An experimental study of intermittent spray cooling above the Leidenfrost point

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Abstract
An experimental study is reported on intermittent spray cooling in the film boiling regime. The presented measurements are conducted to quantify the effect of injection frequency on transient surface temperature as well as heat transfer coefficient, whereby, the coolant quantity is kept constant. It is observed that low injection frequencies lead to reheating during the injection cycles with decreasing surface temperature due to the reduced thermal driving force. Nevertheless, the measured decrease in surface temperatures along a serious of consecutive injection cycles shows that the cooling efficiency is enhanced with decreasing injection frequencies. At high injection frequencies, the liquid does not completely vaporise, and the formation of a liquid film becomes the limiting factor of the cooling efficiency.

Introduction

Spray cooling heat transfer in the film boiling regime is of great importance to attain stable and uniform cooling. At this, spray cooling using intermittent sprays has been suggested as a technological concept in terms of effectiveness and controlling of the cooling potential [1]. An improved knowledge of the interaction between pulse duration and injection frequency is required to devices strategies, not only to reduce the thermal stresses and distortion in components but also reduce of coolant quantity.

The spray cooling process possesses a complex nature and depends on spray parameters, such as droplet size, velocity and mass flux, but also on liquid and surface properties. Previous works [1][2] have shown that neither the injection frequency nor pulse duration changes significantly the droplet diameter and axial velocity distribution in wide range of operating parameters. Thereby, changing in heat transfer can not be ascribed to changing of spray properties and a research program is being conducted aimed at characterising the effect of injection frequency on the transient surface temperature as well as the heat transfer coefficient in the film boiling regime.

Methods and Materials

The experimental configuration consists of a BOSCH port fuel injector directed perpendicular to a sheet made of Inconel 600 (100 x 60 x 0.3 mm), which is directly electrical heated. A schematic of the experimental setup is shown in Figure 1. Using a self-build triggering system, the injection frequency, the pulse duration and the number of injections are controlled. The pulse duration Δt_{inj} is set to 7.5 ms and the injection frequency f_{inj} is adapted to realise duty cycles, defined as $DC = (\Delta t_{inj} \cdot f_{inj}) \times 100\,\%$ [3], from 5 % to 20 %. During these experiments, the impinging distance is kept constant and equal to 150 mm and the injection pressure is set to 7 bar. The produced water spray features under these working condition a mean diameter of about 50µm as well as a mean velocity of about 5 m/s and the total spray angle is about 25 deg.

An infrared camera (Flir ThermaCam Sc 3000) records the surface temperature with a sampling rate up to 750 Hz. Hereby, one camera image correspond to a certain time, and surface temperatures are obtained for the whole impact area of the spray. The temperature information of each camera image is converted to a 2-dimensional Matlab matrix, whereby, the matrix size corresponds to the number pixel for the length and the width of the Inconel 600 sheet. The data are further processed in Matlab to a 3-dimensional matrix, whereas the third component is the time.

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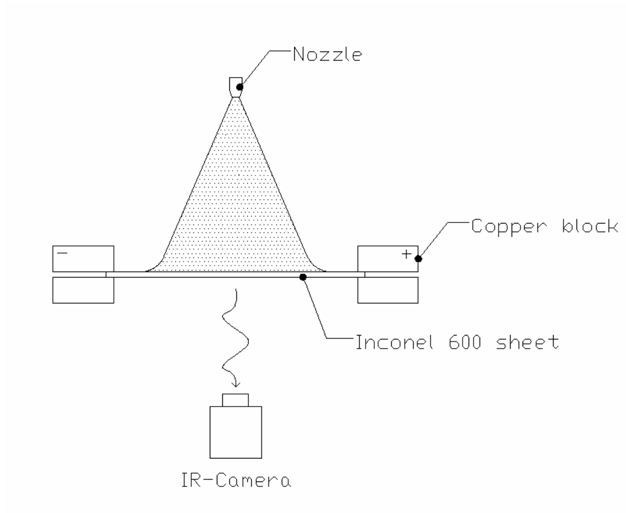

