CHAPTER
ONE

INTRODUCTION

Cavity is a learned word . . . it
denotes hollowness or empty space.

Webster's Dictionary

1.1 HISTORY

Newton,[1] in his *Optiks* in 1704, was the first person to record the observation of cavitation in the low pressure region formed between rolling surfaces. He was examining Newton's rings formed between a convex lens and a plane glass surface and says:

> When the Water was between the Glasses, if I pressed the upper Glass variously at its edges to make the Rings move nimbly from one place to another, a little white Spot would immediately follow the center of them, which upon creeping in of the ambient Water into that place would presently vanish.

Newton goes on to say:

> Its appearance was such as interjacent Air would have caused, and it exhibited the same Colours. But it was not air, for where any Bubbles of Air were in the Water they would not vanish. The Reflexion must have rather been caused by a subtiler Medium, which could recede through the Glasses at the creeping in of the Water.

Newton apparently did not realize that this effect was due to air coming out of solution under the action of the reduced pressure and then redissolving. Skinner[2] has found that this effect is much more pronounced with a more viscous liquid like glycerine or lubrication oil. When these are illuminated with oblique light quite large vacuous spaces, frequently broken up into a number of small bubbles, are obtained (Fig. 1.1). He found that an even better technique is to use a deeply coloured liquid, such as a strong solution of fuchsin in glycerine, with transmitted light. This red solution is so deeply coloured that even up to the point where the lenses are nearest some colour shows, and that light is only brightly transmitted at the place where there is a break in the liquid.

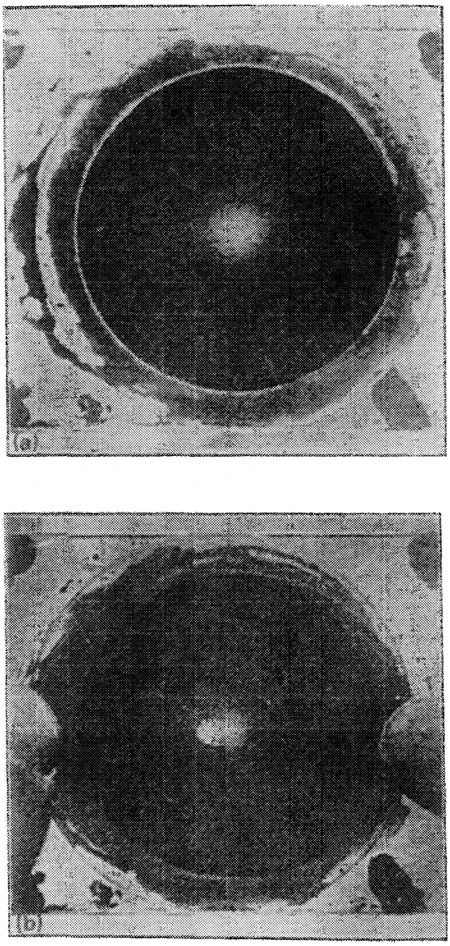

Figure 1.1. (a) Convex lens lying on a plane with fuschin–glycerine solution between them (transmitted light). (b) The same lens being rolled (transmitted and reflected light). (Skinner.[2])

The tendency which the screws of steamships have, in certain circumstances, to 'lose their hold' on the water and consequently to let the engines race had mystified engineers in the nineteenth century, although Euler[3,4] had anticipated this in 1754 in his work on the theory of turbines. Reynolds[5] in 1873 investigated the problem by a classic series of experiments with a model boat 30 inches long having a screw 2 inches in diameter driven by a spring. Reynolds showed that the racing could occur even when no part of the screw was exposed to the air, but that provided the screw was deep enough no racing occurred. He concluded that the admission of air behind the blades of a propeller will reduce the power of the propeller to supply itself with water.

A famous case, where the performance of a ship was well below her design speed of 27 knots, occurred in 1893 in the trials of the destroyer HMS *Daring*. Barnaby and Parsons[6] traced the reduced speed to poor propeller performance due to the formation of water vapour bubbles on the blades. Shortly afterwards the first turbine ship, the *Turbinia*, met similar difficulties. Parsons[7] realized that:

> The excessive slip of the propellers beyond the calculated amount and their inefficiency, indicated a want of sufficient blade area upon which the thrust necessary to drive the ship was distributed – in other words, the water was torn into cavities behind the blades. These cavities contained no air only vapour of water, and the greater portion of the power of the engine was consumed in the formation and maintenance of these cavities instead of the propulsion of the vessel.

