Vol 17 No 7, July 2008
1674-1056/2008/17(07)/2580-10
Chinese Physics B
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The pressure field in the liquid column in the tube-arrest method*

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(Received 12 December 2007; revised manuscript received 29 January 2008)

We have been using the method of tube-arrest as a means of producing transient single cavitation bubble. In the present paper we seek to comprehend the mechanism of production and inquire into the structure of the *ab initio* pressure field in the arrested liquid column. The generated pressure wave is shown by combining the theoretical analysis with the experimental observation to be a slightly varied version of water hammer. With relatively clean liquid, the magnitude of the tension peak generating the TSB is likely to reach of several millions Pa. It is also shown that the so generated cavitation bubble originating from the gas-containing bulk liquid is in 'violent' motion.

Keywords: tube-arrest method, original pressure wave, water hammer, origin of violent cavitation bubble

PACC: 4755B, 6260

1. Introduction

The tube-arrest method[1] was first proposed by Chesterman[2] in 1951. Schmit[3] introduced a seeded bubble nucleus in 1954. Wang and Zhang in 1964[4] and 1966[5] followed this modifying procedure to produce large transient single bubbles (TSB) in several liquids, photographed the bubble growth and inspected their luminescence. Overton and Trevena *et al* in 1981[6] and 1984[7] applied this method to creating a tension pulse in a water column and gave an explanation for the oscillating nature of the observed pressure field in terms of the behaviour of cavitation bubble collapse. In 1996[8] and 1997[9], Williams *et al* obtained the detailed structure and gave an improved explanation for such a pressure field. Trevena *et al* are interested and successful in using this method to determine the tensile strength of liquids.

In the past few years we have applied this method that is modified by introducing seeded nucleus to the study of behaviour of the cavitation bubbles. Following the idea in Ref.[6], we use a monitoring transducer that is, however, simply a small piezoelectric plate with a thickness of 0.09cm and a diameter of 1.03cm, mounted on the outside surface of the tube bottom. The main part of our experimental set-up is shown in Fig.1. The inner diameter of the glass tube is 2.5cm. Other details may be found from Ref.[10].

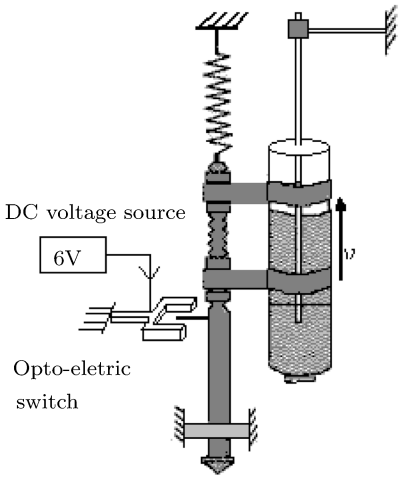


Fig.1. The main part of our experimental setup.

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From our earlier reports, Ref.[10] and an unpublish work,[1)] it can be found that the transient single bubbles (as against the stable single bubble SSB[11]) generated by the tube-arrest method are all luminescent in the various liquids we studied, including glycerin and high viscosity silicone oil. This situation is very different from that associated with the usual stable single bubbles, which is at least at low acoustic intensities.[12,13]

Among the liquids we studied, ethylene glycol and 1,2 propylene glycol gave rise to single bubbles which could be one order of magnitude brighter than those produced in the other liquids. Furthermore, the intensity of luminescence of TSBs in ethylene glycol showed a consistent increase to some rough maxima and decrease to some rough minima correspondingly when the glass tube was repeatedly pulled and arrested.

In order to comprehend these phenomena, to disclose more features of the TSBs and to understand more of the nature of the method we are using, we seek, in the present paper, to look into the original pressure field in the liquid column that generates the TSB. By 'original' we mean the pressure field that has existed before the appearance of the cyclic pressure and tension record that was well studied in Refs.[6–9] and that is often observed in our own early experiments also.[10] Figure 2 shows two examples of our version of the pressure wave of this type which we call 'type-2'. Reference [9] exhibits an apparently more refined record, which possibly resulted from a transducer arrangement different from ours. References [7, 9] ascribed the occurrence of this type of pressure wave to the inception of a cavitation bubble. What we try to find is then the 'original' pressure field before the appearance of any such a 'cavitation bubble' in the arrested tube.

