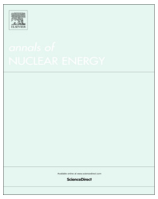
Annals of Nuclear Energy 113 (2018) 162–170

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene



Investigation of droplet behaviors for spray cooling using level set method

Mehrdad Shahmohammadi Beni [a], Jiyun Zhao [b,*], K.N. Yu [a,*]

[a] Department of Physics, City University of Hong Kong, Tat Chee Avenue, Kowloon Tong, Hong Kong
[b] Department of Mechanical and Biomedical Engineering, City University of Hong Kong, Tat Chee Avenue, Kowloon Tong, Hong Kong

ARTICLE INFO

Article history:
Received 9 March 2017
Received in revised form 23 September 2017
Accepted 26 September 2017

Keywords:
Droplet dynamics
Level set method
Heat transfer
Two-phase flow
CFD

ABSTRACT

The droplet dynamics and heat removal is one of the popular research streams in spray cooling applications. The increase in the water droplet temperature as a result of its impact on the hot solid surface would determine the efficiency of the heat removal that is crucial in some sensitive applications such as spray cooling in depressurization systems in commercial nuclear power plants. Computer modelling of the underlying mechanism of the liquid droplet interaction with the hot solid surface would be necessary. The accuracy and the reliability of these models are important in simulating the multiphysics phenomena such as droplet dynamics and heat removal. In present work, the level set method coupled with heat transfer was used to simulate the water droplet impact on an isothermal solid surface. The changes in the temperature of water droplet were found to be highly dependent upon its size and the impingement speed. Topological variations in the droplet shape as a result of its impact onto the solid wall would cause abrupt changes in the temperature of the water droplet. In addition, the droplet detachment, coalescence and flattening were found to strongly influence the temperature of the droplet which would evidently affect the heat removal efficiency in the spray cooling systems employed in the commercial nuclear power plants. Furthermore, we demonstrated that the level set method had the ability to produce more accurate estimations of the water droplet dynamics when compared to the Volume-Of-Fluid (VOF) method in simulating the droplet behavior.

1. Introduction

In recent years of advanced improvements in the capability of computers, many physical phenomena can be modelled precisely using computer simulations. In many cases where experimental measurements might be tedious or impossible, there will be a complete reliance on computer simulations. Therefore, the completeness, accuracy and reliability of the models being used in such sensitive areas are vital to the society and the environment. The current powerful computer resources need to be fully exploited, so that precision and accuracy of obtained computational results would be further enhanced. The Computational Fluid Dynamics (CFD) technique is widely used in simulating fluid behavior such as single and multiphase flow in both laminar and turbulent regimes (Norton and Sun, 2006). This technique tends to be computationally expensive and requires relatively large amount of computer resources for large and complex systems. However, considering the powerful computing power available in recent years, simulation of complex fluid behavior has become more convenient.

The investigation of fluid dynamics and heat transfer parameters such as temperature and speed are useful when the heat removal efficiency of spray cooling systems needs to be determined. The importance of the droplet dynamics is mainly due to the many industrial applications, including spray cooling (Jia and Qiu, 2003; Hsieh and Luo, 2016), ink-jet printing (Van Dam and Le Clerc, 2004) and anti-icing (Meuler et al., 2011; Mishchenko et al., 2010). The first method used to simulate the droplet impact on a solid surface was developed by Harlow and Shannon (Harlow and Shannon, 1967) who used the “marker-and-cell” (MAC) finite difference method. The viscosity and the surface tension were neglected in the initial model of MAC to simplify the problem. Tsurutani et al. (1990) introduced the enhanced MAC method that included the surface tension and viscosity, and also heat transfer when considering the spread of a cold liquid droplet on a hot surface.

The Lagrangian formulation was used by Zhao et al. (1996) in order to model the cooling of a liquid microdroplet. The influence

---

* Corresponding authors.

E-mail addresses: jiyuzhao@cityu.edu.hk (J. Zhao), peter.yu@cityu.edu.hk (K.N. Yu).