Barnaby and Parsons[6] and Barnaby and Thornycroft[8] wrote papers describing this phenomenon and pointing out that the propellers created voids and clouds of bubbles when the lowest pressure round the blade dropped to a particular value. Barnaby and Thornycroft[8] say in their paper that '"*Cavitation*", as Mr Froude has suggested to the authors that the phenomenon should be called, appears to manifest itself when the mean negative pressure exceeds $6\frac{3}{4}$ pounds per square inch'. This is the first time that the word 'cavitation' appears in the literature.

Parsons' experience with the *Turbinia* trials had led him to experiment. First he worked with a saucepan of hot water on a stove, and then with a 12-in diameter closed tank containing a side window.[9] A later tank, built in 1895,[4,10] is the first cavitation tunnel ever made (see Frontispiece). It is still in existence at the Department of Naval Architecture and Shipbuilding at the University of Newcastle upon Tyne. The oval closed circuit was made of a copper tube of rectangular cross-section. The propeller shaft was inserted horizontally into the upper limb of the tube and was driven from outside, first by a small steam engine and later by an electric motor. Photographs were taken through windows on either side of this upper limb with an arc lamp. To produce the cavitation more easily, Parsons pumped away the air from the surface of the water above the propeller.

Parsons was then able to develop a satisfactory wide-bladed propeller design but, even so, it required nine such propellers to drive the *Turbinia*, three on each of the three shafts. However, a speed of 32 knots was then attained.

In 1910, Parsons[9] built a large cavitation tunnel at Newcastle upon Tyne for testing 12-in diameter propellers. The tunnel was a closed loop with a flow path of 66 ft. The main piping was 36 inches in diameter, and the measuring section was 2.25 ft wide by 2.5 ft deep, with glass windows enabling illumination from a large searchlight to give photographs with exposures down to 1/30 000s.

Hutton[11] has written an interesting study of the history and ramifications of cavitation, with many rare references.

1.2 DEFINITIONS

Cavitation is the formation and activity of bubbles (or cavities) in a liquid. Here the word 'formation' refers, in a general way, both to the creation of a new cavity or to the expansion of a preexisting one to a size where macroscopic effects can be observed. These bubbles may be suspended in the liquid or may be trapped in tiny cracks either in the liquid's boundary surface or in solid particles suspended in the liquid.

The expansion of the minute bubbles may be effected by reducing the ambient pressure by static or dynamic means. The bubbles then become large enough to be visible to the unaided eye. The bubbles may contain gas or vapour or a mixture of both gas and vapour. If the bubbles contain gas, then the expansion may be by diffusion of dissolved gases from the liquid into the bubble, or by pressure reduction, or by temperature rise. If, however, the bubbles contain mainly vapour, reducing the ambient pressure sufficiently at essentially constant temperature causes an 'explosive' vaporization into the cavities which is the phenomenon that is called *cavitation*, whereas raising the temperature sufficiently causes the mainly vapour bubbles to grow continuously producing the effect known as *boiling*. This means that 'explosive' vaporization or boiling do not occur until a threshold is reached.

There are thus four ways of inducing bubble growth:

1. For a gas-filled bubble, by pressure reduction or increase in temperature. This is called *gaseous cavitation*.
2. For a vapour-filled bubble, by pressure reduction. This is called *vaporous cavitation*.
3. For a gas-filled bubble, by diffusion. This is called *degassing* as gas comes out of the liquid.
4. For a vapour-filled bubble, by sufficient temperature rise. This is called *boiling*.

The situation is complicated because the bubble usually contains a mixture of gas and vapour.

Looking at it another way, we may distinguish between four different kinds of cavitation according to how it is produced:

1. *Hydrodynamic cavitation* is produced by pressure variations in a flowing liquid due to the geometry of the system.
2. *Acoustic cavitation* is produced by sound waves in a liquid due to pressure variations.
3. *Optic cavitation* is produced by photons of high intensity (laser) light rupturing in a liquid.
4. *Particle cavitation* is produced by any other type of elementary particles, e.g. a proton, rupturing a liquid, as in a bubble chamber.