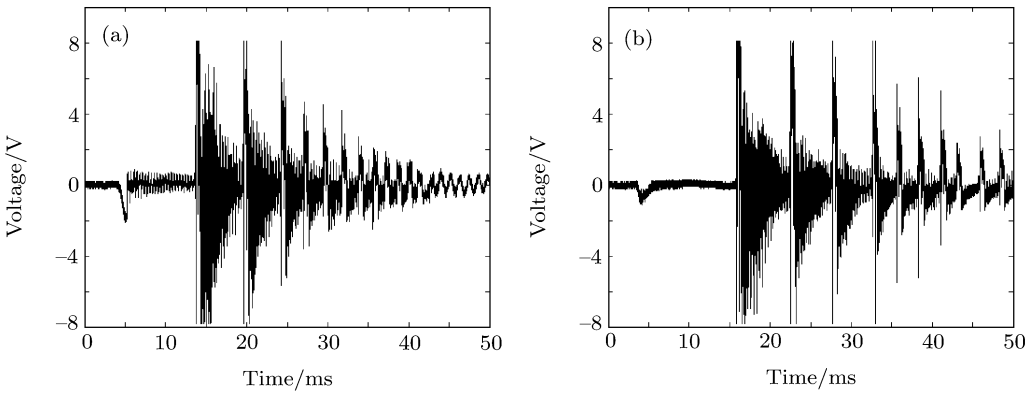


Fig.2. Some examples of the (type-2) pressure wave in water after origination of a 'cavitation bubble' without (a) and with (b) a seeded nucleus.

2. Theoretical prediction with a simple model

We start with a straightforward theoretical prediction of the pressure field as produced in an arrested liquid column. We shall use a simple model of the involved liquid; by 'simple' we mean that the liquid is assumed to be a single-phase continuous medium. Refinement of the liquid nature will be discussed later.

Consider the liquid column in a vertical glass tube. Let x denote the vertical height measured from the bottom of the liquid column which is also the bottom of the glass tube. The equation of motion of the liquid is then

$$\frac{\partial^2 Y(x,t)}{\partial t^2} = c^2 \frac{\partial^2 Y(x,t)}{\partial x^2} - g, \tag{1}$$

where $Y(x,t)$ is the displacement of the liquid element. The boundary values of $Y(x,t)$ are

$$\begin{cases} Y(0,t) = 0, & \text{(2a)} \\ -E_x \dfrac{\partial Y}{\partial x}(L,t) = P_{\mathrm{u}}, & \text{(2b)} \end{cases} \quad \text{for} \quad t > 0,$$

and its initial values are

$$\begin{cases} Y(x,0) = 0, & \text{(3a)} \\ \dfrac{\partial Y}{\partial t}(x,0) = V, & \text{(3b)} \end{cases} \quad \text{for} \quad 0 \le x \le L.$$

In Eq.(2b), L is the height of the liquid column, P_u is the gas ullage pressure over the surface of the liquid,

[1)] We also studied briefly TSB in some aprotic liquids, acids and alkalis. The results were presented orally in WCU-UI 2995, Beijing but not submitted in written form.

E_x is the effective longitudinal modulus of elasticity of the liquid column,[14]

$$E_x = \frac{B}{1 + \frac{B}{\frac{s}{d}E}}, \tag{4}$$

where B is the bulk modulus of the liquid and $\frac{s}{d}E$ the stiffness of the tube wall, of which the Young's modulus is E, s the thickness while d the diameter of the cylindrical tube. In Eq.(1), c is the wave speed in the liquid

$$c = \sqrt{\frac{E_x}{\rho}}, \tag{5}$$

where ρ is the liquid density. In Eq.(3b), V is the speed of the tube at the instant of arrest.

This boundary value problem can be solved through the conventional procedure of applying the variable separation method and the Fourier series expansion (see, for example, Ref.[15]). Thus, the solution for the displacement $Y(x,t)$ can be shown to be

$$Y(x,t) = u_0(x) + u(x,t) \tag{6}$$

with

$$u_0(x) = \frac{\rho g}{2E_x}x^2 - \frac{1}{E_x}(P_{\rm u} + \rho g L)x \tag{7a}$$

and

$$u(x,t) = \frac{8LV}{\pi^2 c}\sum_{i=1,3,5,\ldots}^{\infty}\frac{1}{i^2}(\sin\frac{i\pi}{2L}x)\left(\sin\frac{i\pi c}{2L}t\right), \tag{7b}$$

for $0 < x < L$, $t > 0$, while the solution for the pressure $P(x,t)$ is

$$P(x,t) = -E_x\frac{\partial Y(x,t)}{\partial x} = p_0(x) + p(x,t) \tag{8}$$

with

$$p_0 = P_{\rm u} + \rho g(L - x) \tag{9a}$$

and

$$p(x,t) = -\frac{4V}{\pi c}E_x\sum_{i=1,3,5,\ldots}^{\infty}\frac{1}{i}\left(\cos\frac{i\pi}{2L}x\right) \times \left(\sin\frac{i\pi c}{2L}t\right). \tag{9b}$$

An example of the numerical solution is given in Fig.3 for the pressure wave at several values of x in water in a glass tube with L=0.4m. The other parameters are taken to be E_x=2.20×10^{9}Pa, V=0.8m/s, c=1.5×10^{3}m/s, and P_u=1.01×10^{5}Pa. It may be added that in practice, if the effects of tube friction and fluid damping are included, the pressure wave will