https://doi.org/10.1016/j.anucene.2017.09.046
0306-4549/

of liquid properties and interfacial heat transfer during micro-droplet deposition on a glass substrate was studied numerically by Bhardwaj et al. (2007), where the droplet diameter and impact velocity were fixed to be 80 μm and 5 ms^{-1}, respectively. The complexity of the associated transport phenomena was also highlighted (Bhardwaj et al., 2007). On the other hand, the spray cooling system or more fundamentally, the heat removal by the water droplet is an important aspect of nuclear thermal hydraulics which is also necessary to achieve an effective post-LOCA cooling and in many other engineering applications. Li et al. (2011) studied the impact force caused by liquid droplet impingement onto a rigid wall, and showed that the evolution was dominated by the compressibility of the liquid medium. In recent years, the Volume-Of-Fluid (VOF) method has been widely used due to the enhanced computational capacities. Recently, there were excellent and leading studies published in the *Annals of Nuclear Energy* regarding the use of VOF method in numerical simulation of melt interaction with water (Thakre and Ma, 2015; Thakre et al., 2013; Thakre et al., 2015; Gu et al., 2015; Lin et al., 2014), which presented a promising use of the VOF method in simulating complex multiphase systems. In addition to the VOF method, the level set method was devised by Osher and Sethian (Osher and Sethian, 1988), which was developed for interface tracking in two or three dimensions. Moreover, the level set method was used in a variety of applications such as shape recognition (Kimmel et al., 1996), crystal growth, dendrite solidification (Sethain and Strain, 1992), propagation of cold plasma in cell buffer medium (Shahmohammadi Beni and Yu, 2015), cold plasma mixing with blood (Shahmohammadi Beni and Yu, 2017) and two fluid problems (Mulder et al., 1992; Olsson and Kreiss, 2005; Lan et al., 2014; Nagrath et al., 2006; Sussman et al., 1994). Sussman et al. (1999) developed an adaptive level set method for application of incompressible two-phase flow, which was used to simulate the air bubble and water drop in both two-dimensional axisymmetric and fully three-dimensional geometries. A number of methodologies were proposed to improve the initially developed level set method, with the ultimate goal of precisely simulating two-phase flow problems (Peng et al., 1999; Enright et al., 2002; Sussman et al., 1998). The readers are referred to Osher and Fedkiw (2001) and references therein for more details regarding the overview of the level set method. As regards the application of level set method in spray cooling Selvam et al. (2006) used a simplified two-dimensional model to study the effect of gravity on heat transfer of spray cooling with the main focus on the phase change, in which the interface between the liquid and the vapor was tracked by the level set method. In addition, the computer modelling of spray cooling problems and the methods used to solve multiphase flow problems were reviewed (Selvam et al., 2005).

In the present work, a complete three-dimensional multiphysics model was built using the Finite Element Method (FEM) to track the droplet movement, impact and rebounce from the solid surface during its impact period, using the level set interface tracking method coupled with heat transfer. The two phases involved in the present work were water and air; this enabled us to perform a sensitivity study on different radii and initial speeds of the water droplet. Due to complexities in the present multiphysics model, the solid surface temperature was assumed to be below the boiling temperature of water. The present work also demonstrated that the level set method provided a better estimation of the experimental results regarding droplet dynamics when compared to the VOF method. The present level set model was found to be promising in the simulation of droplet dynamics and it could be a useful tool for future development and optimization of spray cooling systems in commercial nuclear power plants with special attention to high accuracy and reliability modelling.

2. Materials and methods

The level set method was used to capture the evolution of a water droplet in air as it moved down with the prescribed initial speed under gravity. In this model, the water droplet was initially placed at a specific distance (1.5 cm) from the upper surface of the solid interface, which enabled the interface initialization and further analysis of the ambient air effect on the fluid dynamics and heat transfer of the moving water droplet. The continuous tracking of the water droplet interface with respect to simulation time led to time-dependent scoring of the fluid dynamics and heat transfer parameters which were important for the precise determination of heat removal efficiency.

2.1. Geometry and computation scheme

In order to perform sensitivity studies using the present model, we chose three different radii for water droplets placed in a fixed air column. The summary of the geometries and dimensions of the domains involved in present work are shown in Table 1.

The initial speeds of the water droplets were assumed to be 0.5 and 1.0 ms^{-1} in the downward (-*z*) direction. The overall simulation time of 1 s was employed so that the heat transfer and fluid dynamics parameters could be obtained before, during and after the impact onto the hot solid plate, which had a fixed temperature of 70 °C (i.e., below the boiling temperature of water). The system setup is schematically shown in Fig. 1. The distance between the center of the water droplet and the solid surface was fixed at 1.5 cm for all cases studied in the present paper.

2.2. Level set method coupled with heat transfer

Information on the implementation of the level set method including the major equations in the current multiphysics model will be shown here. The simplified level set variable ϕ defined for a domain denoted by ψ is

$$\phi = \phi(r, t), \quad r \in \psi \tag{1}$$

where t is the time. Eq. (1) can be converted to an evolution function that describes the moving interface, which in the present case is located between the water droplet and the surrounding ambient air. This evolution function is

$$\frac{\partial \phi}{\partial t} + u \cdot \nabla \phi = 0 \tag{2}$$

where u is the velocity. The standard level set function which contains the level set variable ϕ would take different signs at different sides of the interface. Considering a two-phase fluid system consisting of α and β phases, ϕ would be zero at the interface and takes positive or negative values in each domain with different phases, which is controlled by the Heaviside function:

$$\zeta(x) = sign[\phi(x)] = \begin{cases} -1 : \phi < 0 \\ 0 : \phi = 0 \\ +1 : \phi > 0 \end{cases} \tag{3}$$

The level set function would detect the transition between the two phases using the Heaviside function. However, the abrupt changes between the two phases arising from the sign function

Table 1
Summary of geometries and dimensions for the air column and water droplets.

Domain	Geometry	Dimensions
Air column	Rectangle	$1 \times 1 \times 2\ \mathrm{cm}^3$
Water droplet	Sphere	radius = 0.1, 0.2, 0.4 cm