Bachelor Assignment

Ambient air pressure influence on the dynamic Leidenfrost temperature of impacting droplets

I.C.W.T.A. van Veldhoven B.F. van Capelleveen

28th July 2014

Supervisors: C. Sun & H.J.J. Staat

Chair: Physics of Fluids
Abstract

Water droplets impacting a superheated silicon surface either exhibit boiling via contact (contact boiling), where they make direct contact with the surface, or boiling via a vapour film which separates the droplet from the surface (film boiling, Leidenfrost boiling). The transition from contact to film boiling depends, *ceteris paribus*, on the surface temperature and the kinetic energy of the droplet. In this study this relationship is investigated for the ambient air pressure. The conditions under which each regime is observed are determined experimentally. After verifying previous results at atmospheric pressure, we show that the transition region occurs at significantly lower temperatures at a set kinetic energy when pressure is decreased. We propose a qualitative relation for this change and present physical arguments as to why the ambient pressure influences this boiling behaviour. We also show that the maximum deformation $\beta = D_{\text{max}} / D_0$ of impacting droplets in the film boiling regime scales with the Weber number, $\text{We}$, as $\beta \sim \text{We}^{0.35}$, regardless of surface temperature or ambient pressure. This scaling is, within error margins, in line with the theory, which predicts a scaling of $\beta \sim \text{We}^{\frac{2}{3}}$. 
## Contents

1 Introduction  2

2 Theoretical Aspects  4
  2.1 Boiling .............................................. 4
      2.1.1 Pool boiling .................................... 4
      2.1.2 The Leidenfrost effect .......................... 6
      2.1.3 Boiling at low pressures ......................... 6
  2.2 On the boiling of droplets ........................... 8
      2.2.1 Sessile drop boiling .............................. 8
      2.2.2 Impacting drop boiling ........................... 8
      2.2.3 Drop shape ...................................... 9
      2.2.4 The vapour layer ................................ 9
  2.3 Hydrodynamic behaviour ................................ 10
      2.3.1 Spreading upon impact ............................ 11

3 Experimental Aspects  14
  3.1 Experimental Setup ................................... 14
  3.2 Experimental Parameters ................................ 15
  3.3 Image Analysis ...................................... 16

4 Results  17
  4.1 Boiling regime ...................................... 17
      4.1.1 Classification .................................... 17
      4.1.2 Phase diagrams water on smooth silicon, varying pressure .... 19
      4.1.3 Pressure dependency of the transition region ............ 21
  4.2 Maximum deformation .................................. 22
      4.2.1 Spreading ........................................ 22
      4.2.2 Fit model ........................................ 23
      4.2.3 Pressure influence ................................ 23

5 Conclusions  24

A Matlab Code  25

Bibliography  30
Chapter 1

Introduction

Impacting droplets are one of the most occurring phenomena on earth. First and foremost, rain hitting leaves, pools and pavement can be observed on a daily basis. In engineering, applications such as fuel injection, spray painting, spray cooling, fire extinguishing, ink-jet printing and plasma coating involve a wide variety of drops of various sizes, speeds, and materials, impacting a wide range of surface structures and surface temperatures. In these processes the outcome of the impact is an important aspect in determining the effectiveness of the operation. For example, how easily a liquid jet breaks up into small droplets determines the quality of fuel injection.

In cooling techniques as pool boiling or jet impingement, high heat dissipation rates can be provided, but they generally fail to insure a uniform cooling. Comparatively, spray cooling technology is of increasing interest since it is characterised by high heat transfer rates, uniformity of heat removal and small fluid inventory [1]. Because of these reasons, drop impacts on heated surfaces have been studied experimentally, analytically and numerically in recent years [1–9].

When, however, the surface to be cooled is at a temperature higher than the boiling point of the coolant, a phase transition from liquid to vapour can occur at the surface. This opens new possibilities. Electrical systems need to be cooled without the coolant leaving residue or having too much contact with the chip [10]. For this the Leidenfrost point is of interest, as all impacts at temperatures above this point are nonwetting.

Tran et al. [7] have sought to describe the Leidenfrost point as a dynamic quantity, changing with the incident velocity of impacting droplets. With the right temperature distribution and knowledge of velocity dependence, one can cool with almost no residue or splashing. For this the Leidenfrost point of different impact velocities is important as one cannot easily change the temperature of a surface to be cooled. But one can change the morphology of the surface [8, 11] to either decrease [8] or increase $T_L$.

In addition to this, more research was done recently regarding the pressure influence on static Leidenfrost droplets [12–14]. A reason for this is the application in macro- and microfluidic devices. Here the residue issue is of importance again. Another aspect of the Leidenfrost droplets comes into play. Leidenfrost droplets show almost no friction [15] and can thus be easily transported through these devices. Celestini et al. [14] proposed using the pressure dependency of the boiling temperature of water to achieve a Leidenfrost point...
at room temperature (see section 2.1.3). Emmerson et al. [12, 13] showed that an increase in ambient pressure provided an increase in the Leidenfrost temperature. From this, one can assume a curve of the Leidenfrost points as a function of pressure that changes with the pressure.

Research has been done independently on pressure dependency and the dependency on impact velocity, but research has yet to be done on both parameters at the same time. Therefore a relation between the impact velocity and ambient pressure could have been neglected, which might greatly influence both the predicted location of the Leidenfrost point and the spreading behaviour at impact. It is possible to conduct an experiment similar to Tran et al. [7] in which impacting droplets are observed for both variable impact velocity and ambient pressure. The outcomes of these impacts are collected in a phase diagram [9] from which the transition curve for a specific pressure is found. The control parameters in these diagrams are the impact velocity and the surface temperature, since both are pressure independent.