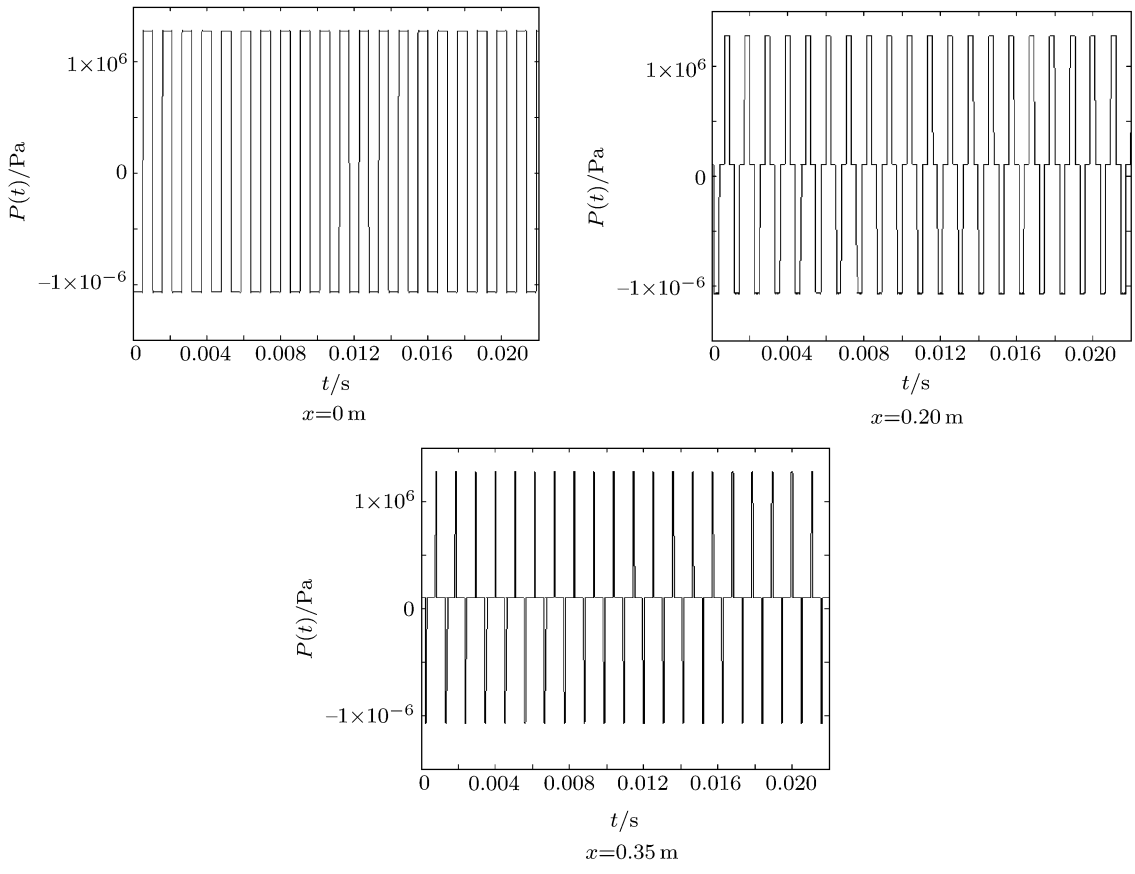


Fig.3. Theoretically predicted pressure wave as a function of t at several different values of x, with L=0.4m.

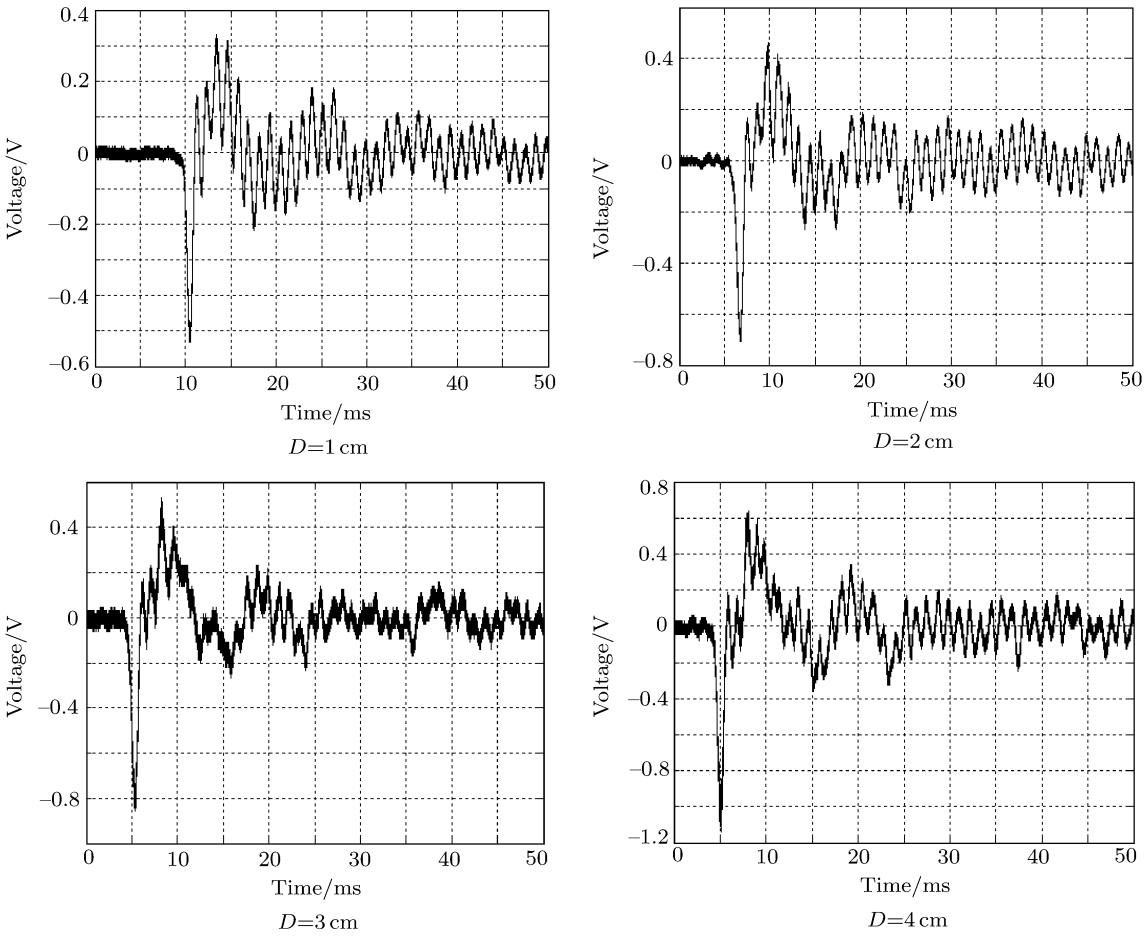
decay with time; furthermore, if the tube is not instantaneously arrested as assumed in Eqs.(3a) and 3(b), the wave cycle will depart from the rectangular form.

