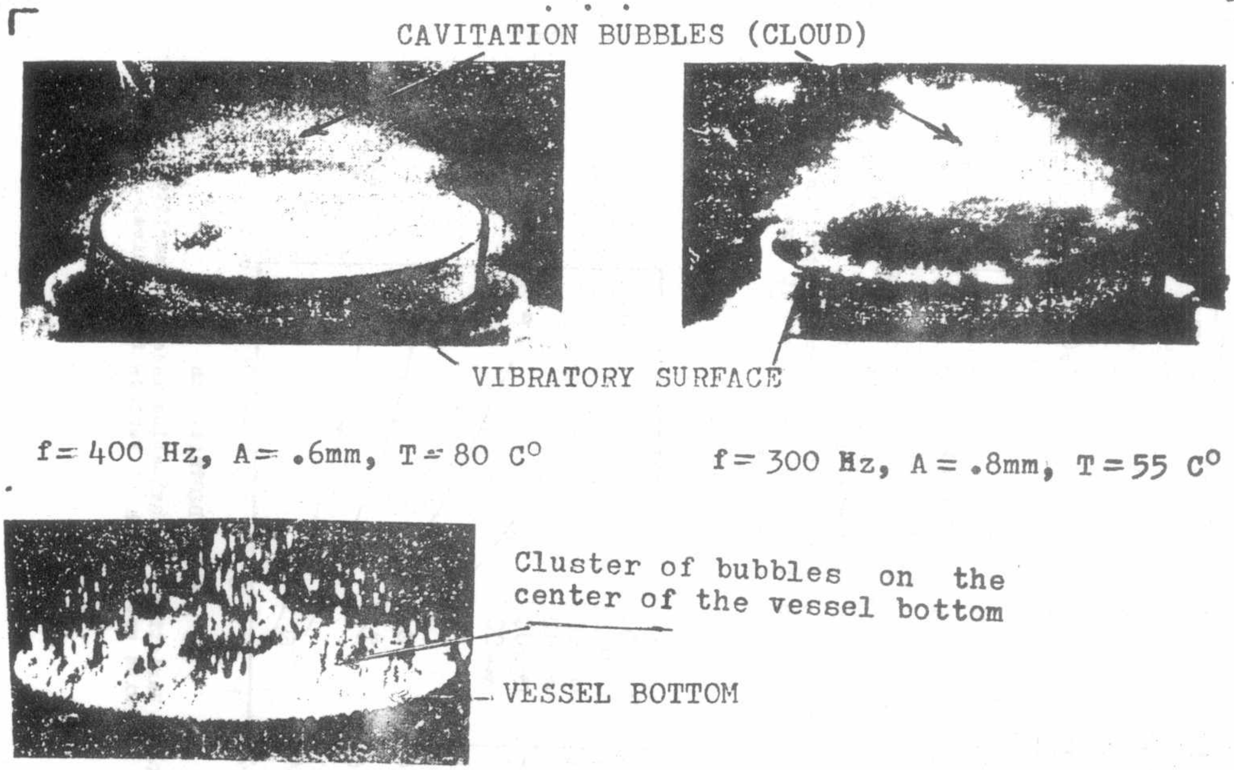
