MULTIPHASE FLUID FLOW-THEORY AND PRACTICE

by

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Preface

The general field of liquid cavitation has been thoroughly covered in the book Cavitation (1970), of which the present author is one of the co-authors. However, this previous book was limited in its coverage to cavitation, and of course, also reflected research results only to the period of the late 60's. It did, however, cover the basics in its field most comprehensively.

The present book is of broader scope, being in the general field of multiphase flows, and it attempts to bring the research coverage of Cavitation completely up to date. It does not attempt to cover the entire field of multiphase flow, but rather specializes in those applications involving particularly energy-intensive phenomena wherein either the vapor or gas phase is in the form of bubbles in a continuous liquid (e. g., cavitation), or alternatively, the liquid phase is in the form of droplets in a vapor gas continuum (e. g., wet steam flows). The scope of the book, and the relationships between the phenomena covered are discussed further in the Introduction (Chapter I).

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Chapter I

I. Introduction

The technical subjects considered in this book involve primarily vapor or gas bubbles in liquids. or liquid droplets in vapors or gases. Both of these generalized flow regimes include many important features in common, i. e. . features which are basically quite closely related. These include the processes of (a) nucleation; (b) growth and collapse or simply gradual diminuation; (c) effects on the overall flow regime due to the replacement of single-phase by multiphase flow, and the resultant effects upon machine performance,--or the appearance of erosion.

Major technical applications to which the above considerations obviously directly apply are; cavitation, wet steam (or other vapor) flows, and rain erosion of high-speed aircraft or missiles. Except for the lack of major erosion problems, any boiling or condensation applications fit. With regard to erosion in cavitation or liquid impingemnnt phenomena, it has been historically well recognized (1, e. g.) that metallic erosion produced by either process is often of very similar appearance. In fact starting in the 1930's and continuing today, experimental impact facilities (2, 3, e.g.) with impact velocity in the range of 100 m/s have been used to evaluate the supposed "cavitation" resistance of materials used in the construction of hydraulic turbines, pumps, marine propellors, etc. This usage was based on some of the earliest cavitation damage research experiments (3), and upon the later recognized close similarity in the damage produced by either process. Today this earlier observed similarity is entirely consistent with theoretical expectations deriving from relatively recent and careful basic research using both ultra-high-speed photography (1, 4-8, e. g.) and very complex computerized numerical analyses (1, 9-12 e. g). It has been shown that, at least in common engineering flowing systems, cavitation bubble collapse in close enough proximity to a wall to be damaging is a highly asymmetrical process, resulting in the formation of a high-velocity liquid microjet, which strikes the wall, and is at least a major contributor to the damage. Thus, according to present knowledge, cavitation damage includes an important contribution from liquid impact. Curiously enough, the direct liquid drop (or jet) impact erosion processes as encountered with the aforementioned wet vapor or rain drop impact flows may also include a secondary cavitation phenomenon within the impacting liquid slug.

Another flow regime involving important erosion, with or without cavitation, is that of slurry flows. In these cases the erosion probably includes a contribution from solid as well as liquid particle impact.