The first goal of this research is to create a detailed \((T, v_i)_P\) diagram showing the transition lines of the various pressures for the impact on dry silicon. Starting with confirmation of the results of Tran et al. [7], the Leidenfrost temperature is determined for different impact velocities at different ambient pressures. In addition the hydrodynamic behaviour of the drops during the impact will be investigated and compared to results found in [7, 8, 11]. Due to the continuous vapour layer during impact, the surface can be seen as superhydrophobic [16] and therefore can be compared to hydrodynamic models in that field.
Chapter 2

Theoretical Aspects

This chapter will review impacting droplets on dry smooth superheated surfaces. In order to reach this point, various aspects are first developed. First the phenomenon of boiling is elaborated from its most basic state to the Leidenfrost effect. Then droplet boiling is dealt with in depth. Finally the hydrodynamic aspects of impacting droplets are treated via the development of an energy model.

2.1 Boiling

First and foremost, one needs to know what boiling is. However, boiling is a broad concept with many definitions. One can define boiling purely as the phase transition from liquid to gas states. Or as the temperature after which the Gibbs free energy is lowest without van der Waals bonds present. Finally boiling can be described as a liquid that reaches a temperature, $T_b$, after which a phase transition will occur. Physically this means that the vapour pressure of the liquid has become equal or smaller than the ambient pressure exerted on it [17]. In this research the last definition is used to explain boiling. Since the experiment deals with varying ambient pressure, boiling as an equilibrium of vapour and ambient pressures is most relevant.

2.1.1 Pool boiling

When dealing with a submerged heater in a pool of initially stagnant liquid, we speak of pool boiling [18]. When the heater has a temperature $T > T_b$, with $T_b$ the boiling temperature, it is superheated and boiling can occur. Depending on the excess temperature ($i.e. \Delta T = T - T_b$) four boiling phenomena can be observed, which are shown in figure 2.1.1. Figure 2.1.2 shows the heat transfer curve, from which these four regimes are distinguished.

The first of these regimes is natural convection boiling. This regime exists up until an excess temperature of $+4^{\circ}C$ and is characterised by circular convection streams, caused by the relative density difference between liquid close to and far off to the heater surface. Due to this convection current, the liquid will not evaporate, until the free surface of the liquid reaches the boiling temperature, which only happens after the entire body reaches this temperature.
When the excess temperature increases, a second boiling regime is entered. This regime is called nucleate boiling and is no. 2 in figure 2.1.1. In this regime, vapour will nucleate at specific sites on the heater. These are often cracks or uneven areas where the heater area per unit of liquid volume is relatively large [18]. Initially the boiling is characterised by singular vapour bubbles, but as $\Delta T$ increases, these bubbles will become a more clustered and continuous stream, as seen in no. 3 in fig. 2.1.1.

These slugs are source to an ever increasing layer of vapour between the heater and the liquid. This increase eventually leads to isolation and is the cause for the maximal heat flux, which can be seen in figure 2.1.2. This brings the boiling in its third regime, that of transition boiling. Here boiling is so rapid that unstable films along the heater are present, only the temperature is not high enough to sustain these films. However, due to the partial films, the heat flux greatly decreases, because of the poor conductivity of vapour. The minimum is called $q''_{\text{min}}$ or the Leidenfrost point and occurs when the film is first stable.

If the temperature is increased even further, the film will remain firmly in place and conduction will take over to provide for an increasing heat transfer, despite the insulating layer. Obviously, this regime is steady until the heater surface reaches the melting point of its composite materials.

Boiling in pool, therefore goes from vapour-less convection, through singular bubbles then onto ever more violent and big slugs and patches of vapour up until a steady film is present between the heater and the body of liquid.

![Figure 2.1.1: Four steady regimes of pool boiling in water at 1 atm and their transition regimes. (Reprinted from [19])](image)
2.1.2 The Leidenfrost effect

Since its discovery by J.G. Leidenfrost in 1756 [20] the Leidenfrost effect has kept the attention of physicists and engineers. Much research on the parametric dependency of this phenomenon has been done. Mostly the determination of the Leidenfrost point for different surfaces [16, 21].

The Leidenfrost point is the temperature at which the transition from the 'contact' to 'film' boiling occurs. The reason for this effect is that the liquid evaporates so quickly that a thermally insulating vapour layer lifts up and prohibits contact. Thus decreasing the heat flux and, in the case of a droplet, extending the lifetime. The Leidenfrost point indicates the lowest heat flux in the boiling region. This point is characterised by liquid levitating over the heater surface, never actually touching the surface, but still evaporating at a high enough rate to suspend its body from the heater.

2.1.3 Boiling at low pressures

The introduction of this section already touched on the pressure dependence of the boiling point. As the ambient pressure drops, one would assume that the temperature at which the vapour pressure equals the ambient pressure decreases. The Clausius-Clapeyron relation
seeks to ratify this pressure dependency [22]. It states:

\[
\frac{dP}{dT} = \frac{L}{T \Delta v} \tag{2.1.1}
\]

With \( \frac{dP}{dT} \) the slope of the coexistence curve, \( L \) the specific latent heat, \( T \) the temperature and \( \Delta v \) the specific volume change of the transition. As this experiment deals with temperature of water well below the critical point of 374°C this relation can be approximated with \( \Delta v = v_g \), with \( v_g \) from the ideal gas law. The relation now becomes:

\[
\ln P = \frac{L}{R} \left( \frac{1}{T} \right) + C \tag{2.1.2}
\]

Which holds for transitions between the gaseous and liquid states of a substance. This relation, however, has unknown constants which inhibits the determination of the boiling point at a specific pressure. The Antoine equation [23] provides a three parameter fit for this curve, which otherwise would have to be determined empirically:

\[
T_b = \frac{1730.63}{8.07131 - \log_{10} P_v} - 233.426 \tag{2.1.3}
\]

With the parameters used for water of temperatures between 1 and 100 degrees Celsius and \( P \) in mmHg. As \( P_v \) is the vapour pressure, one can set this equal to the ambient pressure and find the boiling points of water at varying pressure. Figure 2.1.3 shows the boiling point of water versus its ambient pressure. It is clear that within change of pressure an order of magnitude, the boiling point changes in the same order of magnitude, implying great influence from the ambient pressure.