On examining the plots in Fig.3, one may note that they are very similar to those of the pressure wave in a water hammer well known in hydrodynamics (for example, see Ref.[16]) except that here, initially the negative pressure peak leads the positive. Physically, the similarity is understandable if a vertical pipe is used for the water hammer and the flow on the outlet side of the instantaneously closed valve is studied. Instead of the liquid pushing against the closed valve, the liquid now rushes away from it but will later surge back. So it may be said that the tube-arrest apparatus acts as a varied version of water hammer.

3. Experimental findings on the 'original' pressure wave

3.1. The experimental pressure wave

After many trials including a slight change of the structure of the tube stop to ensure as much as possible the instantaneous arrest of the tube, we have obtained consistently a new form of the pressure wave in the arrested tube, very different from the form which used to show up in the earlier days as illustrated in Fig.2. This new type of waveform can now be procured regularly by controlling the following two factors: (1) the degree of cleanliness of the liquid (water or ethylene glycol in this paper), and (2) the magnitude of tension applied to the liquid, which can be regulated by adjusting the distance D of pulling down the glass tube before releasing it to be arrested suddenly by the tube stop. In fact, the two factors are complementary; the cleaner the liquid, the larger the value of D which can be used, and vise versa. An example of a series of pressure waves of the new type in water is displayed in Fig.4. The waves are monitored by a small piezoelectric plate mounted at the bottom of the glass tube, and therefore they correspond to $x \approx 0$. For Fig.4, the filtered (0.2–0.3μm pore size) tap water is first degassed in a glass container at 1000Pa for 6h and then transferred to the glass tube and re-degassed at 1000Pa for 1h. The glass container and the glass tube have been both cleaned beforehand.



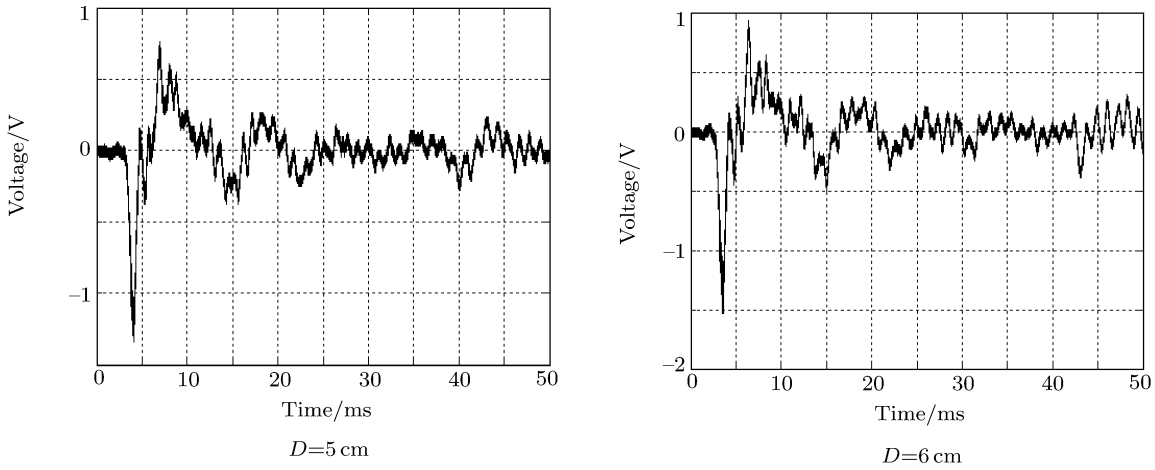


Fig.4. A series of experimental 'original' ('type-1') pressure waves in water for various values of D and L=40cm.