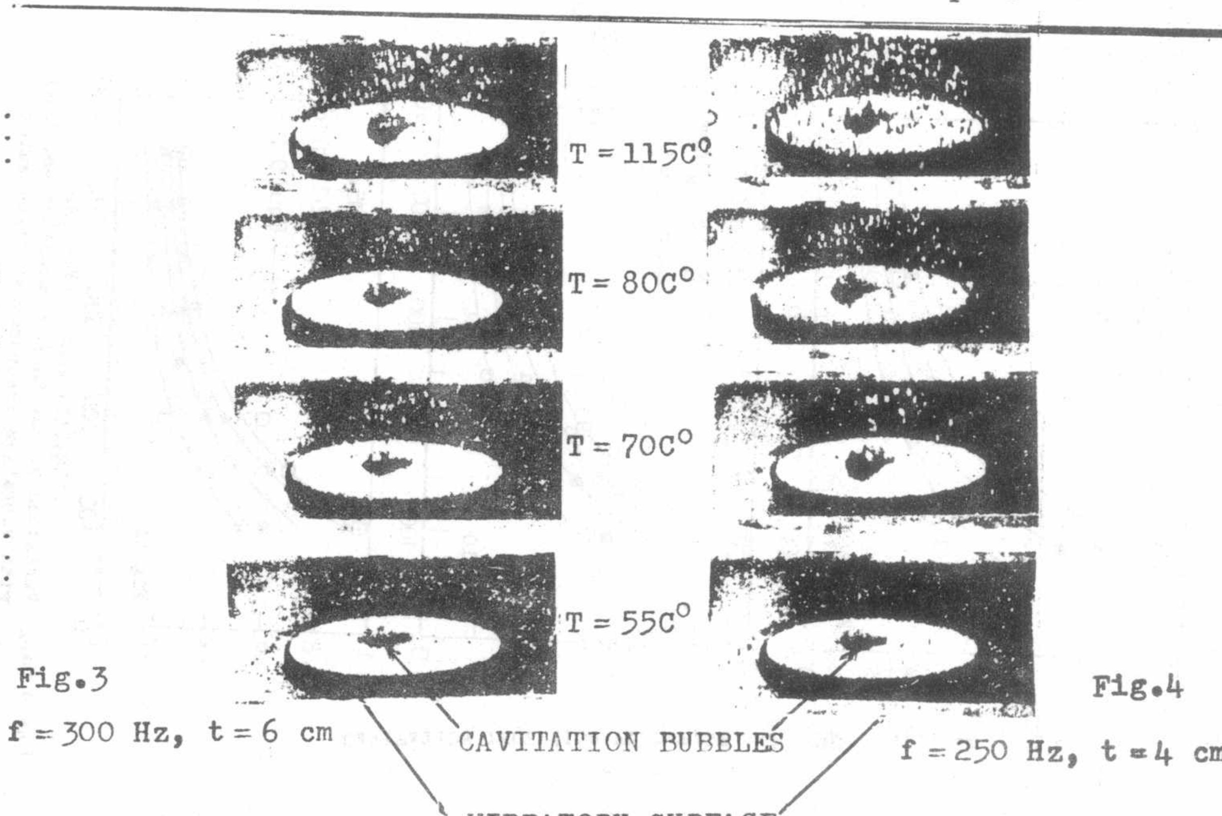


