A Numerical Study of Vapour Layer Heights

Dalton J.E. Harvie and David F. Fletcher
Department of Chemical Engineering
University of Sydney

Abstract

Numerical simulations, using the previously validated BOUNCE code, are performed on n-Heptane and water droplets. The objective was to examine the dependence initial droplet and solid temperatures have on vapour layer heights generated during film boiling droplet impacts. The Volume of Fluid (VOF) and viscous vapour layer algorithms that form the BOUNCE code are briefly described, and a new treatment of radiative heat transfer between the solid and liquid phases is detailed.

1 Introduction

Droplet impacts upon hot surfaces occur in a wide variety of industrial, environmental and domestic applications. During such an impact, heat is transferred from the solid to liquid phase via the processes of convection and radiation. If the heat transfer rate during the impact is high enough, vapour is produced at the lower surface of the droplet which may suspend the droplet above the solid surface. If no contact between the solid and liquid phases occurs during the process, the impact is defined to be a film boiling impact. Such impacts are the subject of this study.

In this paper a numerical study is performed using n-Heptane and water droplets, to determine the effect that droplet subcooling and solid temperature has on initial vapour layer heights. The vapour layer is defined as the region between the droplet and solid surfaces, and the vapour layer height as the distance between these two surfaces. Impact simulations are performed using BOUNCE, a code which has been previously shown to predict both the hydrodynamic and thermodynamic behaviour of film boiling impacts under a wide variety of conditions [1].

Although a significant amount of literature on film boiling droplet impacts is available, no experimental studies have been able to directly measure the height of the vapour layer beneath a droplet during an impact. Some researchers have attempted to calculate vapour layer heights using a knowledge of heat transfer rates [2, 3], however, given the small length and time scales involved in droplet impacts, such measurements are subject to significant uncertainty. A full review of the experimental and limited analytical studies conducted in this area is given in Harvie [1].

This paper is divided into two main sections. In the first, we briefly describe the BOUNCE impact model. Special attention is devoted to the radiative heat transfer model, which has been introduced in this study. In the second section, the numerical simulations are presented, and a brief discussion of the results and their implications is given.
2 The BOUNCE Droplet Impact Code

The BOUNCE code is composed of two algorithms: A Volume of Fluid (VOF) algorithm is used to model the deformation of the droplet as it interacts with the solid surface. A second algorithm models the fluid flow within the vapour layer, as well as modelling the heat transfer that occurs within the solid, liquid and vapour phases. Detailed descriptions of both algorithms can be found in Harvie [1].

2.1 The Volume of Fluid Droplet Algorithm

The BOUNCE VOF code is based on the well-documented SOLA-VOF code of Nichols, Hirt and Hotchkiss [4], however the algorithm has been extensively modified to reflect advances that have been made in computational free surface flows over the past two decades. Simulations are performed in two dimensional cylindrical coordinates.

The location of the droplet free surface is calculated using a Volume of Fluid (VOF) method [4]. Under this method, a VOF function is defined which has the value of one within the droplet, and zero in the surrounding atmosphere. As the VOF function does not vary in a continuous fashion between fluid phases, advection of the function requires a special technique. The technique chosen for these simulations was that of the Defined Donating Region VOF advection algorithm [1, 5], this being a volume conservative algorithm ideally suited to computationally expensive problems which require both high spatial accuracy and advection stability.

Surface tension is applied using the Continuum Surface Model (CSF) model of Brackbill, Kothe and Zemach [6]. Surface curvatures are calculated using the method outlined by Kothe, Mjolsness and Torrey [7], with a correction included to account for the position of the actual fluid interface relative to the cell in which the force is applied [1]. The pressure force resulting from the viscous vapour layer, which is calculated by the separate vapour layer code, is applied using an interface region surface force [1]. The method of application is analogous to the method used to apply the surface tension force, although the vapour layer force is applied only to the lower surface of the droplet, and for stability is implemented using an iterative implicit solution technique.

2.2 The Viscous Vapour Layer Code

Both in the analysis and computational solution procedure, the vapour layer problem is divided into two sections. In the first, a simplified form of the Navier Stokes equations is solved to determine the fluid velocities and pressures existing within the vapour layer. Required for this solution is a knowledge of the vapour generation rates at the base of the droplet. These rates are provided by the second section, which involves an analysis of heat transfer rates occurring within the solid, liquid and vapour phases.

