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# Heat transfer in the film boiling regime: Single drop impact and spray cooling

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ABSTRACT

In this study a model for the heat transfer into a single drop impacting onto a hot solid substrate in the film boiling regime is developed. The model accounts for the expansion of the thermal boundary layers in the spreading drop and in the solid substrate, and for the evaporation of the liquid phase, leading to the creation of a thin vapor layer. An explicit expression for thickness of the vapor layer is obtained from the energy balance at the liquid-vapor and vapor-solid interfaces. The theory allows prediction of the heat transferred from the hot substrate to the single drop during impact. This quantity is then used for the development of a model for an average heat transfer coefficient for spray cooling in the film boiling regime. The model accounts for the probability of drop interactions on the wall, when the droplet number density in the spray is high. The theoretical predictions for the heat transfer coefficient agree well with existing experimental data.

## 1. Introduction

The study of a single drop impact onto a heated wall is motivated by a wide range of industrial applications such as spray cooling [1–3], fuel injection and atomization, or particle formation and encapsulation in a fluidized bed. In recent years a trend towards higher operating temperatures and pressures can also be observed, in order to optimize combustion processes and to make engines and gas turbines more efficient or to reduce pollutants.

Various aspects of this phenomenon have been previously investigated experimentally: heat transfer associated with drop impact [4], breakup probability [5], impingement angle at which drop breaks up [6,7], and temperature at which drop rebounds [8,9]. The diameter and the velocity of secondary droplets obtained as a result of the impact of a drop chain have been characterized using image processing in [10]. It has been shown that these quantities depend on the wall temperature and on the frequency of drop impact.

At very high substrate temperatures, significantly exceeding the saturation temperature, the liquid does not remain in contact with the solid. The vapor layer dividing the liquid from the hot substrate exhibits a pressure distribution which suspends the impacting drop above the surface [11]. One of the important parameters characterizing this nature of film boiling is the minimum film boiling temperature (or Leidenfrost temperature). The first model introduced to predict the Leidenfrost temperature was based on the Taylor instability of the vapor/liquid interface [12]. In this theory the spacing between bubbles and their size was determined by the most unstable wavelength of the Rayleigh-Taylor instability. The Leidenfrost temperature was then evaluated from the condition of the minimum heat flux.

Another type of model is based on the assumption that the Leidenfrost temperature is determined by the stability of homogeneous nucleation in the liquid near the hot wall [13]. In [14] the collapse of the vapor film in the film boiling regime is explained by the non-uniformity of the surface heating. The presence of local cold spots on the surface is associated with conditions of the minimum heat flux temperature.

The model presented in [15] can serve as a model for the prediction of the Leidenfrost temperature corresponding to drop impact onto a rigid substrate. In this study the bubble nucleation and growth and the interaction with the thermal boundary layer are analyzed. Since the flow in the drop is not known, empirical correlations for the energy loss are introduced into the model, which is finally fitted to the experimental data for the Leidenfrost temperature. Accordingly, the Leidenfrost temperature increases when the drop impact velocity increases. This observation is confirmed by several experiments [8,16].

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**Nomenclature**

*Symbols*

| | |
|---|---|
| $B$ | dimensionless coefficient |
| $c_p$ | specific heat capacity |
| $D_0$ | drop diameter |
| $D_{\max}$ | maximum spreading diameter |
| $D(t)$ | spreading diameter |
| $e$ | thermal effusivity |
| $G$ | dimensionless coefficient |
| $h$ | vapor layer thickness |
| $K$ | dimensionless coefficient |
| $L$ | latent heat |
| $\dot{m}$ | mass flux density |
| $n$ | number of spreading drops |
| $\dot{N}$ | number flux density |
| $p$ | pressure |
| $p_d$ | probability density function |
| $p(n;\lambda)$ | interaction probability |
| $\dot{q}$ | heat flux |
| $Q$ | heat |
| $r$ | coordinate |
| $R(t)$ | drop spreading radius |
| $Re$ | Reynolds number |
| $t$ | time |
| $T$ | temperature |
| $U_0$ | drop velocity |
| $We$ | Weber number |
| $z$ | coordinate |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | thermal diffusivity |
| $\delta$ | thermal boundary layer |
| $\nabla$ | Laplace operator |
| $\eta_{\text{wet}}$ | effective wetted ratio |
| $\vartheta$ | coordinate |
| $\rho$ | density |
| $\xi$ | similarity variable |
| $\lambda$ | thermal conductivity |
| $\chi$ | dimensionless constant |