![Figure 2.1.3: Boiling point of water as a function of vapour pressure, via the Antoine equation (2.1.3). Vapour pressure is set equal to ambient pressure, to determine phase transition temperature. The Antoine equation has a relative deviation of maximal ±2% is this range.](image-url)
2.2 On the boiling of droplets

2.2.1 Sessile drop boiling

If the body of liquid is removed and replaced by a single droplet of water, one is a step closer to boiling of impacting droplets. All the boiling regimes developed in the previous section are present in this type of boiling. As can be seen in figure 2.1.2 the heat transfer, with all other parameters held constant, follows the same pattern as pool boiling. However, due to the small mass of the droplet, it is now viable to describe boiling via a lifetime \( \tau \). When the heat transfer is low, lifetime will be high and the other way around. A plot of this relation is provided by Biance et al. [24] and shown in figure 2.2.1. The peak visible in the figure, corresponds with \( q''_{\text{min}} \), the heat transfer discussed in the previous section. As noted, this point is the Leidenfrost point and is characterised by levitating, non-wetting droplets that evaporate slowest. In this regime, the temperature in the droplet is found to be at a constant 99±1°C [24]. Figure 2.2.1 shows a very clear minimum, only some 10 degrees above the boiling temperature. This is the burnout point, which indicates transition from nucleate to transition boiling. The peak visible in this figure is the Leidenfrost point, which represents the transition from the transition boiling to film boiling.

2.2.2 Impacting drop boiling

Analogous to the previous sections, the case of an impinging droplet on a superheated plate presents different regimes of boiling. These can be classified according to wetting or non-wetting, where the difference is in direct contact between the droplet and the surface [7, 8, 11, 15], the latter being at and beyond the Leidenfrost point. In the wetting regime, the droplet can exhibit nucleate boiling when the excess temperature is low enough to allow a full impact before internal temperature reaches \( T_b \). With increasing temperature, this boiling becomes ever more present, until the droplet boils directly on impact. After this point, boiling enters the transition regime where a small vapour layer can exist before

Figure 2.2.1: Lifetime \( \tau \) of a sessile droplet, deposited on a heated surface as function of its temperature. (Reprinted from [24])

Figure 2.2.2: Phase diagram for water droplet impact on a heated surface showing: contact boiling regime (red), gentle film boiling regime (blue), spraying film boiling regime (green). The dashed lines are drawn to guide the eye. (Adapted from [7])
impact. This is however too thin to absorb the impact of the droplet and thus some contact with the surface will occur.

As noted before, once a ‘dry rebound’ is achieved, the temperature has transcended the Leidenfrost point. The boiling is then in the film-boiling regime. Different from a static droplet boiling, another regime after film boiling is observed [7]. This boiling is accredited to the bursting of vapour bubbles in the liquid film. As the impact velocity is increased, the liquid film gets thinner and it is easier for the boiling bubbles to burst through the liquid’s upper surface as can be seen in figure 2.2.2.

If the impact velocity increases, will the Leidenfrost temperature also increase? On the one hand, the droplet spends only a few milliseconds on the solid, so the vapour film might be thinner than in the sessile situation. On the other hand, the impinging drop presses on the film with a dynamic pressure $\rho V^2$ much larger than the hydrostatic pressure in a static case. Hence dynamic film boiling is more demanding than static levitation, and the Leidenfrost temperature $T_L$ can be shifted to higher values and increases with $\text{We}$ [7, 15, 25].

In order for the vapour film to be stable, the rate of vapour generation should be sufficient to feed the film to sustain the weight of the drop. When the drop has an impact velocity, there should be extra vapour generation to prevent the drop from touching the surface. As the Weber number increases, so does the impact velocity. This means that as the Weber number increases, the surface temperature should be higher to get the needed extra vapour to sustain the vapour film [7].

2.2.3 Drop shape

Young’s relationship for the contact angles of a droplet on a surface, $\cos \theta = (\gamma_{SV} - \gamma_{SL})/\gamma_{LV}$ solves to $\theta = 180^\circ$ for the case of film boiling, since the vapour is both the surrounding gas as the liquid. Since Leidenfrost is non-wetting, the droplets are quasi-spheres on and during impact [15]. This means that the hydrodynamic behavior is expected to show similarities with drop impacts on superhydrophobic surfaces at room temperature, which show rebounding.

Figure 2.3.1 shows the shape evolution of a Leidenfrost droplet in the time dimension. It is clear that the impact is somewhat elastic in nature, which can be attributed to both the compression of the vapour layer and the surface tension of the droplet restoring the least energy configuration. The next section will deal in depth with the phenomenon and its mathematical model.

2.2.4 The vapour layer

Thickness

The thickness of the vapour layer on which the Leidenfrost droplet floats is of order $\delta \sim 20\mu m$ in the static case, for droplets of about 2mm in diameter, as determined by Bianca.
[24] and Gottfried [16]. In this sessile state, they found the vapour layer to be of an decreasing thickness scaling with the initial radius and $\Delta T$ of the droplet and the surface [24].

However this type of vapour layer is only present in this experiment after all the kinetic energy of the impinging drop is gone. The vapour layer of the dynamic regime is of interest here. It turns out that in this regime, the thickness of the layer is one of an order of magnitude smaller, $\delta \sim 2\mu m$, than in the static case with similar surface temperatures [7].

**Pressure influence**

Celestini et al. [14] have controlled the behaviour of the static Leidenfrost point for varying pressures at a set temperature. They argue that lower pressure, also decreases the excess temperature necessary to obtain the Leidenfrost boiling. The droplet, therefore, has a lifetime order 10 larger at 50 mbar than at atmospheric pressure [14]. In addition the vapour layer has a retraining pressure on the spreading liquid, thus destabilising the spreading front and pushing it back upward. This would mean that at low pressures this effect decreases, in effect making it more difficult for a stable film layer to exist. However when the drop spreads on impact, the vapour is squeezed out from between the drop and the surface, so more vapour needs to be generated to sustain the vapour layer. This vapour can only flow outward. As the plate temperature gets higher, more heat is transferred through the vapour, so more vapour is generated. More vapour means a higher flow velocity. This is not observed in experiments [7, 8, 11]. This lack of temperature dependence is most likely caused by a balance between the thickness of the vapour film the drop and the temperature of the plate, where a higher temperature will result in a thicker vapour film. Similarly a lower pressure should make it easier for the vapour layer to flow outward, as the pressure on the vapour created by the droplet is constant, but the pressure difference is higher. But this will most likely result in a thinner vapour layer, as the surface of the droplet is also under stress from this lower pressure and might thus not press as hard on the vapour layer as in the atmospheric case.