Viscous vapour flow solution By assuming that the height of the vapour layer is small in comparison with the radius of the droplet, and that this height changes only slowly with time and radial displacement, the incompressible Navier Stokes momentum equations in two dimensional cylindrical coordinates can be reduced to a one dimensional viscous flow equation. This equation is integrated to yield an expression for the pressure existing beneath the droplet in terms of the vapour layer volume flowrates and the vapour layer
geometry. Effective ‘slip’ velocity discontinuities are assumed at the liquid-vapour and solid-vapour interfaces to model the molecular behaviour of the gas at the boundary with another material. Vapour layer flowrates are calculated from an integral continuity equation, which expresses these flowrates as functions of the vapour generation rate and the lower droplet surface velocity. An integral transport equation is also solved for the volume fraction of droplet vapour and air throughout the layer.

**Droplet vaporisation velocity** The droplet vaporisation velocity is defined as the velocity at which vapour is produced at the lower surface of the droplet. In order to calculate this velocity, heat transfer rates within the solid, vapour and liquid phases must be calculated.

Heat transfer within the solid is calculated using a simplified form of the heat diffusion equation, where conduction within the radial direction has been neglected. Heat transfer within the liquid is calculated using a similar equation, however within the liquid convection in both the axial and radial directions is included. Constant temperature boundary conditions are employed in both the liquid and solid phases at the internal extremities of the temperature mesh. At the liquid-vapour and solid-vapour interfaces the gradient of the temperature is related to the heat transfer rates into the liquid and solid phases using Fourier heat transfer relationships. Also, effective temperature ‘slip’ discontinuities are employed at these interfaces to model the molecular behaviour of the gas in contact with another material.

Within the vapour layer, assumptions regarding the geometry of the vapour layer and temperature difference across the height of the layer can be employed to show that the temperature gradient across the layer is linear. Consequently, the heat transfer rate by conduction across the layer is uniform at each radial location.

In order to extend the range of solid temperatures over which the BOUNCE simulations are valid, radiative heat transfer between the solid and liquid phases has been included in this study. For the radiation calculation, the droplet surface is assumed to be constructed of a number of horizontal rings, each corresponding to a column of computational vapour layer cells. Only radiation to or from the lower surface of the droplet is considered, and for simplicity, no radiative heat transfer between any two liquid surfaces is calculated. The upper surface of the solid is also assumed to be composed of a number of rings, each corresponding to a column of computational vapour layer cells. There is no radiative heat transfer between solid surfaces.

In developing the radiative heat transfer solution, it was assumed that both the liquid and solid surfaces were ‘opaque’ and ‘grey’. The opaque surface assumption is justified on the grounds that at the temperatures considered in this study, the majority of radiation incident on either the solid or liquid is absorbed by molecules located within 1 μm from the outer surface of that material [8]. The grey surface assumption has been assumed for reasons of simplicity, and because specific and accurate data on the absorptivity of surfaces considered in this study are not readily known. Note that simulations show that heat transfer by radiation is generally of a smaller magnitude than heat transfer by conduction during an impact simulation. Thus, any inaccuracies introduced into the calculations resulting from assumptions used here are of only a minor significance.

The radiation solution procedure involves calculating linear expressions between the radiosity of each radiative surface, the coefficients of which are dependent on view factors
between all surfaces defined in the radiation geometry. These linear equations are solved via a LU decomposition matrix inversion method [9], and implemented into the vapour layer heat transfer analysis using an iterative implicit solution technique.

3 Simulation Results

In this section we present simulations of both n-Heptane and water droplet impacts, to analyse the effect the initial solid temperature and initial droplet subcooling has on vapour layer heights generated during each impact.