From now on, we shall call the type of wave illustrated in Fig.4 the 'original' or 'type-1' pressure wave because it is obtained before the origination of the cavitation bubble and the appearance of the type-2 wave. A similar pressure record as displayed in Fig.4 has been obtained in ethylene glycol, but it is not shown here.

3.2. Two important wave parameters

The pressure wave which actually develops in experiment, shown in Fig.4, appears to differ from that theoretically predicted as shown in Fig.3. Differences in feature between the two kinds of wave are not unexpected, for example, the departure of single tension-pressure cycle from the rectangular form may be caused by the departure of the actual tube arrest from instantaneousness. Here, we first try to find, instead, some features which inherently agree between the two kinds of pressure waves, theoretical and experimental. Later we shall discuss possible reason for the disagreement in the waveforms.

3.2.1. The wave frequency

We study the wave frequency f and measure or compute its variation with L, the height of the liquid column, for relatively clean water and ethylene glycol. The actual degree of cleanliness is not very critical as long as the combination of this degree and the value of D is kept within the limit of having the wave of type-1 generated. The results are shown in Figs.5(a) and 5(b).

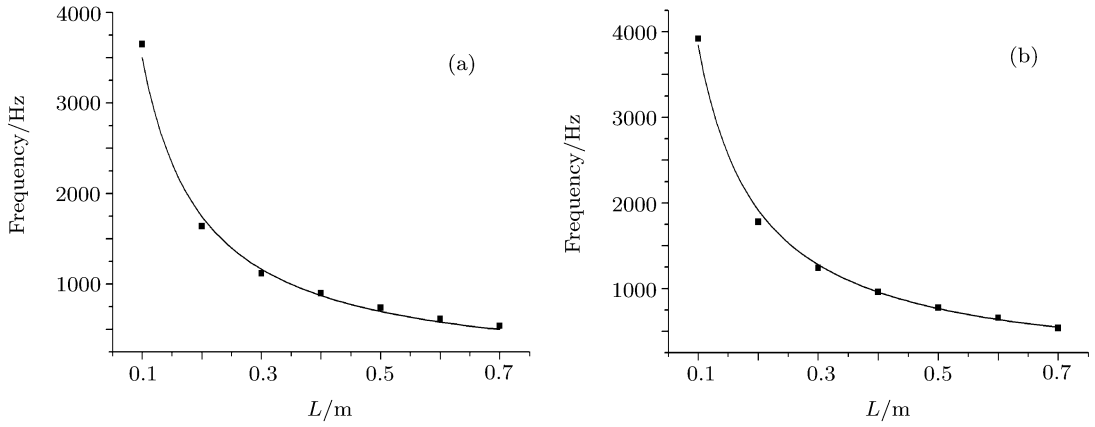


Fig.5. Experimental curves f versus L for (a) water and (b) ethylene glycol.

From the figure it is seen that the experimental variation follows the theoretical relation $f = c/(4L)$ and that the experimental curves determine the sound speeds for water as 1415m/s and for ethylene glycol as 1541m/s from which the measured values of c are reasonable (presently T=27°C).

3.2.2. The first tension peak

In all the numerous records of the experimental 'original' pressure wave so far obtained by us, the most outstanding peak is the very first tension peak that has the largest magnitude T_1 among all the peaks. Furthermore, as will be seen below, this first tension peak of the type-1 pressure wave continues into the type-2 pressure wave.

The magnitude T_1 increases clearly with the value of D increasing. Some examples of the variation of this magnitude T_1 with D are shown in Fig.6 respectively for water and ethylene glycol at different degrees of liquid cleanliness.

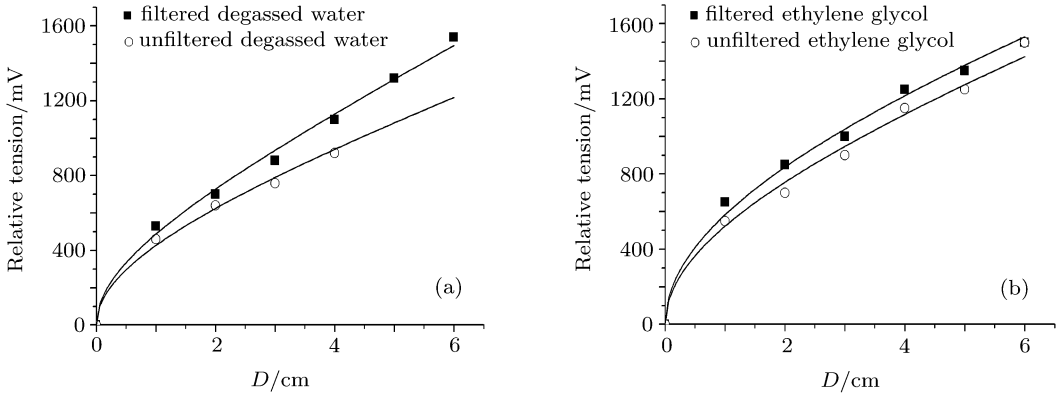


Fig.6. Variations of the magnitude of the first tension peak T_1 (mV) with D, in (a) water and in (b) ethylene glycol at two degrees of cleanliness of the liquid, with L=40cm.