**2.3 Hydrodynamic behaviour**

Due to the vapour layer, formed when in the film-boiling regime, the adhesion between the surface and the droplet decreases dramatically. Because of this decrease of adhesion, the impact of a droplet in the film-boiling regime could perhaps be compared with the impact of a droplet on a super-hydrophobic surface at room temperature. After an impact of the droplet on a super-hydrophobic surface, the droplet will rebound [15, 26, 27], this also happens after a impact of a droplet with the silicon surface, when in the film-boiling regime. In this section the behaviour of droplets after impact will be discussed, only droplets in the film-boiling regime will be considered in this section.
2.3.1 Spreading upon impact

After the impact of a droplet on a surface, the droplet will slow down in vertical direction. Due to inertia the droplet will deform in horizontal direction. While slowing down, the kinetic energy of the droplet will decrease and is used to establish a greater surface, which needs energy due to the surface tension of the liquid. When the kinetic energy has the minimum value, the surface of the deformed droplet will be at the maximum value, the diameter of the droplet at this stage is called $D_{\text{max}}$. Because of the surface tension there is a force inwards and the droplet will contract and the surface area of the droplet will decrease. The energy that is released when the surface area decreases, is converted back to kinetic energy, that’s why the droplet rebounds.

In this report the amount of deformation of the droplet is denoted as the dimensionless spreading diameter, $\beta = D_{\text{max}}/D_0$ with $D_{\text{max}}$ the maximum value of the diameter of the droplet and $D_0$ the diameter of the droplet before impact as can be seen in figure 2.3.1. There are different models how $\beta$ could depend on the measured quantities, these different models differ only in which parameters can be neglected, in the next paragraphs three of these different models are discussed. The first two models are based on impacting drops on super-hydrophobic surfaces at room temperature, the third model is based on droplets in the film-boiling regime.

![Figure 2.3.1: Time evolution of a rebounding droplet, with definitions of $D_0$ and $D_{\text{max}}$: (a) moment of impact, with $D = D_0$, (b) spreading phase, (c) maximum spreading with $D = D_{\text{max}}$, (d) rebound](image)

**Impact with no dissipation**

The deformation is a balance between the kinetic energy and the surface energy, since the Weber number is the ratio of inertia and surface tension it can be useful to look at this number. The Weber number for a droplet with density $\rho$, surface tension $\sigma$, velocity $V_0$ before the impact and initial diameter $D_0$ is:

$$\text{We} = \frac{\rho V_0^2 D_0}{\sigma} \quad (2.3.1)$$

If $\text{We}$ is smaller than 1, the surface tension is small with respect to the inertia force, so the droplet deforms only slightly [28]. When $\text{We}$ is much greater then one, deformation as in figure 2.3.1 will be seen.
If there is no dissipation of energy while the droplet deforms, all the initial kinetic energy will be converted into surface energy at maximum deformation:

\[ mV_0^2 \sim \sigma D_{max}^2 \Rightarrow \rho D_0 V_0^2 \sim \sigma D_{max}^2 \]  \hspace{1cm} (2.3.2)

Where \( m \) is the mass of the droplet. In this case the surface energy of the droplet before impact is neglected. So this model will only apply to droplets with a great deformation surface with respect to the initial surface, so droplets with large Weber numbers. In rearranging the parameters of equation 2.3.2 a scaling of \( \beta \) can be found.

\[ \frac{\rho D_0 V_0^2}{\sigma} \sim \frac{D_{max}^2}{D_0^2} \Rightarrow \beta \sim We^{1/2} \]  \hspace{1cm} (2.3.3)

However, in the many experiments which have been done in this field, always a lower scaling has been found [26]. So another model is needed to explain the spreading of a droplet correct.

**Gravity puddle model**

In the model of energy conservation, the energy dissipation of the droplet at impact has not been taken into account. However there is a way to omit the dissipation, for which another model is needed.

The form of the droplet at impact can be compared with the form of a droplet at rest on a surface at room temperature. This droplet at rest deforms due to gravity acting on the droplet. The capillary length of the droplet at rest, \( l \), is defined as \( l \sim \sqrt{\frac{\sigma}{\rho g}} \) where \( g \) is the acceleration on the droplet [29]. For an impacting droplet the acceleration at impact is different, since the droplet experiences acceleration due to the impact with the surface. The droplet has a typical time \( t_a \sim D_0/V_0 \) to slow down from an impact velocity \( V_0 \) to a velocity of zero, so the acceleration at this moment is \( a \sim V_0/t_a = V_0^2/D_0 \). With this acceleration substituted the height of the droplet at maximum deformation:

\[ l \sim \sqrt{\frac{\sigma}{\rho V_0^2/D_0}} \]

For droplets with a high Weber number, the shape at maximum deformation can be approximated as a flat disk. So, with conservation of volume, \( D_0^3 \sim l \cdot D_{max}^2 \) and rearranging the terms a scaling of \( \beta \sim We^{1/4} \) is found. This scaling is in line with experimental data [26, 30].

