Observation method to obtain information on the vapour film during the collision of droplets with hot walls

Roth N., Straub T. and Weigand B.

Institute of Aerospace Thermodynamics
University of Stuttgart
Pfaffenwaldring 31
70569 Stuttgart, Germany

The collision of droplets with hot walls has been studied, for the wall temperatures above the Leidenfrost temperature rebound of the droplets was found. The wall is then not wetted by the droplet liquid. The focus of the present study lies on the thin vapour film between the wall and the droplet liquid. The properties of this film are essential for the modelling of heat transfer processes during droplet impact. A method has been developed to observe the spatial extension of the vapour film and to give a qualitative spatial distribution of the film thickness. It was found, that the thickness is smaller at the beginning of the droplet impact and that it increases at later stages of the process. In a first estimation it was found, that the film thickness may be below $0.5\,\mu$m. Then gas kinetic effects may have to be taken into account to describe the heat transfer processes.

1. Introduction

When droplets collide with a wall for instance in a combustion chamber of an aero-engine the droplet may stick on the wall and wet the wall or it can be rebounded (reflected) depending on the boundary conditions like droplet velocity or better droplet momentum perpendicular to the wall, roughness of the wall, wall temperature, and the properties of the droplet liquid. Even if the wall has room temperature, for a small droplet momentum, rebound of the droplets can be observed on a smooth wall [1].

During the collision of droplets with a hot wall, where the wall temperature is above the Leidenfrost temperature, reflection of the droplet normally can be observed, as shown in the upper picture of Fig. 1. In this picture a stream of monodisperse droplets collides with a smooth hot wall [2, 3]. In between the droplet liquid and the wall a vapour film or vapour cushion is formed, which prevents the droplet liquid from wetting the wall. Due to the vapour film, the friction between the droplet liquid and the wall is very small. As there is no direct contact between the hot wall and the droplet liquid, the heat exchange between droplet liquid and wall is quite different from the wetted case. The thickness of the film influences the heat flux essentially.

The rebound of the droplets can be modelled using direct numerical simulation. The

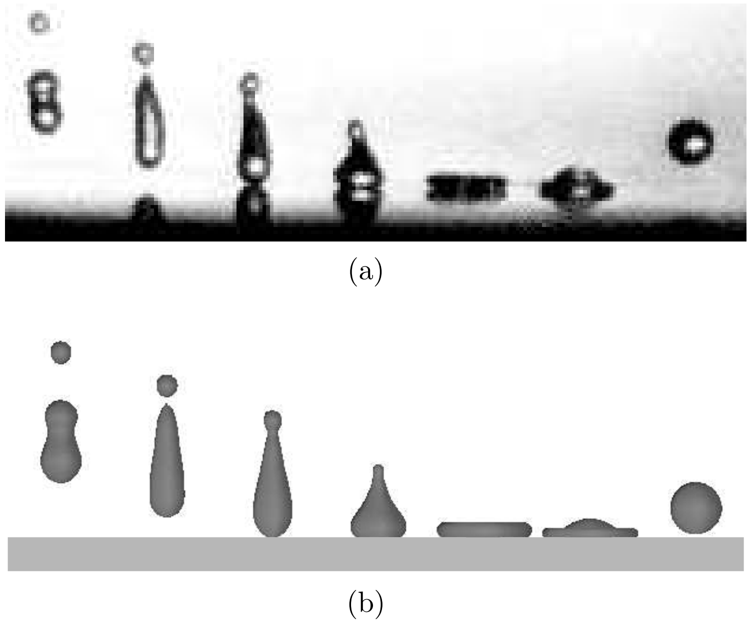

Fig. 1. Rebound of a monodisperse droplet stream from a heated wall with the wall temperature above the Leidenfrost temperature. The droplets move from left to right and impinge with a certain angle onto the wall (a). Numerical simulation with zero friction between droplet liquid and wall (b). The contact angle between droplet liquid and wall has been assumed to be 180°. The numerical results have been obtained with the in house Volume-of-Fluid code FS3D.

program code used for the simulation is an in house code (FS3D) and the results are shown in the lower picture of Fig. 1. The code is based on the Volume-of-Fluid method [4]. Here it was assumed, that there is zero friction between the droplet liquid and the wall, and the contact angle is 180 degrees. The heat exchange between droplet and wall can not be simulated yet. It is expected, that the thickness of the film is much to small to be resolved by the computational grid. Therefore, a model has to be developed in future in order to describe the heat transfer processes. Here in this paper an experimental method is presented, which allows to give a first estimation of the film thickness and of its spatial extension.