Fig.2: Potographs of developed cavitation on vibratory surface and on the vessel bottom at 2 cm water depth.



Figs.3&4: Potographs of inception cavitation around the central region of the vibratory surface at various conditions.

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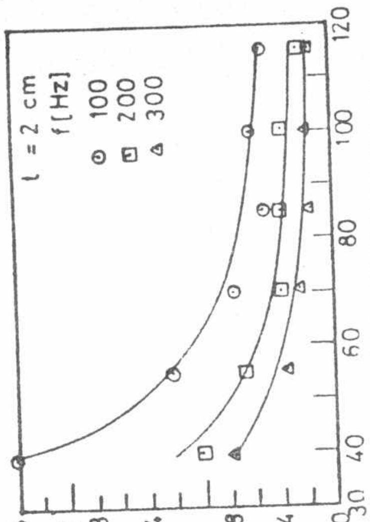


Fig.12. Variation of cavitation inception vibration amplitude with water temperature at fixed vibration frequencies.

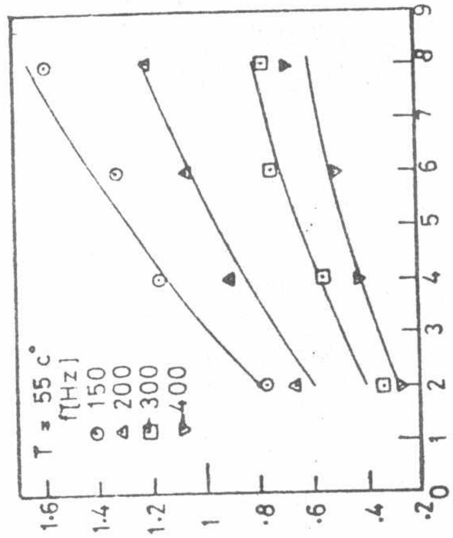
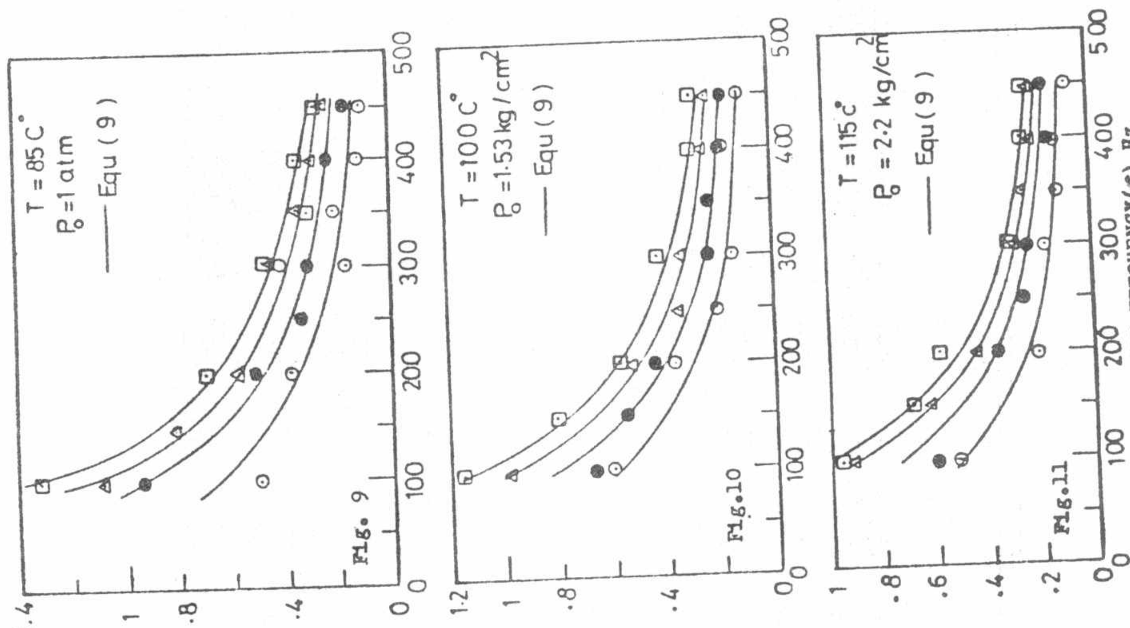


Fig.13. Variation of cavitation inception amplitude with water depth at various frequencies.



Figs 9 toll. Variation of cavitation inception amplitude with vibration frequency at fixed water depths: ⊙,2; ●,4; △,6; ⊡,8 cm.

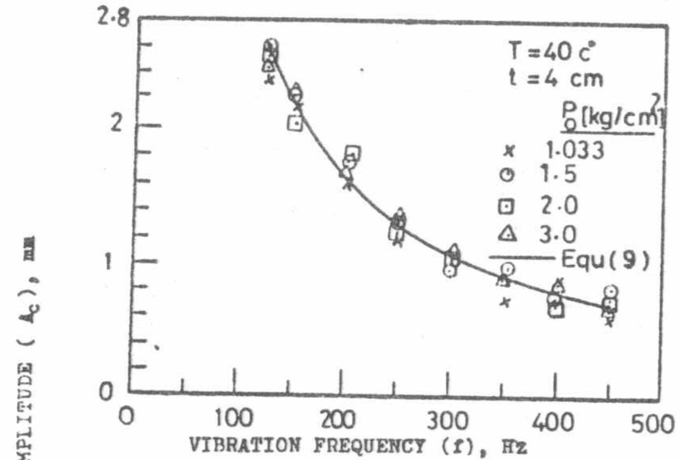


Fig.5. Variation of cavitation inception vibration amplitude with vibration frequency at various vessel pressures.