*Subscripts*

| | |
|---|---|
| 0 | initial wall conditions |
| c | solid-fluid interface |
| $D_0$ | initial drop conditions |
| f | liquid film |
| sat | saturation |
| v | vapor film |
| w | wall region |

Numerous studies are devoted to the investigation of an inclined drop impact at the film boiling regime at the temperatures well above the Leidenfrost temperature [17,18].

Heat transfer during drop impingement can be categorized into the commonly known boiling curve regimes: (i) wetting contact cooling regime, (ii) nucleation, (iii) transition and (iv) film boiling [19].

In the film boiling regime, above the Leidenfrost temperature, the flow is influenced by the appearance of a thin vapor layer between the liquid and the substrate surface. Various breakup modes observed in experiments at various surface temperatures and impact parameters can be subdivided onto (i) rebound, (ii) breakup and rebound, (iii) breakup due to the vapor blowing through the liquid lamella, (iv) droplets ejection from the upper surface of the lamella, (v) complete lamella disintegration, (vi) complete lamella disintegration followed by the very fast radial motion of the fragments [20].

Generally, when the initial wall temperature increases, the breakup of the impacting drop into a myriad of very small secondary droplets occurs at lower impact velocities [21]. The increased temperature leads to higher values for the pressure in the vapor layer under the liquid drop and then to a stronger upward acceleration of the drop, promoting drop instability.

The main subject of the present study is the introduction of a predictive theoretical model for heat transfer during drop impact in the film boiling regime. The model considers the emergence and expansion of the thermal boundary layers in the spreading drop and in the solid substrate [22]. The energy balance at the solid-vapor and vapor-liquid interfaces allows prediction of the evaporation rate and the evolution of the thickness of the vapor layer. Then the heat collected by an impacting drop from a hot substrate is estimated. Finally, an expression for the heat transfer coefficient $\alpha$ is obtained for spray cooling, which accounts for the heat of a single drop impact and for possible drop interactions on the substrate. The theoretical predictions for $\alpha$ agree well with existing experimental data.

## 2. Observations of a single drop impact

To investigate and characterize drop impact phenomena on hot surfaces a high-speed camera system has been used. The experimental setup can be divided into the heating system, the drop generation, the illumination system, the CMOS high-speed cameras (CMOS side and top) and the computer control unit. The setup is shown schematically in Fig. 1.

To record side-view and bottom-view images of the drop impact we use two synchronous CMOS high-speed cameras (2 × *Phantom V12.1*) with a maximum resolution of 1280 × 800 pixel at 6242 frames per second. Both high-speed cameras have been equipped with a 60 mm micro lens (*Nikon AF NIKKOR 1:2.8 D*) and spacer rings (*Nikon*). With this apparatus a spatial resolution of 84 pixels/mm for the side-view and 60 pixels/mm for the bottom-view is achieved. The illumination system (LS-1) is a 120 W LED spotlight (*Constellation 120 E*) and is placed behind the drop to yield shadowgraphy imaging. To achieve a homogeneous background a 3 mm optical diffuser plate (D) between the LED spotlight and the experimental setup is used.

Different thermodynamic regimes have been observed for impact of doubly distilled water drops onto a polished aluminum substrate: Evaporation (a), nucleate boiling (b), foaming (c), transition (d) and film boiling (e). A comparison of rebound and atomization regime at a surface temperature of $T = 330\,^{\circ}\mathrm{C}$ is shown in Fig. 2. The Reynolds number is $Re = 2300$ for the rebound (left) and $Re = 5000$ for the atomization (right) experiment. Because of the higher Reynolds number on the right experiment, the spreading diameter is significantly higher; hence, the lamella is much thinner than on the left experiment. For this reason, fast rising and growing bubbles can produce holes in the lamella ($t = 1.60$ ms) which rapidly expands ($t = 2.14$ ms). This leads to