2. Experimental Setup

As demonstrated in [1], the wetting of a glass prism, which has been used as the wall, can be detected in observing the total reflected light. In the experiments described here a similar setup has been built. A schematic view of the optical setup is shown in Fig. 2. The light from the flash lamp, which has a very short duration of approximately 200 ns, is split by the beam splitter. One part of the light (light path B) is directed vertically upwards parallel to the side of the prism the droplet impinge on. The monodisperse droplet stream produced by the droplet generator is imaged by camera B [5]. The short illumination by the flash lamp allows to freeze the droplets.

The side of the prism, on which the droplets impinge on, is illuminated from behind by the other part of the light (light path A) in a way, that the light is reflected totally back into the glass at the surface. This light is detected by camera A, which images the surface of the prism, on which the droplets impinge.

In Fig. 3 images of cameras A and B are shown. The image of camera B on the right hand side shows the droplets impinging on the prism surface. The droplet stream arrives from the right hand side and hits the prism surface under a certain angle. Mirror images of the droplets caused by the glass surface can be observed with this adjustment of camera B. It can be seen, that the wall is wetted and a liquid film is driven from right to left by the droplet stream across the prism surface. Then, when wetting occurs, the wetted regions of the surface appear dark or black in the totally reflected light observed

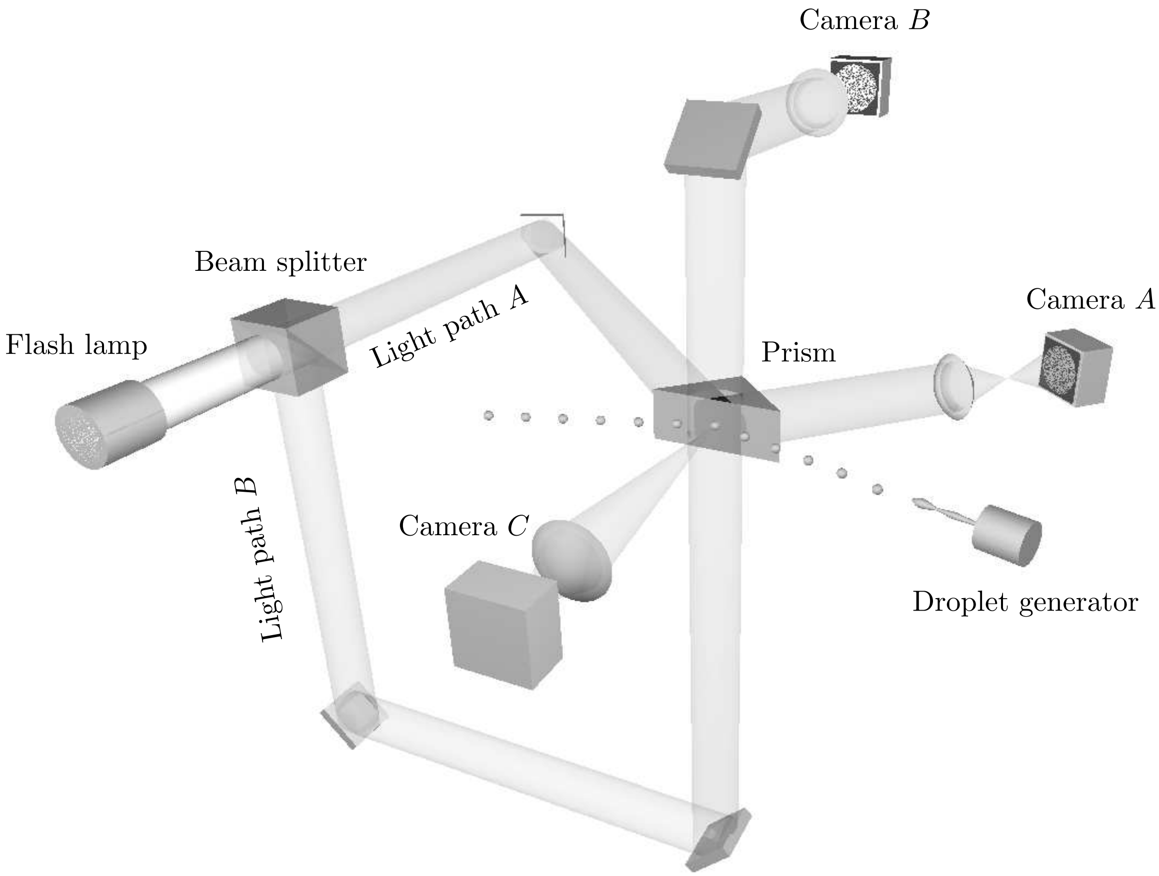

Fig. 2. Schematic view of the optical setup. Camera A detects light from light path A, camera B detects light from light path B, and camera C detects light scattered by the impacting droplets at the surface of the prism.

Fig. 3. Images of camera A on the left and of camera B on the right hand side. On the picture on the left the wetted region of the prism surface clearly can be detected. On the picture on the right the corresponding droplets of the droplet stream moving from right to left can be seen forming a liquid film on the prism surface.

by camera A. The corresponding image is shown on the left hand side of Fig. 3.
With camera C the front side of the prism is imaged. If the surface is wetted the light, which is totally reflected in case with no liquid film, enters the droplet liquid in the wetted regions and is partly scattered towards camera C.