In Fig.6 the magnitude of T_1 is specified in units of 'mV' because it is measured by the piezoelectric plate at the bottom of the glass tube. We have tried to transform it into the proper units of 'Pa' at first by using a commercial hydrophone immersed in the liquid, but we found that in the pulling and arresting process, bubbles always originated from some minute crevices of the hydrophone. Next we used a home-made small hydrophone, inserted it into a small glass tube, calibrated the glass-tube-sealed hydrophone and used it to measure the developed tension. To be true, bubbles did not evolve but there was an indication that the presence of the hydrophone disturbed the expansion of the liquid and thus reduced the reliability of measurement.

As an alternative, we determine T_1 from the theoretical relation

$$T_1 = P\left(0, \frac{L}{c}\right) = P_{\mathrm{u}} + \rho g L - \frac{V}{c} E_x, \qquad (10)$$

in which $P(x,t)$ is given by expression (8), x is taken to be 0 while t_1 is taken to be L/c. For c in the equation we use the value determined from the f versus L curve in Fig.5, and for V we measure it by using a speed meter with a probe seated on the side of the up-moving glass tube containing the liquid. The measured V versus D for water with L=0.4m is given in Fig.7(a), and the corresponding T_1 versus D curve with T_1 measured in 'Pa' is shown in Fig.7(b). And for the filtered degassed water the curve is described in Fig.6(a). Precisely speaking, the value of T_1 in the experimentally determined pressure wave is consistent with that in the theoretically predicted only if in the real experimental process, and the first tension peak of magnitude T_1 has not lost any energy. Judging from the multiplicity of curves in Fig.6 for different degrees of cleanliness of the liquid, one may infer that the theoretical T_1 in Fig.7 is an upper limit which is closer to the real value, when the liquid is cleaner. Some more discussion will be made in a later section.

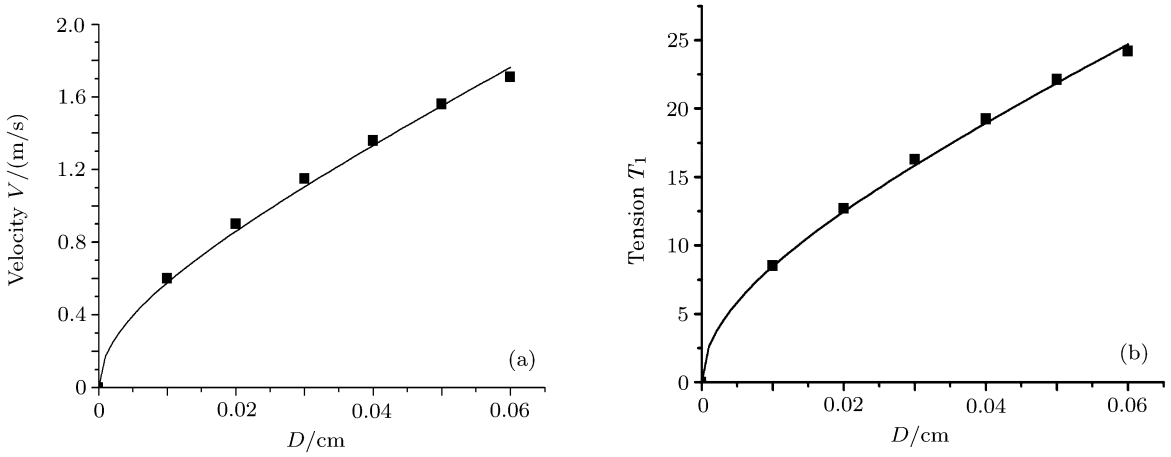


Fig.7. Experimental V versus D curve (a) and semi-theoretical T_1 versus D curve (b), for filtered and degassed water of Fig.6(a) L=0.4m. Here T_1 is in '10^5Pa'. According to the theory for a spring, the V versus D curve is theoretically expected to be a branch of a hyperbola passing through the origin.

3.2.3. Some more relevant measurements

We also made two more measurements, firstly on the variation of T_1 with the height measured in the liquid column and secondly on the variation of the time of start of the initial pressure wave with the measured height. Since the glass-tube-sealed hydrophone has to be used, the results of measurement are rather crude but they do show the trends. It may be said that the experimental results indicate respectively a decrease of T_1 and a barely perceptible delay of the time of start, with the height of the hydrophone in the liquid column.

4. Transition of the pressure wave from type-1 to type-2

It has been mentioned above that for a specific degree of cleanliness of liquid, one can obtain the pressure wave of type-1, up to a certain value of D, i.e. up to a certain value of the applied tension T_1. Now if some threshold of D is surpassed, the pressure wave will automatically transform from type-1 to type-2. Without a seeded nucleus, the type-2 pressure wave actually may have the waveforms slightly different from that shown in Fig.2(a), of which some examples of which are illustrated in Fig.8.