**Spreading on vapour flow**

In the model of energy conservation and the gravity puddle model, only impacting droplets on surfaces at room temperature are considered. Also a model for droplets in the film-boiling regime can be developed. In the film-boiling regime, a vapour cushion is generated.
and the droplet does not touch the surface. When the droplet deforms during impact, the droplet will become a flat disk and the film is squeezed between the droplet and the surface. So to sustain the vapour film between the droplet and the silicon surface, more vapour needs to be generated. Since the continuously generated vapour can only flow radially outwards, this viscous flow may increase the maximum deformation and so another scaling can be found. In Tran et al. [8] the scaling is mathematically derived:

\[
\beta \sim \left( \frac{\mu_v k_v \Delta T}{\rho_v \sigma L D_0} \right)^{1/10} \text{We}^{3/10}
\]

With \(\mu_v\) is the viscosity of the vapour, \(k_v\) is the thermal conductivity of the vapour, \(\Delta T\) is the temperature difference between the silicon surface and the surface if the droplet, \(\rho_v\) the density of the vapour and \(L\) the latent heat of evaporation. Since \(\mu_v, k_v, \rho_v, \sigma, L\) and \(D_0\) are constant and \(\Delta T^{1/10}\) is negligible due to the tenth root, \(\beta\) scales as \(\beta \sim \text{We}^{3/10}\).

**External Influences**

When one looks at the three different scaling laws, no pressure dependency can be found, since the surface tension [31], the density and viscosity do not vary with different pressures. Also the thermal conductivity and latent heat of evaporation are pressure independent [18]. It’s therefore plausible that \(\beta\) is constant over the different pressures.

Also the spreading could depend on the temperature of the droplet or the environment. However the temperature of the chamber is kept constant at room temperature and also the temperature of the water is around 24°C. The surface tension decreases at higher temperature [32] but the amount of decreasing is negligible at the temperature scale in these measurements [7].
Chapter 3

Experimental Aspects

This chapter is focussed on elaborating the setup used to investigate the boiling states of impacting water droplets. It deals in detail with the experimental parameters used, both static and control. Finally the data aquisition from the high speed recordings will be discussed.

3.1 Experimental Setup

In order to find a reliable transition region between boiling states, one must record many impacts. Those results will, however, only give way to meaningfull interpretation as long as the experiment is repeated under the same conditions. A setup is needed where the conditions (i.e. ambient temperature, ambient pressure) can be controlled and set as constant.

The setup used consists of a stainless steel vacuum chamser, with two windows at either side to allow external lighting and visibility for the high speed camera (Photron Fastcam SA1.1). This chamber is connected to a vacuum pump in order to realise low local pressures, as can be seen in figure 3.1.1. In addition, an adjustable heater is placed underneath the impact surface to set the temperature of the surface (silicon). Due to the closed nature of the system, an active water-based cooler is used to keep the walls of the chamber at a constant temperature, to combat the radiation and convection heating from the silicon surface.

Figure 3.1.1: Schematic drawing of the entire setup used to record impacts. Substrate, 6 is heated by the heater, 2 and droplet are fed through a tube, 4. This is recorded at 10,000 fps by the camera 1. The pump, 3 keeps the ambient pressure in the vacuum chamber, 5 at a constant value.
To create drops of a uniform diameter $D$, liquid (in this experiment Milli Q water) is pushed out from a syringe pump at a controlled rate, by use of a syringe pump (Harvard PicoPlus), into a tube and into a steel capillary needle. The rate is set as to create spherical droplets underneath the needle’s tip in such a way that detachment due to gravity occurs from a stationary state. The diameter of the droplet scales with the outer diameter of the used needle. Further, the impact velocity can be adjusted by either raising or lowering the tube in the opening in the lid of the vacuum chamber.

In figure 3.1.2 a schematic sideview of the inside of the vacuum chamber is shown. The heater consists of three radially inserted heating components and is controlled via a PID system. It is assumed that there is infinite internal heat transfer and negligible heat loss at the interface of the heater and the substrate and that therefore the probed temperature is equal to the temperature of the surface. This is valid, because only highly conducting materials are used, and the other interface is between the heater and air, which is a very bad heat conductor.

3.2 Experimental Parameters

The temperature of the plate $T$, the Weber number, $\text{We} = \frac{\rho D_0 V_0^2}{\sigma}$ and the ambient pressure in the vacuum chamber, $P$ are the control parameters for the experiment. At the very least these parameters need to be known in order to come to a valid conclusion. All, except $D_0$ and $V_0$ can be set and determined beforehand. In table 3.2.1 the values of the known parameters are given, these are taken form literature or set experimentally. The temperature is measured with a probe within the heater, but is assumed to be equal to the surface temperature of the substrate. With use of an external probe it was determined that this equilibrium came to be some time later and would differ being up to three degrees Celsius lower with the internal probe. Measurements done after this equilibrium was achieved had an uncertainty of one degree Celsius. Due to leakage within the vacuum chamber, the pressure varied with three mbar from the setpoint. The diameter of the drop, $D_0$ can be determined from the liquid properties and the diameter of the needle and the impact velocity $V_0$ from the height of the needle. However, this is both a tedious task and an inaccurate one. As the diameter varies with three percent and in the impact, air drag is neglected. It was therefore decided to use the already present high speed recordings.
to determine these parameters. For the method see section 3.3 and Appendix A. For all experiments a Photron Fastcam SA1.1 is used. A frame rate of 10,000fps and a shutter speed of 1/60,000s was used.

\[
D_0 = 2\text{mm}, \quad V_0 = 3\text{m/s (max)} \\
\tau_c \approx \frac{D_0}{V_0} = \frac{2 \cdot 10^{-3}}{3} = 0.7 \cdot 10^{-3}s
\]

So this framerate allows for a more than sufficient velocity determination and visual clarity to observe the boiling behaviour, as well as the determination of the droplet diameter.

