VOF method developed for the evaporation of liquid droplets that come into contact with heated surfaces

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ABSTRACT

The study of the evolution of the mass of a liquid droplet and its average temperature in the case of collision between a solid surface and liquid droplet can be carried out using the Volume of fluid method VOF. The dynamics of the drops will be investigated at the moment of impact on a heated plane wall until a steady state is reached. During this transition period, the average temperature of the drop vaporization process is estimated. The lifetime of a drop of liquid is determined from a static point of view, upon contact with a hot surface. The equations applied are Navier-Stokes energy and vapor transport.

Keywords:

droplet, VOF, heated plate, evaporation.

Introduction

In many engineering fields, the thermal transfer between an ideal liquid and a solid surface has become important in the case of cooling and in the study of phase transformations. Heat transfer to the drops increases the average temperature of the liquid, while vaporization takes place. Based on the duration of evaporation of the drops, four different evaporation regimes can be identified mainly, depending on the temperature of the wall: evaporation of the film, boiling of the core, boiling in transition, and boiling of the film. Another important parameter affecting the cooling of the wall surface and which is essential not only for the physical description of this phenomenon, but also for its numerical simulation, is the value of the contact angle.

Simulation set-up and investigations

The present paper presents a simulation study conducted to assess the influence of the water droplet that comes into contact with a heated flat surface. The dynamic evolution of the drop that falls due to gravitational acceleration is shown. The Shape of the drop changes over time and is defining at the time of impact with the flat surface. ANSYS Flent simulation environment using the VOF method was used to simulate evolution. Figure 3 shows the evolution of the volume fractions that occur at the impact with the surface. The impact of a liquid droplet on a hot surface induces a flow that is considered to be two-dimensional and axially symmetric. To identify each phase separately, the Volume of fluid method VOF [2], is applied, defining the following fraction [1], denoted by α:

$$\alpha = \frac{V_{fl}}{V_{tvc}} \tag{1}$$

where V_{fl} – liquid phase volume, V_{tvc} – total control volume, α equals 1 inside the liquid, 0 in the gas phase and with values between 0 and 1 in the collision area. The transport equation of α, taking into account the effects of evaporation and liquid thermal expansion, is given by [1]:

$$\frac{\partial a}{\partial t} + \nabla(au) = -\frac{1}{\rho_l}\frac{\dot{m}_e}{V_{ce}} - \alpha\frac{1}{\rho_l}\frac{D\rho_l}{Dt} \tag{2}$$

The moment equations expressing both phases are written as:

$$\frac{\partial(\rho\vec{u})}{\partial t} + \nabla\cdot\left(\rho\vec{u}\otimes\vec{u} - \vec{T}\right) = \rho\vec{g} + \vec{f}_\sigma \tag{3}$$

where $\vec{T}$ is the stress tensor, $\vec{u}$ is the speed and f_σ is the volumetric force due to the surface tension. The value f_σ is equal to $f_\sigma = \sigma\cdot\kappa(\nabla_a)$ where σ is the numerical value of the surface tension and κ is the curvature of the collision area. Also, the energy transport and vapor transport equation are solved:

$$\rho c_p\frac{DT}{Dt} = \nabla(k\nabla T) + \frac{Dp}{Dt} - \frac{\dot{m}_e L}{V_{ce}}(1-\alpha)\rho_g\frac{DC}{Dt} = \nabla\left[(1-\alpha)\rho_g D_{AB}\nabla C\right] + \frac{\dot{m}_e}{V_{ce}} \tag{4}$$

For the liquid and vapor mixture phase, most of the physical and thermodynamic properties are calculated as a function of α, using linear interpolation between the values of the two phases [1].

$$\rho = \alpha\rho_l + (1-\alpha)\rho_g$$
$$\mu = \alpha\mu + (1-\alpha)\rho_g \tag{5}$$
$$P_r = \alpha P_{rl} + (1-\alpha)P_{rg}$$

The model used is based on Fick's law, which uses the local concentration gradient in the collision area as a driving force and assuming that the interface is saturated. The evaporation rate is given by:

$$\dot{m}_e = \frac{dm}{dt}\rho_g D_{AB} A_{l-c}\left(\frac{dC}{dn}\right)_s$$
$$A_{l-c} = V_c|\nabla\alpha| \tag{6}$$

Fick's based model is independent of the flow conditions and the shape of the liquid-air interface [1]. The performed simulation takes place in a closed environment consisting of a cylinder that on the underside is heated to a temperature of 1500 *°C*. The drop that falls is 2 *mm* in diameter and is considered to be a pure substance. The drop of water falls from a height of 20 *mm* on a hot aluminum surface. The impact velocity is about 1.0 *m/s.* The volume of the drop was determined assuming that the drop is a spherical section. Certain settings and steps were used to obtain the simulation. In a first stage the geometry and mesh were created according to figure 1 and 2.