This setup allows to heat the prism above the Leidenfrost temperature. Then it is possible to observe rebound of the droplets at higher droplet velocities. The heating device is not shown in Fig. 2.

3. Observations with droplet rebound

If the wall temperature is fairly above the Leidenfrost temperature the vapour film between droplet liquid and glass surface is build up and becomes thick enough, that no disturbances of the totally reflected light can be observed during the impingement of the droplets. However, when the wall temperature is decreased or the droplet momentum perpendicular to the prism surface increased, circular ring shaped shadows are observed at the locations were the droplet impact on the surface as shown in Fig. 4.

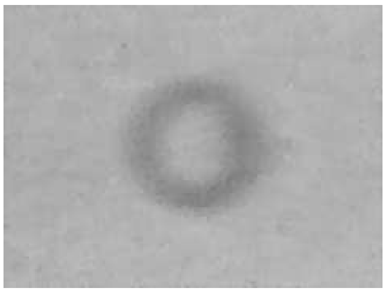

Fig. 4. Circular ring shaped shadow observed in the totally reflected light by camera A. The shadow corresponds to the impingement of a droplet.

What is the explanation for these shadows observed only without wetting with a vapour cushion between the droplet liquid and the wall? When light is totally reflected at the border to a medium, which is optically thinner, part of the light enters the medium with the lower refractive index. These light waves travel parallel to the surface and are called evanescent waves [6]. The intensity of these evanescent waves decays exponentially in the direction perpendicular to the surface. If a particle enters the region close to the surface, where the evanescent waves are significantly strong, the evanescent waves are scattered by the particle and the scattered light can be observed. This effect is used for instance within a "Total Internal Reflection Microscope" (TIRM) [7]. On the other hand the light, which is scattered, is missing in the part of light, which is totally reflected. In Fig. 5 the interaction of a droplet impinging on a wall and the evanescent waves is shown schematically.

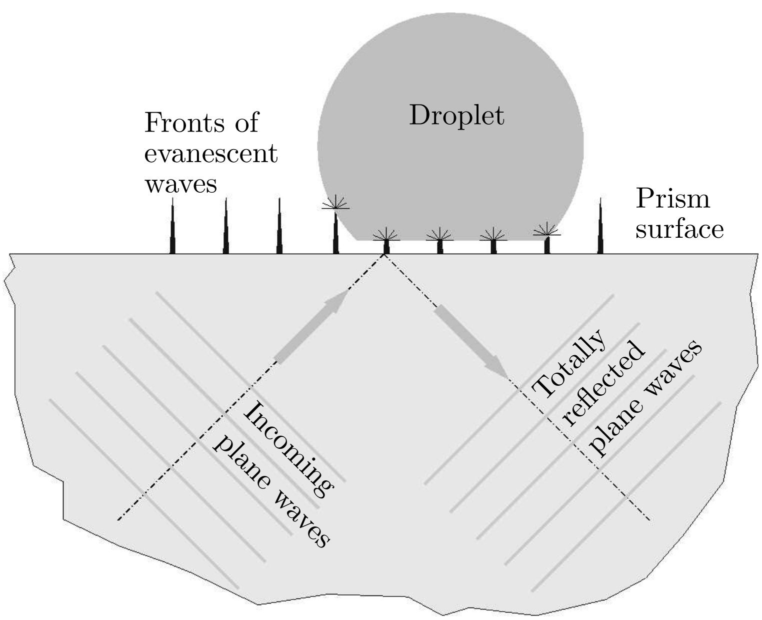

Fig. 5. Sketch of the interaction of the droplets with the evanescent waves. The incoming plane waves are reflected totally at the prism surface and the evanescent waves travel parallel to the surface; the wave fronts are indicated by the peaks on the surface. The intensity of the evanescent waves decays exponentially perpendicular to the prism surface.