All calculations were performed using uniform square computational cells, of side length 0.06 mm. The initial droplet diameter was 1.5 mm, and in all cases the initial droplet velocity was 0.8 ms\(^{-1}\). For the n-Heptane droplets this corresponds to an impact Weber number in the range 32 \( \leq \) We \( \leq \) 47, while for water 13 \( \leq \) We \( \leq \) 17. Note that the Weber number is defined as

\[
\text{We} = \frac{\rho dv^2}{\sigma} \tag{1}
\]

where \( \rho \) is the liquid density, \( d \) is the droplet diameter, \( v \) is the initial droplet velocity and \( \sigma \) is the surface tension coefficient of the liquid. The analysis presented in Harvie [1] shows that at these Weber numbers, BOUNCE is able to accurately predict at least the initial spreading of each droplet impact. In each test, simulations were initiated with the droplet base separated from the solid by approximately 1.5 mm, and were continued for 2 ms beyond the initial ‘contact’. Thus, only the initial impact and deformation of the droplets was investigated.

The initial solid surface temperature used in these simulations was varied between 300 °C and 1500 °C, and the initial subcooling of the droplets between 75 °C and zero subcooling (saturated conditions). Note that the saturation temperature for n-Heptane at atmospheric pressure is within two degrees of the same temperature for water. Thus, n-Heptane and water droplets at the same levels of subcooling are at approximately the same absolute temperature. A high thermal conductivity stainless steel surface was employed in all computations.

Figure 1 shows the maximum Knudsen numbers, \( K_{\text{max}} \), generated during the initial stages of each impact. The Knudsen number is defined here as the ratio of the molecular free path of the vapour mixture within the vapour layer to the height of the vapour layer. The Knudsen numbers calculated during the water impacts are all larger than those calculated during the n-Heptane impacts. The n-Heptane molecule \((\text{CH}_3 \text{CH}_2)_6 \text{CH}_3\) is much larger than the water molecule. Consequently, at the same temperature and pressure, n-Heptane vapour has a smaller mean free path than steam, and thus a smaller Knudsen number.

An analysis presented in Harvie [1] showed that when the maximum Knudsen number experienced during an impact exceeded approximately 0.05, BOUNCE was not able to predict the hydrodynamic or thermodynamic behaviour of the droplet. It was found that the assumption of a molecular slip flow regime beneath the droplet invalidated the simulation results in these cases. Further, experimental evidence suggests that when the maximum Knudsen number exceeds this value during an impact, direct contact between the liquid and solid phases occurs, often leading to vapour layer collapse and transition or nucleate boiling.
Examining Figure 1, it is clear that the majority of water impacts with an initial water subcooling larger than 40°C are violating this Knudsen number criterion. Based on previous validation work, this suggests that a water droplet at 25°C impacting a surface whose temperature is below 1300°C, or alternatively a water droplet at 60°C impacting a surface whose temperature is below 800°C, will result in a transition or nucleate boiling impact, under these impact conditions.

Figure 1 also shows the minimum vapour layer heights experienced during the initial stages of each impact. Generally these heights are of a similar magnitude for the n-Heptane and water impacts, although the water heights show a greater dependence on changes in the initial droplet and solid temperatures.

The minimum vapour layer heights calculated increase with an increase in the solid temperature, and decrease with an increase in the initial subcooling of the liquid. The minimum height increases with an increase in the solid temperature, because the greater the temperature difference across the vapour layer, the greater the heat transfer across the vapour layer and the greater the rate of vapour production at the lower surface of the droplet. The minimum height decreases with an increase in initial droplet subcooling, because the lower the temperature of the liquid, the more sensible heat is required to bring the temperature of the droplet surface to saturation conditions, and the less vapour is generated.
The variation of minimum vapour height with droplet subcooling is greater for water than it is for n-Heptane because the product of the thermal conductivity, specific heat and density is larger for water than it is for n-Heptane. As a consequence, the surface temperature of a n-Heptane droplet reaches saturation conditions more rapidly than the surface temperature of the water droplet during the approach towards the solid. Thus, vapour production can occur at a greater distance from the solid under a subcooled n-Heptane droplet than under a similar water droplet.

4 Conclusions

Simulations performed using the BOUNCE code have shown that vapour layer heights experienced during a film boiling droplet impact are strongly dependent on both the temperature of the impact material, and initial subcooling of the droplet. For the n-Heptane and water droplets considered, the minimum vapour layer heights calculated during the initial stages of each impact increased with an increase in solid temperature, but decreased with an increase in liquid subcooling. It was also found that the maximum Knudsen numbers calculated during the water droplet impacts were higher than those calculated during the n-Heptane impacts, a result which may have implications as to the stability of some film boiling water droplet impacts.

References


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