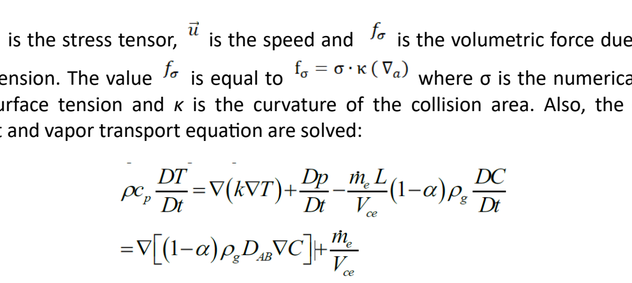

Fig. 1. The geometry of simulating a drop of liquid.

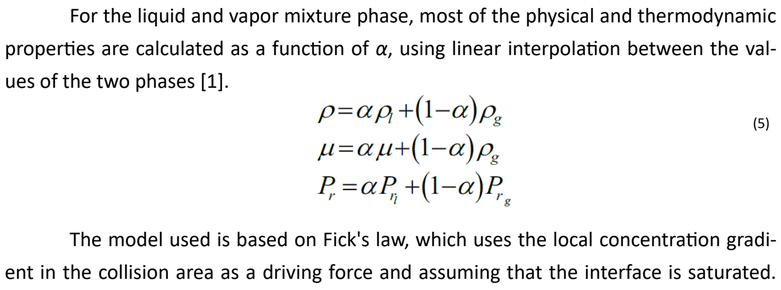

Fig. 2. The geometry of simulating a drop of liquid.

Results and discussions

For the presented work, the dynamics of the liquid drop is present in the image below. The evolution of the velocity vectors at the moment of impact and the dynamic evolution of the drop are observed in figure 3.