When a droplet impinges on a hot surface above the Leidenfrost temperature, the wall is not wetted, as already mentioned above. However, the droplet liquid may be as close to the surface, that the evanescent waves are scattered by the droplet liquid. In the regions, where this happens, the incident light can not be reflected totally and shadows are observed, as shown in Fig. 4. In addition even the scattered light can be observed by camera C, after intensifying the incoming light by a multichannel plate. This scattered light is shown in Fig 6. The direction of observation is approximately perpendicular to the surface of the prism, where the droplet impinges on. The shadows and the scattered light can be observed only simultaneously.

Fig. 6. Light scattered by a droplet, which has entered a region close to the surface, where the evanescent waves are strong enough. The picture shows the scattered light from the same droplet, at the same time, as the droplet, which has produced the shadow shown in Fig. 4. The observed pattern is different from the pattern in Fig. 4 because the scattered light is refracted by the droplet liquid. Corresponding to the shadow the scattered light disappears during the spreading of the droplet.

Assuming that the incident light has a wavelength of $\lambda = 600\,\text{nm}$ the intensity of the evanescent wave decayed from the value directly at the surface $I(x = 0)$ to the value $I(x = 0) \cdot 1/e$ in a distance of $x_e = 518\,\text{nm}$. Therefore, in order to observe significant shadows, the droplet liquid is very close to the surface in the regions of the shadows. It can be assumed, that this distance is below x_e. A comparison of x_e with the mean free path length of the air molecules under normal pressure results in a Knudsen number of $\text{Kn} \approx 0.34$. For Knudsen numbers in this range gas kinetic effects have to be taken into account for describing for instance the heat transfer.

In Fig. 7 images of cameras A, on the left hand side, and B on the right hand side, are shown at four different stages of the droplet impact. That means, that for each stage on the left the images of the shadows and on the right hand side the correspondent image of the droplet stream is shown. The droplet and the corresponding shadow are marked by upward directed arrows. At the top the earliest and at the bottom the latest stage is shown. The droplets, and with them the shadows, move from right to left. A vapour cushion is formed and a shadow can be observed, as soon as the droplets hit the wall indicated by the approach of the droplet to its mirror image. At the top image the dark shadow belongs to the most right droplet, which has already approached the wall. At later stages the diameter of the shadow and therefore the diameter of the vapour film increases. The intensity of the shadows decreases with time. This indicates an increase of the film thickness, as the intensity of the evanescent waves is lower at larger distances from the surface.

At the first and at the second stage very pale shadows can be observed on the left side of the pictures belonging to the left next neighbour droplets in the droplet stream.

At the front side of the shadows in the direction of motion the intensity is less indicating a larger film thickness. This may be recognised on the images of the droplet streams too.

As can be seen from Fig. 7 the shadows are ring shaped. The ring may be caused by the fact, that droplet liquid evaporates at locations the droplet approaches the heated wall. In the middle of the ring the droplet liquid has been for the longest time near the wall and the evaporating vapour has formed a cushion, which pushes the droplet liquid more away from the wall, whereas in the outer region new liquid approaches the wall.