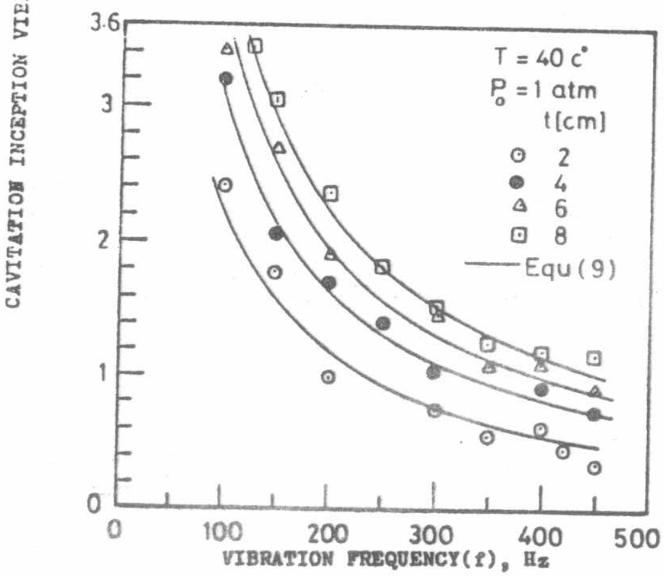
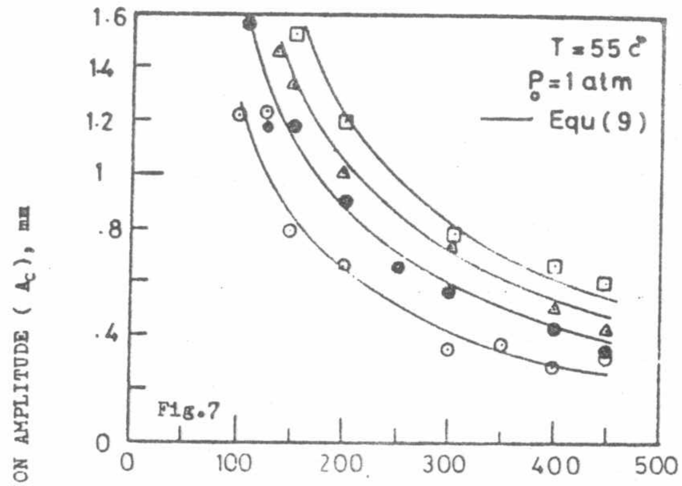
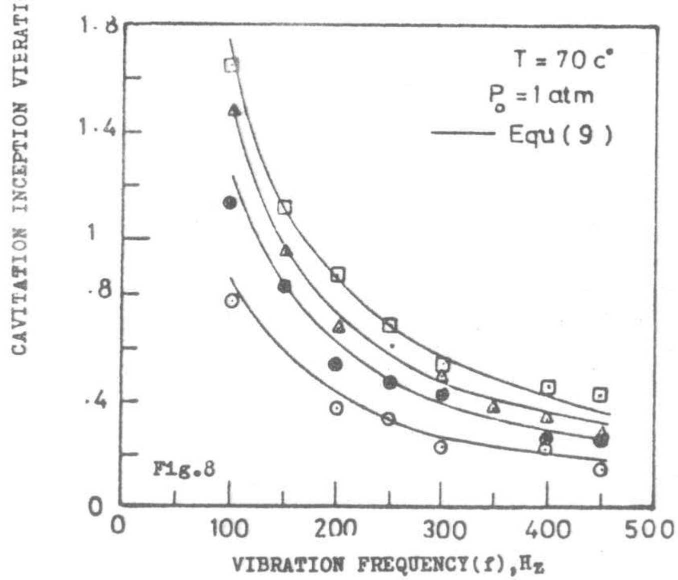


Fig.6. Variation of cavitation inception vibration amplitude with vibration frequency at various water depths(t).





Figs 7&8 . Variation of cavitation inception amplitude with frequency at various waterdepths: ⊙, 2 ; ●, 4 ; △, 6 ; ⊡, 8 cm.