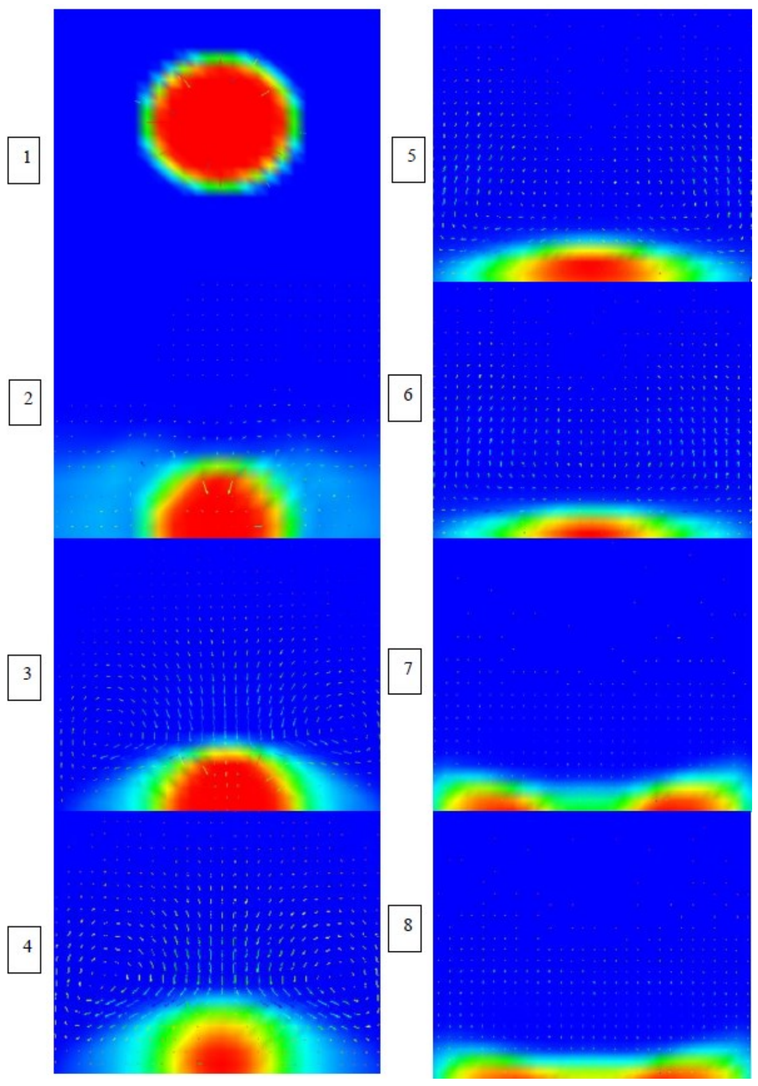

Fig. 3. Evolution of the drop and velocity vectors during impact with the flat surface.

From the simulation it is possible to observe the evolution of volume fractions as a function of pressure (see figures 4 and 5) for the two phases through which the water drops pass.

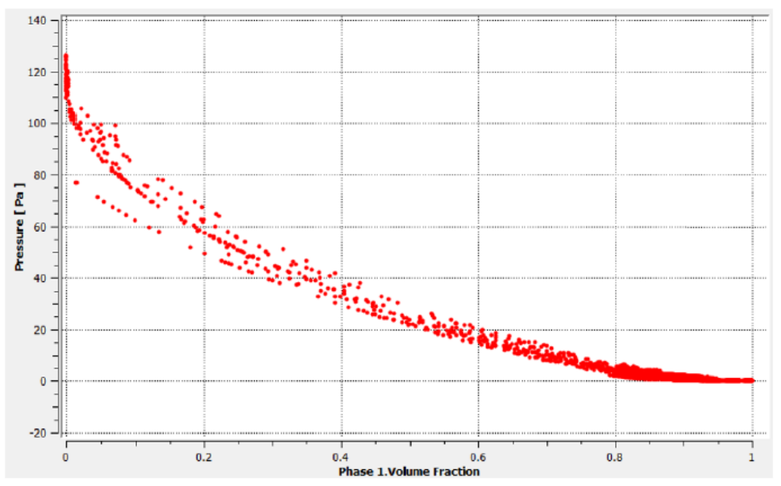

Fig. 4. Phase 1 pressure variation with volume fraction.

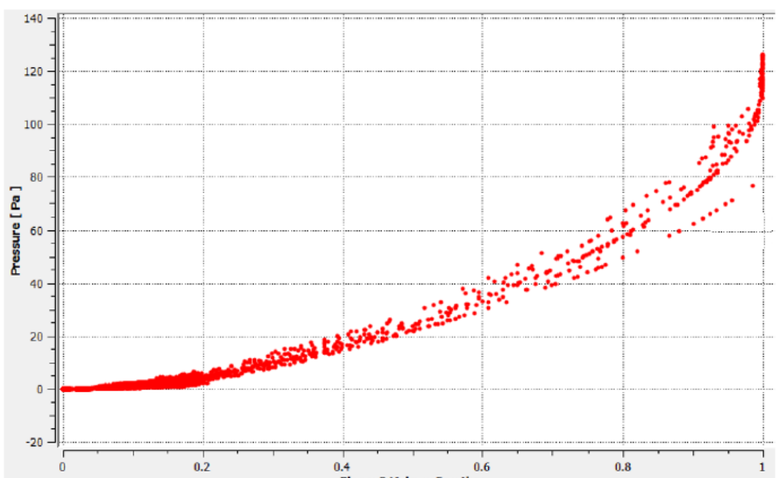

Fig. 5. Phase 2 pressure variation with volume fraction.

Figure 6 shows the evolution of the vaporization of a drop as a function of temperature. Blue for temperatures up to 1500 *°C*, red for boiling temperature values and green for temperatures below boiling point.

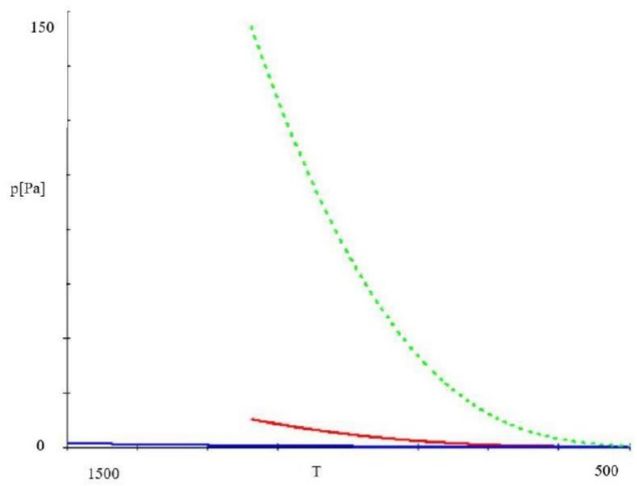

Fig. 6. Vapor pressure variation as a function of temperature.