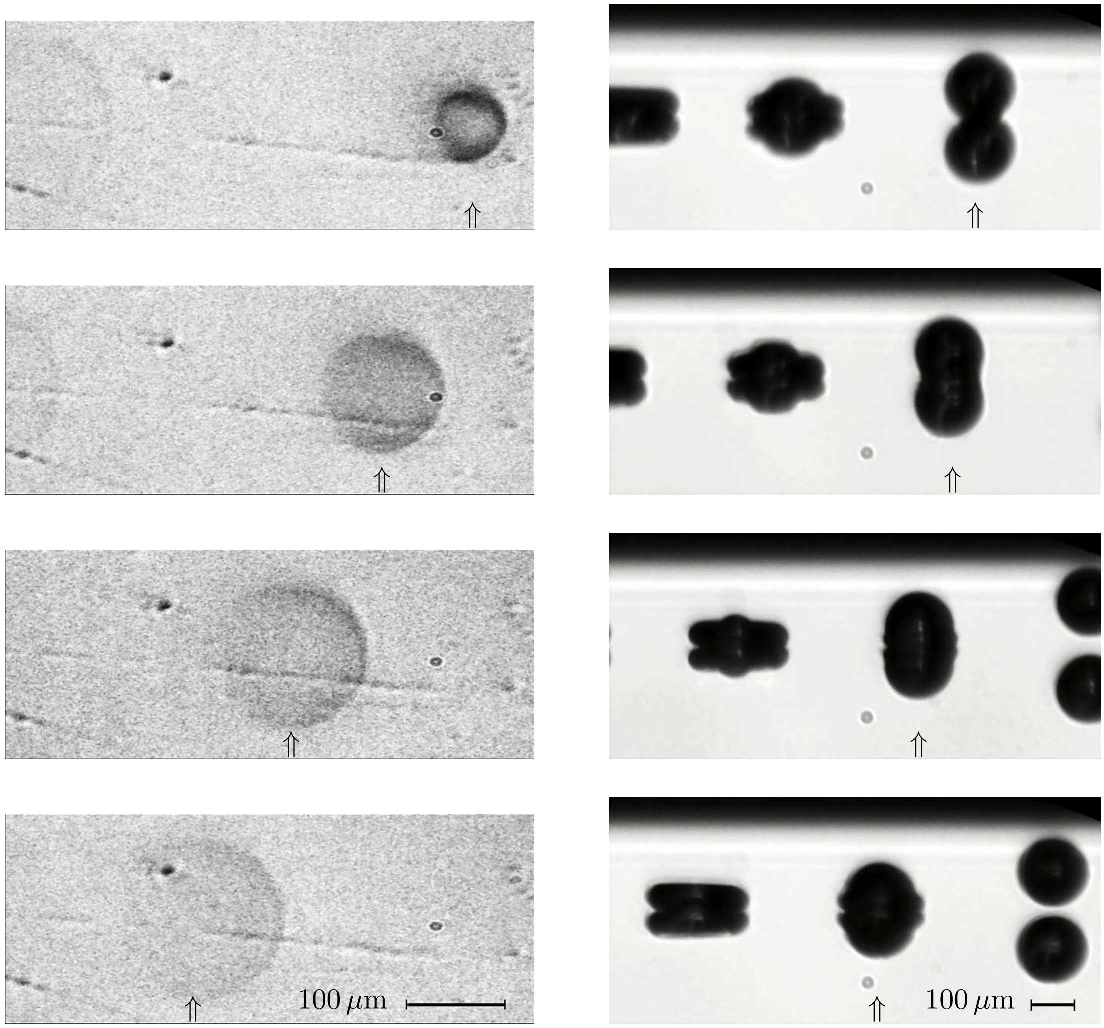

Fig. 7. In the left row shadows observed by camera A are shown at different stages of the droplet impact. In the right row pictures of the correspondent droplets are shown taken by camera B. Corresponding shadows and droplets are marked by upward directed arrows. The cameras and the flash lamp have been triggered simultaneously by the frequence generator stimulating the droplet generator in order to image the same situation at one stage of the droplet impact. To obtain different stages a time delay or phase shift has been applied to the trigger signal.

4. Conclusions and outlook

A method has been described to obtain the qualitative spatial distribution of the thickness of the vapour film between impacting droplets and a hot wall. A first estimation of the film thickness has been given.

This may be a first step in modelling heat transfer processes, as it is now clear that the film thickness is far too small to be resolved by computational grids.

These studies have been performed with the smooth wall of a quartz glass prism. Any disturbances of the surface or an increase of the surface roughness may cause wetting of the surface for a given wall temperature or droplet momentum, because the vapour film may be destroyed. The estimation of the thickness of the vapour film may be a first step for detailed investigations of the influence of surface roughness on the wetting of the surface.

The distribution of the intensity of the shadows is a measure for the film thickness.

As the intensity of the evanescent waves decreases exponentially with distance to the surface, however, this measure is not linear.
One of the next steps will be to obtain numerical data for the film thickness.

5. References

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