Cavitation

Introduction

Cavitation is a complex multiphase phenomenon and as pointed out by Knapp et al. [1] it is not easy to give a concise definition of cavitation and at the same time convey much significant information about it. For this reason three different definitions of cavitation are provided in the following. As a matter of fact cavitation can be defined as:

- the vaporization of a liquid when the static pressure decreases below its vapour pressure [2].
- the formation and activity of bubbles (or cavities) in a liquid [3].
- the breakdown of a liquid medium under very low pressures [4].

Cavitation appears, similar to boiling with the difference that the (phase change) driving mechanism is not a temperature change but a pressure change.

![Figure 1.1: Different driving phase change mechanisms (paths) of boiling and cavitation.](image)

In this respect Fig. 1.1 shows qualitatively how in the case of boiling starting from point A, evaporation can be induced by crossing the vapour pressure saturation curve, $P_V(T)$, at constant pressure. On the other hand in the case of cavitation, cool evaporation can be induced by crossing the saturation curve at almost constant temperature. In fact, in most cases (and especially for cold water) the thermal effects can be neglected.

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1The term formation refers in general way both to the creation of a new cavity or to the expansion of a pre-existing one to a size where macroscopic effects can be observed.
and the cool evaporation can be assumed practically isothermal as showed in Fig 1.1. However in some cases the thermal effects can not be neglected because the thermal exchange needed to the phase change is such that the phase change occurs at temperature lower than the ambient liquid temperature. This temperature difference called *cavitation thermal delay* can be significant for instance in cryogenic fluids such as oxygen, nitrogen, hydrogen which are popular fuels for launch vehicles [4–6].

The precise value of the pressure threshold at which cavitation initiates depends strongly on the purity of the liquid. More precisely it depends on the amount of the cavitation nuclei present in the liquid and the time that nuclei are exposed to the low pressure. Cavitation nuclei are microbubbles of vapour or gas. They can be suspended in the liquid or may be trapped in tiny cracks either in the liquid boundary surfaces or in the solid particles travelling in the liquid.

These *impurities* interfere with the uniform attraction that might otherwise exist between liquid molecules and can thus operate as a starting points for a liquid breakdown that leads to cavitation.

A liquid free or with a very low content of nuclei (such is pure water) can even withstand high negative pressure (tension) without undergoing cavitation. Otherwise the tap water (rich of nuclei), used in most of industrial devices, initiates to cavitate at a pressure close to its vapour pressure.\(^2\)

The interest in cavitation is strictly related to its effects which may be desirable or undesirable. In 1754, the Swiss mathematician Euler guessed the conditions that might cause the appearance of cavitation in rotating flow machinery and its effects on their performances, the intensive study of cavitation phenomena did not start earlier than at the end of the nineteenth century.

The growing interest to cavitation started as a reaction to the disastrous performances of several (screw-driven) steamships. The most famous cases are those of the destroyer HMG Daring and of the first Parson’s turbine ship Turbinia whose performances during the trials in 1893 and 1894, respectively, were well below their design speeds. In fact, despite Euler’s intuition one century earlier, at that time it was not clear yet, that the poor performances were related to the extreme cavitation phenomenon developed on the blades which caused the so called *thrust breakdown*.

In the case of Turbinia however, Parson was able to overcome the problem of cavitation by enlarging the blade area, increasing the number of propellers per shaft from one (original design) to three mounted in tandem. With the new arrangement of propellers the vessel was able to absorb all the power at the correct shaft speed and was also able to reach the remarkable trial speed of 32.75 knots.\(^3\)

\(^2\)For this reason it is common in numerical simulations (considering water as a working liquid) to set the pressure threshold at which cavitation initiate equal to the vapour pressure of the liquid at the free-stream temperature.

\(^3\)In fact with the new arrangement the single propellers were less loaded, with lower pressure fluctuations than in the original design and consequently they were not exposed to extreme cavitation on their blades.
Types of cavitation

Cavitation can appear in both flowing and static or nearly static liquids. In the latter case cavitation can occur when an oscillating pressure field disposing of a sufficiently large oscillating amplitude is applied on the liquid. In this case cavitation is termed *acoustic* and the cavitation pattern is generally composed of one or more bubbles that grow and contract in the sound field. The bubbles can be stable and oscillate for many periods of the sound field, or transient and exist for less than one cycle. In flowing liquids the cavitation appearance is caused by variations in local flow values (pressure, velocity) induced by the geometry of the system (in this work hydrofoil or propeller). In this case cavitation is termed *hydrodynamic*. Depending on the quality of the liquid (presence of nuclei and solid particles), the pressure field in the cavitation zone, as well as on the geometry configuration and roughness of solid-boundaries, it can take different forms. The different possible cavitation patterns can be classified according to [1], [4], [3] in the categories described below, however, it has to be kept in mind that some cavitation patterns can be a combination of several types. Examples of hydrodynamic cavitation over a hydrofoil and propeller are given in Fig. 1.2 and Fig. 1.3 respectively.