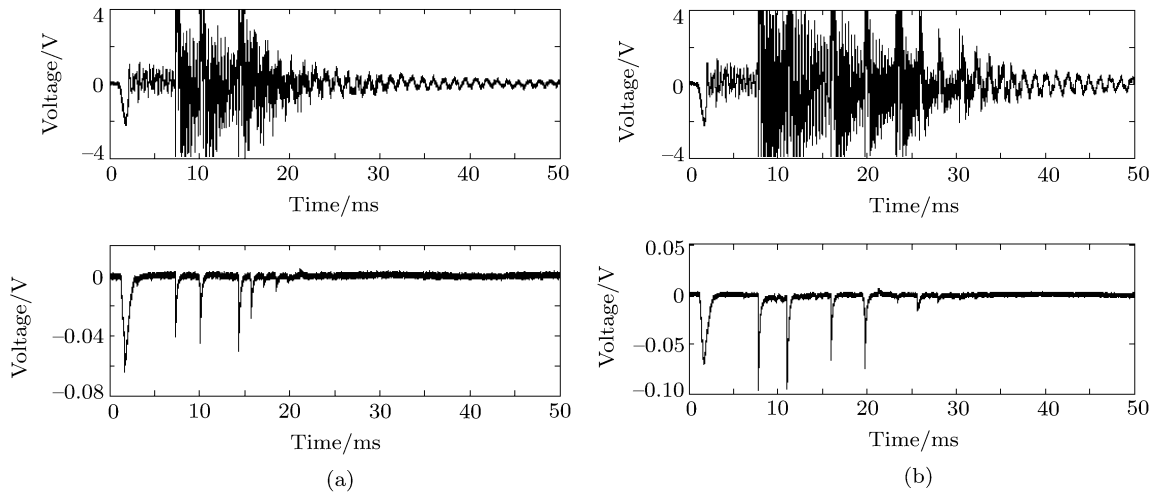


Fig.8. Some examples of the pressure wave of type-2 generated in water without the seeded nucleus and their accompanying luminescences, with (a) water degassed for 6h and the value of D being 4cm; (b)water degassed for 8h and the value of D being 4.5cm.

Also as mentioned earlier, it is generally conceded that the type-2 pressure wave is a product of newly incepted cavitation bubble generated in the liquid by an initial tension pulse. The cavitation bubble grows up till it collapses violently. We therefore take high-speed photographs of the possible bubble (Photron FastCan Super 1Q K series CCD Camera) and also measure its luminescence with a photo multiplier tube (PMT) (Hamamatu R212), near the base of the liquid column. The measured luminescences accompanying the pressure waves are also shown in Fig.8. An example of the high speed photographs will be displayed later in the following section.

Before leaving the subject of transition between the wave types, we may mention briefly two relevant observations. One is that for a sufficiently large value of D, the repeated stressing of the liquid at a constant D may induce the transition from type-1 to type-2 even though at the same level of D the transition did not occur earlier. In fact, the threshold of D for the transition between type-1 and type-2 depends on the times of stressing at various levels of D and very possibly also on the interval between stressings. The other observation is that close to the transition threshold of D, the pressure wave, after transition from type-1 to type-2, may return, on the next stressing, back to type-1.

5. Discussion

We here focus our attention on the following three points.

5.1. Departure of the theoretical waveform of the type-1 pressure wave from the experimental

The theoretically computed waveform of the type-1 pressure wave illustrated in Fig.3 is evidently different from the experimentally observed one illustrated in Fig.4. This may be caused by the simplification that in the theoretical prediction the liquid has been assumed to be a single-phase continuous medium. In practice, the liquid is filled with nuclei. In the tension cycles, nuclei of appropriate sizes will cavitate and while the bubbles expand, the tension peaks will be annihilated.[17,18] This explains the deficiency of the tension peaks in the experimental type-1 pressure wave in the early stage compared with the theoretical result. The very first tension peak at the start of the pressure wave is an exception in that it seems to be always not seriously affected. Likely this is because a finite time, probably of duration less than L/c, is required for a bubble to start growing with a sufficient tension applied.[19]

A more quantitative approach would be to change, in the theoretical computation, the model for the liquid, from a single-phase medium to a liquid containing small gas bubbles, such as that described in Ref.[20].