### 3.3 Image Analysis

The recordings from the high speed camera are used to calculate the diameter of the droplet as well as the impact velocity and the maximum spreading diameter during impact. Since this experiment entails some 600 measurements, a dedicated routine was used and updated to suit the needs [33] for this particular setup. The final code is to be found in Appendix A and the following is a short description. After importing a recording, the script detects the droplet in the frame and follows it to the frame of impact. Ten frames before this impact are taken and the centre of the droplet is tracked in each to determine the velocity. All frames after impact are analyzed in order to determine the maximum spreading of the droplet before bouncing. The code can be set to run in batch mode and returns faulty iterations, to be adjusted by the user. The found variables, velocity graph and impact frame are all saved in order for the user to review the program’s accuracy.
Chapter 4

Results

4.1 Boiling regime

4.1.1 Classification

Ideally, the boiling regimes given in figure 2.1.1 would be used to classify the observed boiling states obtained from the high speed recordings. However, due to the size of the droplet and the nature of the recordings, it is not possible to distinguish from nucleate and transition boiling. Since the main point of the recordings is to accurately determine the Leidenfrost point for a set of parameters, this problem is of no significance. Instead both regimes are bundled and labeled as the contact-boiling regime. Characteristics of this regime are droplets shooting off at impact, the entrapment of vapour bubbles and a spray of small secondary droplets on spreading. Figure 4.1.1a shows a typical recording of this regime. The droplet is impacting on a superheated smooth silicon surface with $W_e = 24$, $T_s = 350^\circ C$.

Due to the plate temperature in this study being too high for convection boiling, this regime is excluded from analysis. This leaves the last regime, the film-boiling regime. This regime takes place for $T_s > T_L$. This regime is characterised as a drop rebounding at the surface, with a vapour film separating the surface and droplet. Figure 4.1.1c shows a typical impact for this regime with a water drop impinging on a superheated silicon surface with $W_e = 23$, $T_s = 400^\circ C$. Note that in section 2.2.2, spraying film boiling was introduced when the temperature lies well above $T_L$. This boiling regime has not been observed and is therefore not included in the classification.

However, observation was made of an intermediate boiling state which is visible in figure 4.1.1b. This boiling is dubbed the transition regime and is characterised by near perfect film boiling, with the exception of a spray of a few secondary drops forming at or almost at maximum deformation. This classification is included to find the Leidenfrost point more accurately and to visualise the transition region more clearly. The measurement in the figure is of a drop impact on superheated silicon with $W_e = 24$, $T_s = 390^\circ C$.

1Note the difference between the transition regime and the transition region. The first is indicative of a boiling state, the second is the region wherein the Leidenfrost point is found and which divides contact and film boiling.
Figure 4.1.1: Classification of the used boiling regimes in the phase diagram for drop impact on a superheated surfaces: (a) $\text{We} = 24$, $T_s = 350^\circ\text{C}$, (b) $\text{We} = 23$, $T_s = 390^\circ\text{C}$, (c) $\text{We} = 23$, $T_s = 400^\circ\text{C}$.
4.1.2 Phase diagrams water on smooth silicon, varying pressure

Many recordings, comparable to those of figure 4.1.1 were made at different plate temperatures and impact velocities in addition to different ambient pressures. After a scan in the temperature range at a set impact velocity and pressure, points around the transition are repeated until an accurate transition temperature is found. In order to make sure that assignment to a specific boiling regime is repeatable in \((T_s, v_i)\_P\) space, all measurements in this region are performed at least three times. When the results are not consistent, more impacts are recorded until there is a clear majority of one of the regimes. With all points collected and classified, a phase diagram is made as in figure 4.1.2. The blue points indicate contact boiling, the green diamonds indicate film boiling and the red squares indicate the transition impacts. In the phase diagram of pressure at 625 mbar two transition regions were found. This is most probably a fault in the measurements as the measurement occurred over multiple days, as a result the data collected at 625 mbar is not included.

As discussed in section 2.3.1 the Leidenfrost point is believed to be at a higher temperature for higher impact velocities. This is indeed the trend observed in figure 4.1.2 and figure 4.1.3a,b,d-f. At 500 mbar, 4.1.3c a different behaviour can be observed, since the reason for this behaviour is unknown it is recommended to redo the measurements at 500 mbar. The figures also indicate an decrease of the transition region and thus the Leidenfrost point at lower pressures.

Figure 4.1.2: Phase diagram for water drop impact on a surface of superheated smooth silicon showing three separate regimes. Ambient pressure was 1000 mbar and the diameter of the droplet 2.3 ± 0.1mm. Indicated with the black brackets are the maximum transitions observed. The Leidenfrost point lies within this region, most likely in the middle of the brackets.
Figure 4.1.3: Phase diagrams for all measured pressures. Impact velocity was chosen in stead of Weber number as the x-axis, because the parameters of the Weber number could not be verified to be pressure independent and would thus impair the credibility of the final phase diagrams. Droplet size was $2.3 \pm 0.1\text{mm}$. The black brackets represent the maximum transition region. The Leidenfrost point lies in this region.
4.1.3 Pressure dependency of the transition region

In order to obtain a pressure dependency of the transition region, all the black brackets in figure 4.1.2 and figure 4.1.3, which indicate the transition regions, are plotted in figure 4.1.4.

As can be seen in figure 4.1.4, most of the transition regions are lowered in temperature at lower pressures. However, this reduction decreases as the impact velocity increases. At a certain velocity the Leidenfrost temperature seems to near a constant around $400^\circ C$ after which it almost does not increase with the velocity. In the measured range, the transition regions at 1000 mbar, 875 mbar, 750 mbar, 500 mbar and 375 mbar all converge to this temperature. The transition regions at 250 mbar and 128 mbar, do not reach a Leidenfrost temperature of $400^\circ C$, but their transition regions are still rising, so it is possible that at a higher impact velocity the 250 mbar and 128 mbar curves will reach this maximum temperature for the dynamic Leidenfrost point. As stated in section 2.2.4 the transition indeed occurs at lower temperature for a lower pressure. The effect is clearly greater at lower impact velocities, implying that the impact has a greater influence on the Leidenfrost
temperature than the ambient pressure. Most likely this is due the vapour layer being itself at a low pressure if the ambient pressure is low, thus more vapour is needed to absorb the impact. This vapour is created more rapidly, since the water boils at a lower temperature. However, at higher impact velocities, this increase in vapour generation falls short.

4.2 Maximum deformation

4.2.1 Spreading

For all the measurements in the film-boiling regime the maximum diameter after impact is determined. In the measurements the ambient pressure varies from 128 mbar to 1000 mbar. The Weber number ranges from 7 to 87 and the initial diameter of the droplet before impact, $D_0$, is $2.3 \pm 0.1$ mm. In figure 4.2.1 the maximum deformation for the different pressures is plotted against the Weber number. In this figure the data from this experiment is compared with the data from Tran et al. [7].