- **Fixed or Attached or Sheet Cavitation** appears as a region of detached flow filled with vapour. Its shape is usually under steady/quasi-steady conditions or changes relatively slowly and/or periodically. If the cavity extents well beyond the body, it is called *supercavitation*. Fixed cavities typically form downstream steep decreasing pressure gradients such is the leading edge of a body.

- **Travelling (Bubble) Cavitation** is characterized by cavities or bubbles which form in the liquid and travel with the liquid as they expand and collapse. The bubbles appear in low-pressure regions of the liquid as a result of fast growing of nuclei present in the liquid and then subsequently collapse when they are convected to higher pressure regions. This type of cavitation most commonly occurs on hydrofoils with a small angle of attack and is less likely to be present in hydraulic machines.

- **Cloud Cavitation** appears as a mist or cloud of very small bubbles. Frequently it is formed by the periodic break up of the sheet cavity. This type of cavitation usually causes engineering problems such as erosion, noise and vibrations, especially when bubbles collapse near the surfaces.

- **Vortex cavitation** occurs in cores of vortices which form in regions of high shear and can appear as travelling cavities or as fixed cavity. This type of cavitation is often present on a propeller blade. In this particular case it looks like a vapour-gas rope that extents from propeller tip far away in the flow field. Moreover it is often observed behind propeller as well as turbine hubs.
Figure 1.2: Examples of cavitation over a hydrofoil: (a) partial leading edge cavitation, (b) supercavitation, (c) travelling bubble cavitation, (d) sheet-cloud cavitation. Figure (a) taken from [7], (b)-(d) taken from [5].

Figure 1.3: Examples of different types of cavitation experienced by a propeller: (a) sheet-cloud cavitation and tip vortex cavitation, (b) tip and hub vortex cavitation (right). Figure (a) taken from [9], (b) adapted from [10].
The cavitation number

The susceptibility of a flow to cavitate is commonly identified by the non-dimensional governing parameter introduced by Thoma in 1920 known as cavitation number or Thoma number defined as:

\[ \sigma = \frac{P_{REF} - P_V(T)}{\Delta P} \]

where \( P_{REF} \) is the reference pressure, \( P_V \) is the vapour pressure at the operating temperature of the fluid \( T \), \( \Delta P \) is the pressure difference characterizing the system.

As a matter of fact the lower is the value of \( \sigma \), the larger is the risk of the appearance of a severe cavitation phenomenon.

In general, the Thoma number can be expressed for the hydrofoil case as:

\[ \sigma = \frac{P_{REF} - P_V(T)}{0.5 \rho L V^2} \]

where \( \rho_L \) and \( V \) are the density and free-stream velocity of the given working liquid, respectively.

For the propeller case as:

\[ \sigma_n = \frac{P_{REF} - P_V(T)}{0.5 \rho_L (nD)^2} \]

where \( n \) and \( D \) are the propeller rotational speed and diameter, respectively.
Cavitation erosion

The negative effects of cavitation such as the thrust breakdown in marine propellers can be also accompanied by excessive levels of noise, vibration and surface erosion. The surface erosion and production of noise are related to the bubble collapse because during collapse a large shock wave (thousands of Pascal) can be emitted, see Fig. 1.4 (left). Moreover, if the bubble collapses near a solid surface a micro-jet perpendicular to the surface can form, see Fig. 1.4 (right).

Figure 1.4: Erosive mechanisms formed during bubble collapse. (left) pressure waves from bubble collapse, (right) microjet formation close to surface. Adapted from [12].

The microjet reaches very high velocities in the final stages of the collapse and can thus induce an overpressure on the surface having the same order of magnitude as that produced by the shock wave. For this reason, shock waves and microjet are both possible hydrodynamic mechanisms of cavitation erosion. If one of the fluctuating forces induced by the phenomenon matches a natural frequency of a portion of equipment vibrations can occur, as for instance on propeller blades.
Nuclei content and roughness

The fluid nuclei content and the wall roughness of a given device are important because they can influence not only the extent but also the structure of the cavity. Fig. 1.5-1.6 qualitatively show how the water nuclei content and the wall roughness can impact on the appearance of the sheet cavitation on a model scale propeller. In fact the fluid with a higher nuclei content is more susceptible to cavitate, and the wall roughness trigger cavitation.

Figure 1.5: Effect of the nuclei content. Lower nuclei content (left), higher nuclei content (right). Figure reconstructed from [12]

Figure 1.6: Effect of the leading edge surface roughness. Lower roughness (left), higher roughness (right). Figure reconstructed from [12]