Figure 1: Schematic of the experimental apparatus

As infrared measurements depend strongly on the emissivity of the surface, the camera facing sheet side is coated with a black painting called Senotherm UHT 600 with a thickness of about 20 µm. Since the emissivity is temperature-dependent, all temperature data of the 3-dimensioanl matrix needs to be subsequently corrected (see [4] for further details). Before the heat transfer algorithms is applied the temperature data are prefiltered for minimise the background noise of the infrared camera. One possible prefilter is

$$\begin{aligned} T^{n}_{j,k,l=0} &= \frac{2\cdot T^{n-1}_{j,k,l} + T^{n-1}_{j,k,l+1}}{3} \\ T^{n}_{j,k,l} &= \frac{T^{n}_{j,k,l-1} + 2\cdot T^{n-1}_{j,k,l} + T^{n-1}_{j,k,l+1}}{4} \\ T^{n}_{j,k,l=l_{max}} &= \frac{T^{n}_{j,k,l-1} + 2\cdot T^{n-1}_{j,k,l}}{3} \end{aligned} \quad . \qquad (1)$$

The number of iteration n is varied in dependence of the temperature gradient. Figure 2 shows exemplarily the measured and the corresponding prefiltered data. The emissivity corrected and prefiltered data are finally used for heat transfer coefficient calculations.

The heat transfer coefficient depends on surface temperature, which is also a function of time, as well as spatial position and is determined in the range of stable film boiling at surface temperatures between 420 °C and 300 °C. For an Inconel 600 plate with thickness of 0.3 mm, the calculated Biot numbers are smaller than 0.1. Therefore, it is reasonable to assume a lumped condition to evaluate the surface heat flux, and the solution of the inverse heat conduction problem is not necessary. Thus, the temperature measured at the backside of the plate is used to represent the temperature at the front side. Furthermore, it is assumed that the surrounding temperature has the same value as the fluid temperature. Considering the negligible radial conduction over the thin plate a lumped system can be applied. The heat transfer coefficient is calculated by

$$\frac{dT}{dt} = \underbrace{\frac{\dot{q}_V}{\rho\, c_p} + \frac{\alpha_{Spray} + \alpha_{Con/R}}{\rho\, c_p\, s} T_{Fl}}_{M} - \underbrace{\frac{\alpha_{Spray} + \alpha_{Con/R}}{\rho\, c_p\, s}}_{N} T \,. \qquad (2)$$

Specific heat capacity c_p as well as the density ρ of Inconel 600 feature only weak temperature sensitivity and are assumed to be constant. The overall heat transfer coefficient $\alpha_{Con/R}$ considers the heat losses due to natural convection and radiation of the camera faced side (see [4] for further details). The electrical heat source can be written using the specific resistance, which is a function of temperature and is experimentally obtained

$$\dot{q}_V = \frac{I^2 \rho_{el}}{b^2 s^2}. \quad (3)$$

The analytical solution for discrete time steps of equation (2) reads as

$$T_i = \frac{M}{N} + \left(T_{i-1} - \frac{M}{N} \right) e^{-N(t_i - t_{i-1})}. \quad (4)$$

For estimation the heat transfer coefficient, a numerical solver is used which solves nonlinear data-fitting problems in the least squares sense.

The analytical solution implies that the electrical resistance ρ_{el} as well as the heat transfer coefficient $\alpha_{Con/R}$ are constant during a time step. Thereby, mean temperatures of each time step are used calculating both.

Results and Discussion

Intermittent spray cooling provides a high potential of definite heat removal from a surface. This requires a precise control of the coolant. Intermittent sprays meet demands by proper matching of pulse duration and injection frequency. The results presented in this paper are aimed discussing the effect of injection frequency on the local time-dependent decrease in surface temperature and the local time-dependent heat transfer coefficient in the film boiling regime. During all experiments, the coolant quantity is kept constant.

The temperature profile of one injection cycle shows Figure 2 for pulse duration of 7.5 ms and two different surface temperatures. During the initial phase of spray impact, a period of direct contact is formed between coolant and surface, whereby, the decrease in surface temperature is rather high. In a second period, a vapour layer is subsequently formed. With decreasing surface temperature during the cooling process, the temperature drop per injection reduces due reduced thermal driving force. For low injection frequencies, the surface temperature could also reheat. Accordingly, the injection frequency should be adapted during the cooling process preventing reheating.