![Figure 4.2.1: Log-log plot of the maximum deformation of rebounding droplets in the film boiling regime at different pressures against the Weber numbers of the droplets before impact. The theoretical fit lines of $We^{1/2}$ and $We^{1/4}$ are given. In addition spreading data from [7] is included (grey asterisks) alongside the $We^{3/10}$ scaling proposed in section 2.3.1](image-url)
4.2.2 Fit model

The measured data is plotted against the Weber number on a logarithmic scale, to verify whether $\beta$ scales exponentially with $\text{We}$, in accordance with the theory. See figure 4.2.1 for this logarithmic plot.

In figure 4.2.1 a linear relation can be observed, the slope of this is 0.35. So $\beta$ scales exponentially with $\text{We}$ indeed, however the scaling is around $\text{We}^{0.35}$ which is different than the first two discussed models in section 2.3.1 which predicted a scaling of $\beta \sim \text{We}^{1/2}$ or $\beta \sim \text{We}^{1/4}$. The reason for this difference is the fact that both models are based on impacting droplets on surfaces at room temperature, so the third model, which is based on a droplet in the Leidenfrost regime, should be better. Indeed the model which predicted a scaling of $\beta \sim \text{We}^{3/10}$ corresponds best with the found data. An error in our data may be due to the fact that the temperature of the droplet is not constant. Many of the pre-factors in the vapour flow model are dependent of the temperature of the liquid. There is a possible increase in temperature from heating of the liquid in the tube. At lower Weber number the temperature of the water can be higher, since the needle is closer to the heater.

As can be seen, the datapoints are systematically higher than the data collected by Tran et al. [7] reason for this difference may be the different determination method for the maximum spreading, which may result in an difference with their data. Tran used an imaga analysis script contingent on edge detection, whereas in this experiment all spreading was determined by manual visual image analysis.

4.2.3 Pressure influence

As predicted, the maximum deformation is independent of the ambient pressure and the internal pressure of the droplet. This independence can be deduced from figure 4.2.1. Since the maximum deformation is independent of the internal and ambient pressure, also the scaling of $\beta$ with $\text{We}$ is independent of the internal and ambient pressure. This can be seen in figure 4.2.1, as all measured points are distributed randomly with a non significant variation.
Chapter 5

Conclusions

Boiling regime

For seven different pressures, ranging from 128 mbar to 1000 mbar, phase diagrams were made for water impacting on a superheated silicon surface. In the phase diagrams three different boiling regimes are distinguished: contact-boiling regime, transition regime and film-boiling regime. At each pressure the dynamic Leidenfrost effect is observed. The dynamic Leidenfrost temperature, which is the transition from contact to film boiling, is increased by increasing the impact velocity, which can be explained by a balance of inertia and the vapour layer that needs to be generated to absorb the impacting droplet.

At lower pressure, the temperature where a transition between contact boiling and film-boiling is observed, decreases. The biggest difference is observed at the lowest impact velocities and thus this variation increases as the pressure decreases. Since for lower pressures, the boiling point of water is also lower, vapour is created at lower temperatures allowing for equivalent vapour generation at lower temperatures, compared to the atmospheric case.

The observed change in the location of the transition region is dependent on the impact velocity. At low impact velocities, the difference caused by a lower pressure is quite significant. Whereas at higher impact velocities this differences decreases to smaller values or overlaps with the atmospheric case all together.

Maximum deformation

In the measured regime, Weber number varies from 7 to 87, the maximum deformation of the droplet scales like the impact of droplets on super-hydrophobic surfaces with the Weber number, according to:

\[ \beta \sim \text{We}^{0.35} \]  \hspace{1cm} (5.0.1)

This power law is independent of the ambient pressure and of the temperature of the surface, for temperature of the surface is greater than the Leidenfrost temperature, since only impacts in the film-boiling regime are considered.
Appendix A

Matlab Code

Impact and Velocity[33]

```matlab
function [D_pix,v_pix,DS_pix,IDtouch,We] = AllInOneAnalysis(Bo,FR,dp,map,...
    ,fp,N,cut,Dg,IDtouch,cam,spread,Tol,Liquid)

% Output variables:
% D_pix = drop diameter (in pixel)
% v_pix = drop velocity (in pixel)
% DS_pix = maximum deformation (in pixel/frame)
% IDtouch = Framenumber of impact
%
% Manual input variables:
% Bo = Boiling state
% FR = Framerate (in fps)
% dp = pixel size (in m)
% N = Amount of frames to use for velocity calculation
% cut = N pixels to include on each side for region of interest (ROI)
% Dg = Initial guessed size of drop (in m)
% cam = Camera setup used
% spread = type of maximum deformation determination
% fp = folder name of current movie
% IDtouch = framenumber of impact (0 when not known, then it is determined)
% global sens;
% global GDS_pix;
% Find the Region of Interest to reduce calculation time
sens=0.9;
GDS_pix = Dg/dp;
[ROI] = RegionOfInterest(map,fp,1,cut);
Dg = GDS_pix*dp; % New guess of drop diameter

% Finding frame of drop impact
[IDtouch] = ImageOfTouch(map,fp,ROI,IDtouch);

% Determining drop diameter, velocity and Weber number
if IDtouch ~= 99
    if strcmp(spread,'waist') || strcmp(spread,'none')
        [D_pix,v_pix,We] = Velocity(map,fp,dp,FR,IDtouch,N,ROI,Dg,Tol,Liquid);
    end
end
```
else
    D_pix=0; v_pix=0; We = 0;
end
else
    D_pix=0; v_pix=0; We = 0; DS_pix = 0;
end

%% -------- Sub functions -------------------------------------------------
function [ROI] = RegionOfInterest(map,fp,FrameNo,cut)
global sens GDS_pix

%% Read image and detect droplet
I = imread(['map','/',fp,'.tif'],FrameNo);
dim = size(I);
I=imadjust(I);