5.2. The nature of the 'cavitation bubble' which induces the type-2 pressure wave

It has been stated above that the type-2 pressure wave is generally considered to be a consequence of the inception of the 'cavitation bubble'. Now it is also stated that during the generation and propagation of the type-1 pressure wave, some cavitation bubbles are incepted, as evidenced by the annihilation of the tension cycles of the pressure wave. Comparing the waveforms of the type-1 and the type-2 waves, one can see that the behaviours of the cavitation bubbles in the two types of waves significantly differ from each other. In the type-2 wave, the cavitation bubble induces (Fig.8) possibly harmonic components during its growth and then induces violent shock waves as well as emits light flashes during its rebound. On the other hand, the cavitation bubbles in the type-1 wave are much quieter. Measurements with PMT also indicate no light emission from the type-1 wave at the tube bottom (x=0) except at the instant corresponding to the first tension peak. See the next section (section 5.3) below. Williams *et al*[9] came to a conclusion that cavitation bubbles in type-2 wave were single, isolated spherical cavitations in the bulk liquid. We took sequentially the high-speed photographs of the cavitation bubbles generated, of which one example is shown in Fig.9. We are inclined to take the view that the 'cavitation bubble', which may crudely be named the 'violent' cavitation bubble, belongs either to the kind formed from 'homogeneous nucleation'[21] or to the kind called by us 'fresh' bubble[22] which is produced from within the gas-dissolving liquid, near the neighbourhood of the bubble monitor. The critical condition or conditions for the inception of the violent cavitation bubble remains to be examined. It is also uncertain whether more than one single cavitation bubble can be generated by the initial tension peak during the transition of the pressure wave from type-1 to type-2.

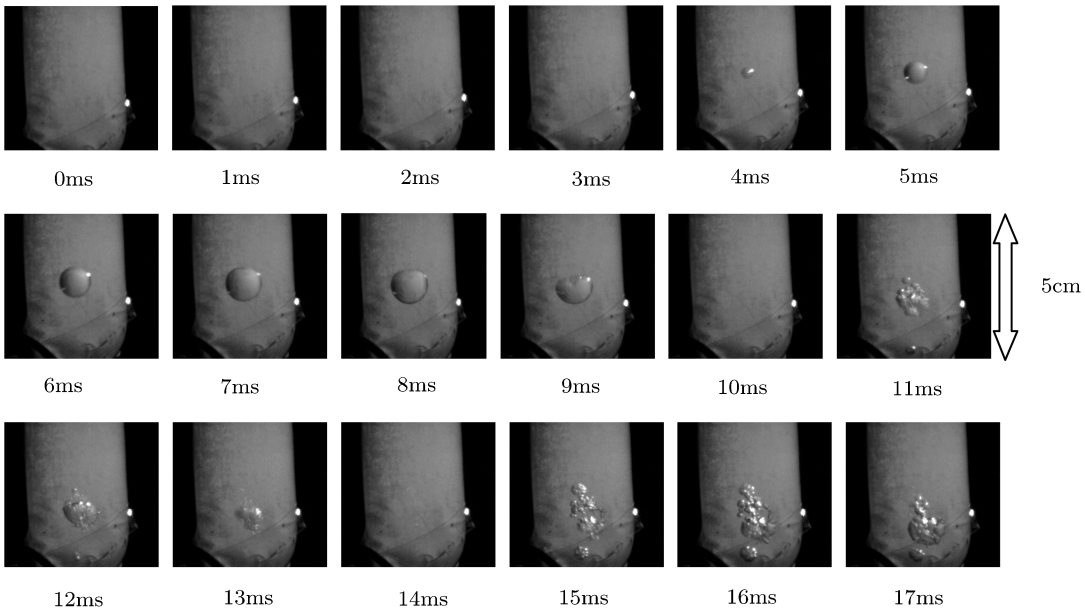


Fig.9. Example of sequence of high speed photographs of the 'violent' cavitation bubbles near the tube bottom. The camera is triggered when the tube is arrested. The height of water column is 40cm; the value of D is 3cm. The tiny white spots in the picture are due to light reflection from the glass tube.

5.3. Origin of the luminescence accompanying the first tension peak

Our attention is also paid to the luminescence accompanying the first tension peak in the type-2 pressure as shown in Fig.8. Many more records of such a luminescence have been obtained in our study. We also have records (not displayed here) of luminescence accompanying the first tension peak in the type-1 pressure wave under certain conditions. Since the luminescence is ascribed to the collapse of a bubble, we can interpret such a display of luminescence as being due to the generation, growth and final collapse of a tiny micro-bubble, (possibly with a radius as small as or smaller than 10^{-7}m) induced by the initial tension peak. It is quite possible that such a tiny micro-bubble is a fresh cavitation produced from within the liquid. Whether it is the origin of the 'violent' cavitation bubble is not known.

Based on the above points of view, a comparison between the present method of tube-arrest for generating TSB and the well-known method of levitation for generating SSB may be made. The TSB is generated from some nucleus or simply from the bulk liquid by a tension peak of very high magnitude (usually several millions Pa) while the SSB is generated from a pre-existing nucleus by continuous acoustic wave (with a pressure amplitude formerly around 10^5Pa, but lately around 10^6Pa). The optical spectrum of the TSB has not yet been measured because we lack for an appropriate means and yet line spectra in addition to featureless continuum would be expected.

6. Conclusion

We have sought to find the 'original' pressure field generated in the liquid column contained in an arrested tube, that is, the pressure field which has existed before any 'violent' cavitation bubble is incepted by the tension pulse created by the tube arrest. We have shown that the original pressure field behaves like a vertical water hammer with a high tension amplitude (possibly 10^6Pa) in a liquid filled with cavitation nuclei. Attention is also paid to the nature of the 'violent' cavitation bubble produced by this special pressure field in a relatively clean liquid as well as to the origin of the light emission intimately accompanying the initial tension peak.

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