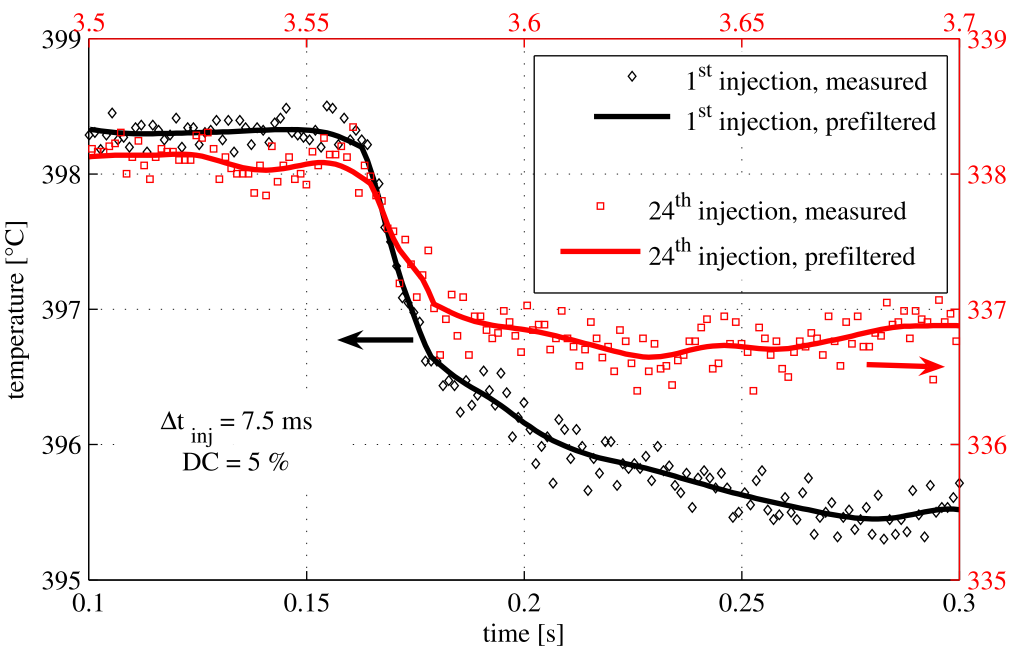

Figure 2: temperature development for two different surface temperatures

If the pulse duration is fixed and the injection frequency increases, the duty cycle increases, and the cooling process becomes faster. Figure 3 indicates the surface temperature decay along series of consecutive injection cycles, whereby, lower injection frequencies lead to an intensified cooling. At high injection frequencies, the cooling liquid does not vaporize completely. The formation of a liquid film becomes the limiting factor of cooling efficiency. It should be mentioned that the cooling time differs, but the mass flux is constant. Obtaining a surface temperature of about 335°C, 26 injection cycles is necessitated for a duty cycle of 20 %, and 21 injection cycles are only required for a duty cycle of 5 %. This corresponds to a reduction of coolant of about 20 %.

Furthermore previous work [2] illustrated that cooling processes at low injection frequencies features a uniform temperature profile during the cooling process above the Leidenfrost point. High injection frequencies lead to strong surface temperature distributions and the local cooling depends on the local mass flux.