% Circel Finder
[centers, radii]=imfindcircles(I,[floor(GDS_pix/2-20) ceil(GDS_pix/2+20)]
    ,'ObjectPolarity','dark','Sensitivity',sens);

% Stel we hebben niet een druppel ontdekt of twee
while size(radii,1)~=1;
    if size(radii,1) == 0;
        sens=sens+0.02;
        [centers, radii]=imfindcircles(I,[floor(GDS_pix/2-20) ceil(GDS_pix/2+20)]
            ,'ObjectPolarity','dark','Sensitivity',sens);
    elseif size(radii,1)>1;
        sens=sens-0.02;
        [centers, radii]=imfindcircles(I,[floor(GDS_pix/2-20) ceil(GDS_pix/2+20)]
            ,'ObjectPolarity','dark','Sensitivity',sens);
    end
end

%% Dropsize
GDS_pix=2*radii(1);

%% Determining the region where the drop is
T = centers(2)-radii-10;
B = dim(1);
L = centers(1)-radii-cut;
R = centers(1)+radii+cut;

if T < 1
    T = 1;
end
if L < 1
    L = 1;
end
if R > dim(2)
    R = dim(2);
end

ROI = {[T B] [L R]};
end

function [IDtouch] = ImageOfTouch(map, fp, ROI, IDtouch)
stop = false;
found = true;
global sens GDS_pix
if IDtouch == 0
    %% Looping to find the image number where the drop hits the surface
    while ~stop;
        IDtouch = IDtouch + 1;
        InfoImage = imfinfo(fullfile(map, '/', fp, '.tif'));
        NumberImages = length(InfoImage);
        if IDtouch > NumberImages
            IDtouch = 100;
            found = false;
            break
        end

        %% Read image and detect edge
        I = imread(fullfile(map, '/', fp, '.tif'), IDtouch, 'PixelRegion', ROI);
        J = I;
        dim = size(I);
        I = imadjust(I);

        %% Find Droplet
        [centers, radii] = imfindcircles(I, [floor(GDS_pix/2-5) ceil(GDS_pix/2+5)], 'ObjectPolarity', 'dark', 'Sensitivity', sens);

        %% Statements to find at which frame the drop hits the surface
        if size(radii, 1) > 1;
            [overlap] = RemoveOverLap(centers, radii, 1);
            if overlap == 1;
                stop = true;
            end
        end
        IDtouch = IDtouch - 1;
    end
else
    %% Read image (and detect edge)
    I = imread(fullfile(map, '/', fp, '.tif'), IDtouch, 'PixelRegion', ROI);
    J = I;
end
if found;
imwrite(J,[map,'/touch/image_of_touch' fp '.tif'],[map,'/touch/_NOTFOUND ' fp '.tif']);
elseif ~found;
I = imread([map,'/',fp,'.tif'],1,'PixelRegion',ROI);
disp(['Geen moment van impact gevonden bij ',fp])
imwrite(I,[map,'/touch/_NOTFOUND ' fp '.tif']);
end
end

%% Velocity
function [D_pix,v_pix,We] = Velocity(map,fp,dp,FR,IDtouch,N,...
ROI,Dg,Tol,Liquid)
global sens GDS_pix

%% Starting and ending images and time
IDend = IDtouch-2;
IDini = IDend + 1 - N;
if IDend == 97;
IDini = 1;
IDend = 8;
N = IDend;
elseif IDini < 1
IDini = 1;
N = IDend;
end

time_fr = 0:N-1; % in frames
time = time_fr/FR; % in second

%% Preallocation of drop position
z_all = zeros(2,N);
r_all = zeros(1,N);

%% Loops to find velocity (Different approach)
for IDfile = IDini:IDend
I = imread([map,'/',fp,'.tif'],IDfile,'PixelRegion',ROI);
I=imadjust(I);
[centers, radii]=imfindcircles(I,[floor(GDS_pix/2-5) ceil(GDS_pix/... 2+5)],'ObjectPolarity','dark','Sensitivity',sens);
if size(centers)==[0,0]
centers = [0 0];
end
if numel(radii)==0
radii = 0;
end
z_all(:,IDfile-IDini + 1) = centers(1,:);
r_all(IDfile-IDini + 1) = radii(1);
%% Drop position
y_pix = z_all(2,:);
y = y_pix * dp;

%% Calculating drop size and velocity
D_pix = 2*mean(r_all);
P = polyfit(time_fr, y_pix, 1); v_pix = P(1);
v_fit = polyfit(time, y, 1); v = v_fit(1);

%% Calculating Weber number
switch Liquid
    case 'water'
        rho = 998; % kg/m3
        gamma = 72e-3; % N/m
    case 'FC-72'
        rho = 1680;
        gamma = 12e-3;
end
We = dp*rho*D_pix.*v.^2/gamma;

%% Plotting and saving for checking
f = figure('visible','off');
plot(time,y,'s',time,time*v_fit(1) + v_fit(2),'r'); box on;
xlabel('time (s)'); ylabel('y (m)');
title(strcat(['V_i = ',num2str(v),' (m/s); D = ',num2str(1000*D_pix*dp),' (mm); We = ',num2str(We)]));
if IDtouch==99
    saveas(f,[map,'/velocity/_NOTFOUND' fp '.tif'])
else
    saveas(f,[map,'/velocity/velocity' fp '.tif'])
end
close(f)

%% -------- Third-party functions -----------------------------------------
function [overlap] = RemoveOverLap(centers,radii,tol)
l=length(centers);
overlap=0;
for i= 1: l
    s=i+1;
    for j=s:1
        d_ij=sqrt((centers(i,1)-centers(j,1)).^2+(centers(i,2)-centers(j,2)).^2);
        k=radii(i)+radii(j)-tol;
        if d_ij < k && radii(j)>0
            overlap=1;
        end
    end
end
Bibliography


[28] D. Richard and D. Quéré, Bouncing water drops, EPL (Europhysics Letters) 50(6), 769 (June 2000).