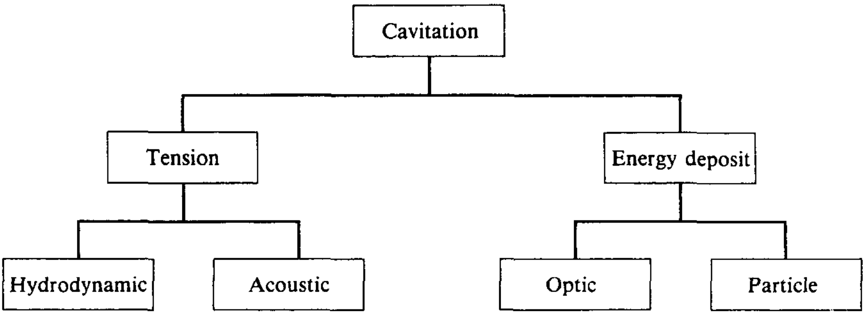

Figure 1.2. Classification scheme for the different types of cavitation. (Lauterborn.[12])

Lauterborn[12] has pointed out that whereas hydrodynamic and acoustic cavitation are brought about by *tension* in the liquid, optic and particle cavitation are achieved by a *local deposition of energy*. He was then able to produce the classification scheme in Fig. 1.2.

1.3 HYDRODYNAMIC CAVITATION

In a flowing system, the liquid velocity varies locally and at the points of highest velocity, low pressures and cavities occur.

Incipient cavitation is the term used to describe the type and stage of cavitation that is just detectable as the cavitation appears.

Desinent cavitation is the term used to describe cavitation just before it disappears.

The conditions which mark the boundary or threshold between no cavitation and detectable cavitation are not always identical. For example, the pressure of disappearance of cavitation has been generally found to be greater, and less variable, than the pressure of appearance.[13]

Three cases of flow cavitation arise:

1. *Travelling* cavitation occurs when cavities or bubbles form in the liquid, and travel with the liquid as they expand and subsequently collapse.
2. *Fixed* cavitation occurs when a cavity or pocket attached to the rigid boundary of an immersed body or a flow passage forms, and remains fixed in position in an unsteady state.
3. *Vortex* cavitation occurs in the cores of vortices which form in regions of high shear, and often occurs on the blade tips of ship's propellers - hence the name 'tip' cavitation.

1.4 ACOUSTIC CAVITATION

In a non-flowing system the ambient pressure can be varied by sending sound waves through the liquid. If the amplitude of the pressure variation is great enough to bring the pressure locally down to, or below, the vapour pressure in the negative parts of the sound cycle traversing the liquid, any minute cavities or bubbles will grow. If the pressure amplitude is increased to produce zero, and then negative, pressures (i.e. tensions) locally in the liquid, the bubble growth is increased. The tiny bubble is thus set into motion, growing and contracting in the sound field. This motion may be of various kinds, usually complicated. Two distinct types of bubble motion are possible: in the first are stable cavities or bubbles that oscillate for many periods of the sound field, whereas in the second are transient cavities that exist for less than on cycle.

Two important characteristics of acoustic cavitation should be mentioned here. The first is that generally it is a non-linear process in that the change in the radius of the bubble is not proportional to the sound pressure. The second is that the high compressibility of the gas bubbles means that much potential energy is obtained from the sound waves when the bubbles expand and that kinetic energy is concentrated when the bubbles collapse. In transient cavitation, this transformation of a low energy density sound wave into a high energy density collapsing bubble occurs because the motion is non-linear. Because it concentrates the energy into very small volumes it can produce very high pressures and temperatures which can erode solids, initiate chemical reactions and produce luminescence.

1.5 OPTIC AND PARTICLE CAVITATION

Optic cavitation occurs when, say, large pulses of a Q-switched ruby laser are focused in a liquid. Breakdown of the liquid occurs and bubbles are formed. The bubbles can then be photographed by a high speed rotating mirror camera.[12]

Particle cavitation is based on the growth of bubbles in a superheated liquid. If a charged particle is sent through the liquid it leaves an ionization trail for a fraction of a second Some of the energy from these ions goes into a few fast electrons, which can give up about 1000 electron volts of energy in a small volume to produce rapid local heating. If the liquid has been superheated by expansion, boiling will occur along the track which will appear as a line of tiny bubbles.

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