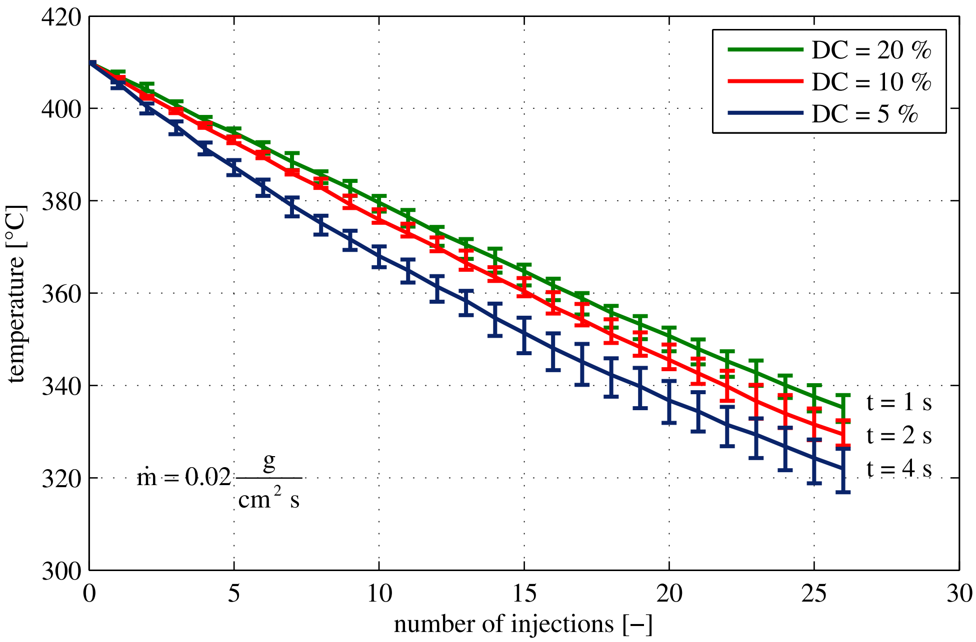

Figure 3: surface temperature decay along a serious of injection cycles

The local heat transfer coefficient is obtained from equation (4), and Figure 4 illustrates the time-dependent heat transfer coefficient for pulse duration of 7.5 ms and duty cycle of 5 %, 10 % as well as 20 %. Generally, heat transfer coefficient evaluates the amount of transferred heat during a certain time step and at a certain impact area. Consequently, cooling processes with higher injection frequency, i.e., higher duty cycle and reduced cooling time, offer enhanced local average heat transfer coefficient. The cooling time for a duty cycle of 5 % is four times larger than for a duty cycle of 20 %. Consequently, a ratio of 4 is expected for their mean heat transfer coefficients for a given mass flux and pulse duration. Due to the above mentioned formed liquid film at higher injection frequencies, the mean heat transfer coefficients differ only by the factor 2.5.

The plot of the heat transfer coefficient features the mentioned two behaviours. With increasing injection frequency, the period with formation of vapour layer is reduced. The maxima are still developed but are less pronounced.

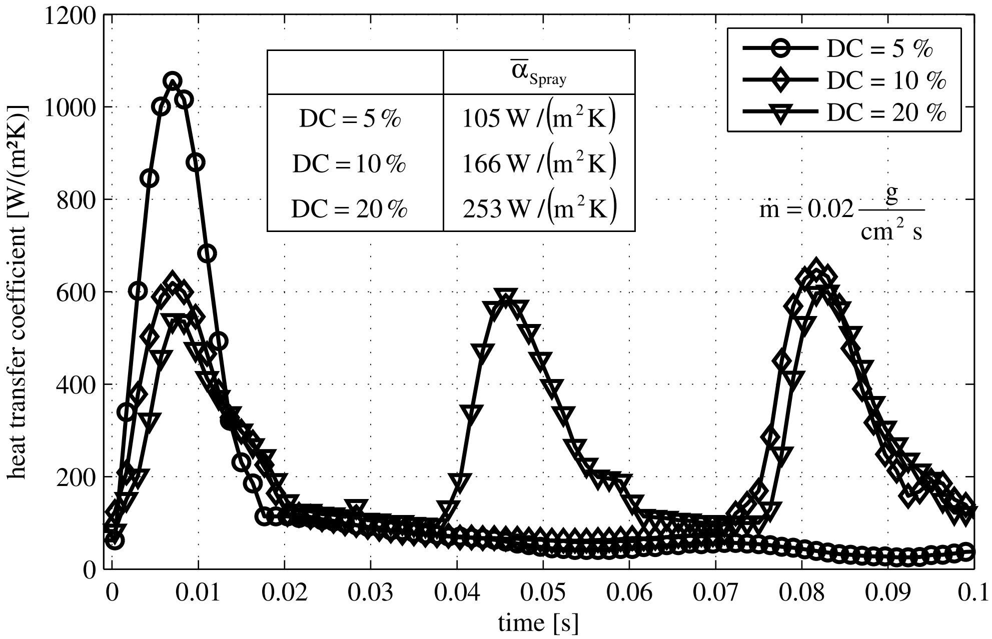

Figure 4: local heat transfer coefficient versus time

Conclusions

This paper reports an experimental study aimed characterising the effect of injection frequency on transient surface temperature and the heat transfer coefficient in the film boiling regime. The measured decrease in surface temperatures shows that the cooling efficiency is enhanced at low injection frequencies. At high injection frequencies, the liquid does not completely vaporise, and the mass flow rate of coolant becomes the limiting factor of the cooling efficiency. However, the surface temperatures reheat during the cooling process at low injection frequencies due to the reduced thermal driving force. An adaptation of the injection frequencies on the cooling would optimise the efficiency.

Acknowledgement

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Nomenclature

b	width
c_p	specific heat capacity
I	amperage
$\dot{m}$	mass flux
$\dot{q}_V$	volumetric heat source
s	thickness
t	time
T	temperature
α	heat transfer coefficient
ρ	density
ρ_{el}	electrical resistance

Subscripts

Con	convection
Fl	fluid
i	time step
j, k, l	dimension of the 3-dimensional matrix

n	number of iterations
R	radiation
Spray	spray

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