Various of the phenomena here under consideration are characterize by extremely high specific energy levels of the fluid. This must, for examp certainly be true of those processes such as cavitation and liquid impingmen erosion which depend upon mechanical actions. In both cases the phenomen act as very strong "mechanical amplifiers" in the sense that the kinetic and pressure energy from a relatively large amount of fluid is concentrated in a much smaller amount. As a case in point, the original analysis of Rayleigh (13) for the symmetrical collapse of an empty sphere (bubble in an inviscid, incompressible liquid) shows the attainment of an infinite pressure and velocity at the center of collapse when the bubble radius becomes zero. Of course this infinite specific energy is then concentrated in a zero mass of liquid. However, as the bubble radius <u>approaches</u> zero, the specific energ of the finite liquid mass surrounding the collapsing bubble becomes extreme high, as does the specifc energy within any gas or non-condensing vapor trapped within the bubble (13-15, e.g.). The overall energy input for this process can be considered, as by Rayleigh, as originating from the pressu energy in the overall static liquid relative to the initial pressure level within the bubble (zero if this is void). While the Rayleigh ideal-fluid spherical collapse model for cavitation bubbles is not considered today entirely valid, as previously pointed out, it is still true that, for one reason or another, a extremely large concentration of specific energy in the liquid must occur if mechanical damage is to result from the bubble collapse. The small size of the resultant pit (6, 8, e.g.), where an 0.1 mm diameter, approximately circular crater resulted from the collapse of a spark-generated bubble of approximately 4 mm original diameter, also indicates that this is the case. Thus, diameter reduction ratio was $\sim$ 40 and volume reduction ratio $\sim$ 64,000. An even more striking indication of the high energy levels within a collapsing cavitation bubble is the phenomenon called "sonoluminescence," the faintly visible, usually bluish light resulting (most strongly at least) from "ultrasonic" cavitation, ie., that induced in a static liquid by the imposition of relatively high-frequency pressure waves. It has more recently also been measured and studied in flowing systems such as a cavitating venturi (16). The most widely accepted present theory for the origin of this light is the very high temperatures created in the gas trapped within a collapsing cavitation bubble (14-16), and the resultant luminescence perhaps of various impurities in the system such as traces of carbon, etc., as well as of the pure gases involved. Calculated temperatures are in the range of 10^3 - 10^4 °K (14-16, e.g.).

As previously indicated, according to present beliefs, cavitation damage results to a large extent from liquid impact, and hence can be considered along with such phenomena per se in regard to mechanical amplification of energy. In the case of liquid impact, again the concentration of the low specific energy levels of a relatively large quantity of liquid into very high specific energy levels of a much smaller quantity, which is then capable of creating mechanical damage, occurs. In this particular case, as in the case of cavitation, the highly transitory nature of the process is instrumental in the result. This is made obvious by the experimental fact (2, e.g.) that impacting water velocities of the order of 100 m/s rapidly erode materials as resistant as stainless steels in quite short exposure times. In this case, the stagnation pressure is only about 50 bar, and hence its imposition cannot account for the observed erosion. However, when the transient phenomenon kown as "water hammer" is considered, the calculated pressure from this velocity is the order of 3500 bar, and even greater pressures are possible due to special geometrical effects (17-19, e.g.). Hence the observed erosion can easily be accounted for by these "water-hammer" pressures, even though the relatively steady-state stagnation pressure is obviously insufficient. In the case of water-hammer, of course, a portion (depending upon the various detailed parameters describing the impact) of the entire kinetic energy of the impacting liquid drop is converted into a very high pressure and kinetic energy in a small portion of the drop, which is in contact with the impacted surface during the collision. Thus, as with cavitation, the specific energy level of the liquid is greatly amplified by fluid-flow effects, but over only a very small time and space domain. Nevertheless, this is sufficient for the provocation of the highly important erosion effects associate with these processes.

Incidentally, light flashes are also observed with liquid impact (20, 21, e.g.) if the velocity is sufficient ($\sim$ 500-1000 m/s). This is possibly due to the compression of the air film between impacting drop and impacted surface, since these experiments, using a liquid gun type device, were conducted under ordinary atmospheric conditions. Again the light emission is indicative of the high specific energy levels involved.

High specific energies are no doubt also involved in many boiling and condensing phenomena, although not so predominently as in the impact and cavitation processes already discussed, and also in slurry and other solid particle flows where erosion results. In the case of boiling, where high degrees of subcooling are involved, the process is almost indistinguishable from cavitation, and hence, the energy levels of bubble collapse are similar. However, this bubble collapse usually occurs well within the fluid so that erosion of containing walls does not usually result. Saturated (non-subcooled boiling does not result in extremely high specific energy levels.

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