Conclusions

The current simulation aims to study the behavior of a drop of liquid that encounters a flat surface. From the studies made to the specialized works[3, 4], it is clear that the increased pressures are found at the point of impact on the frontal face of the drop due to the increased curvature of the free surface of the drop, while at the recoil phase there is a more uniform distribution of the pressure. The vapor concentration field reaches its maximum values at the top edge of the drop due to the high temperatures encountered in this area, as shown by the studies. The temperature of the wall gradually begins to rise from the point where the added heat becomes equal to the energy that is contacted by the drop. The mass evaporated during the transition period is less than 0,01% of the initial mass of the drops. The surface velocity of the drops at the end of the transition period was found to be less than 0.02 [*m/s*], so it follows that the liquid velocities induced by heating and vaporization in the liquid can be much higher. The life of the drops decreases with increasing initial contact angle and surface temperature, while the local evaporation rate from the surface of the drop takes the maximum value at the triple solid-liquid-gas interface line. When the temperature variation of the wall is not considered, the expected vaporization time is faster, since the wall is maintained at a higher temperature that improves the heating of the drop and therefore vaporization. From the calculations and experiments presented in the specialized works it follows that the evaporation time of a drop decreases with the increase of the temperature of the isothermal wall or with the increase of the ambient temperature in the case of the adiabatic wall. From the studied experiments it follows that as the drop approaches the hot wall, a portion of the liquid droplets vaporize and form a thin film. This film prevents physical contact between the drops and the wall. Drops falling on a hot surface above Leidenfrost temperature levitate above the surface due to the formation of the vapor film between the drops and the wall surface. The levitation [5] of the drop on the wall approaches zero as the drop touches the wall and oscillates as the drops spread [5] and retreat across the surface. The maximum lifting capacity is reduced while increasing the number of drops in one direction. In addition, the number of drops in a perpendicular direction leads to a reduction in the spread of drops and increased ascent. The average temperature of the surface of the drops is directly influenced by its lifting from the heated wall. Higher lifting results in a decrease in the average temperature. The evaporation rate is higher when there are more drops because they occupy a larger area. After impact, in the case of several drops, they merge, and the spread and surface are smaller in cases with several drops, and therefore the evaporation rate decreases. The cumulative heat transfer is higher in the case of a single drop compared to the cases with multiple drops. The small drop retains a spheroidal shape throughout the interaction, while the large drop spreads and becomes quite complicated and appears to be on the verge of decomposition. The higher the impact speed, the higher the cooling performance during the impact process. The heat transferred per drop during drip is increasing with the number of Weber, Bond and Jacobs while it tends to decrease with the increase in Reynolds and Prandtl numbers. As the Weber number increases [6] to about 15, the fractional reduction in the perpendicular velocity increases and evaporation is faster due to surface enlargement and transport of vapor. This fractional reduction seems to change a little, with a subsequent increase in what exceeds the level 15. The levitation of the drop reaches the minimum value at about 2.5 [*ms*] (milliseconds) when approaching the wall. Initially the droplets are at room temperature 298*K*. The surface temperature rises steadily towards the saturation temperature to about 2.5 [*ms*]. The maximum scattering moment is reached at t = 3.85 [ms]. At this time [7], a recess is observed in the center of the drop. Numerical results also confirm the formation of a recess in the center of the drop at the maximum moment of scattering. In the early stage of the impact the pressure increases in the vapor layer, especially at the point of stagnation that is reached in the early phase at T = 0.6 [*ms*]. From the studied works it follows that the surface tension becomes dominant and determines the introduction of the drop in the recoil stage between T = 3.85 [*ms*] and T = 7.1 [*ms*]. In conclusion, this paper shows how the vaporization of a drop of liquid that comes into contact with a heated flat surface occurs using the VOF method. In addition, the mechanisms underlying the process of vaporization of a drop in a convective medium are specified.

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