SPRAY CHARACTERISATION AND HEAT TRANSFER DURING COOLING PROCESSES BY INTERMITTENT SPRAYS

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ABSTRACT
Spray cooling is used in many technical areas to cool hot materials. There are different boiling phenomena depending on the surface temperature. So the heat flow varies through these boiling ranges. Large local temperature gradients can cause mechanical tensions and also effect material properties strongly. Intermittent spray cooling offers much potential to ensure a uniform cooling, also in the crossing from film to transition boiling. In this work, a high pressure gasoline direct injector (HDEV-5) is used for spray investigations with water and infrared thermography recordings during cooling processes of a heated nickel alloy sheet. Additional measurements of droplet size and velocity by a phase Doppler analyzer (PDA) are conducted to characterise the spray properties. Furthermore, the local mass flux is determined by using a Patternator. The additional setting parameters of an intermittent spray can be expressed by the duty cycle (DC), which is composed of the frequency and the injection duration. This paper offers a basic characterisation of the spray and various physical mechanisms during a cooling process shown in temperature profiles.

INTRODUCTION

Higher requirements on industrial components or manufacturing processes leads to the demand for new ways of cooling technology. Especially in electronic systems, e.g. the cooling of microprocessors, but also in other applications high heat flux cooling systems had received more attention. Spray cooling is a common application to cool quickly and uniform. This technique provides the latent heat of nearly the entire cooling fluid [1].

Intermittent Spray Cooling (ISC) offers much potential to ensure a controlled cooling process. The parameter settings mass flux and droplet properties of a continuous spray can be extended by the frequency and the duration of injection. These additional values are summarized in the duty cycle $(DC = f_{inj} \cdot t_{inj} \cdot 100\%)$ [2], which gives the control about the length of the injection breaks. These spray disruptions influence the local water saturation and therefore the extracted heat flow of the sheet.

There are different boiling regimes depending on the temperature of the sheet. It is very important to know the Leidenfrost temperature which depends on many fluid properties and parameters of the cooling process, e.g. the droplet diameter and velocity, the local mass flux and the roughness of the sheet. Furthermore it limits the stable film boiling from the transition and nucleate boiling regime. Above that temperature a vapour layer between water and sheet is formed, which has an insulating effect of removing the heat. By cooling below that limit the local heat fluxes grow due to the direct contact of water and solid [3, 4].

Previous works investigated the ISC with low pressure nozzles. Panão et al. [5] cooled a cylindrical copper block with an intermittent multijet spray with 1, 1.6 and 2.2 bar injection pressure. Fest-Santini [2] also used ISC for a study of the heat transfer coefficient in the stable film boiling regime. The applied injector was a Bosch EV14 low pressure (7 bar) gasoline injector and the cooled component was a nickel alloy sheet. It was shown that by using intermittent spray cooling and short injection durations coolant liquid could be saved.

In this work the injection pressure is increased up to 200 bar and the temperature range passes through film-, transition- and nucleate boiling regime. The chosen injector is a currently in the automotive industry used gasoline injection nozzle with water as working fluid. To investigate just one spray jet of the 6-hole injector due to symmetry, one injection hole is orientated vertically down. Furthermore the spray is characterised by PDA and Patternator measurements and visualized by high-speed-camera recordings. The temperature of the sheet during a cooling process is recorded with an infrared camera on the dry side. Initially, investigations of physical basic effects are in the focus and illustrated in temperature profiles.

METHODS AND MATERIALS

The experimental setup is based on a BOSCH® 6-hole gasoline direct injector (HDEV-5) used with water. It is triggered by a TTL pulse of a self-made trigger box and software. The investigated spray jet is separated and orientated vertically down. The material to be cooled is a (150x100x0.1 mm) nickel alloy sheet, which is directly electrical heated. The pressure application operates with nitrogen N_2, which directly loads the piston and has a transformation ratio low/high of 1/2. In addition to the below explained measuring systems, high-speed-recordings with a frequency of 5000 up to 40000 Hz are conducted to visualize the spray and the spray impact. The used camera is a High-Speed-Star-system from LaVision®.

Phase Doppler Analyzer (PDA)

The spray droplets are particularly characterised by their diameters and velocities. These properties are measured with the help of a PDA-system. The schematic experimental setup is shown in Figure 1. Two laser beam pairs create a measuring volume. Any droplet crosses this volume scatter the light of the laser beams and generate a doppler displacement. Trough superposition of the doppler signals of the two laser beams a beat frequency is formed and can be measured with photodetectors. The frequency of that signal is proportional to the particle velocity. The determination of the droplet diameter is based on the effect of phase shifting. The scattered light is detected from a differently arranged receiver with a certain phase shift, which is proportional to the particle size [6].

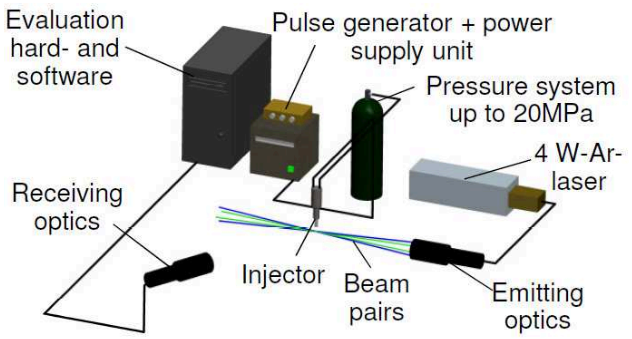

Figure 1: schematic experimental setup of the Phase-Doppler-Analyzer (PDA)

The measuring volume is placed on the position of the nickel alloy sheet by a traverse. The injector was placed above the measuring point. Consequently the distance between the crossed laser beams and the injector is varied from 100, 150, 200 up to 225 mm. In addition the measuring point is adjusted in the horizontal plane in one direction to capture the entire spray angle. Furthermore the injection pressures used are 50, 100 and 200 bar. The time of injection is set to 0.625, 1.25, 2.5 and 5 ms. As in [2] is shown, the PDA measurements are frequency independent.

The mean velocities and diameters are determined on the basis of time classes, which have a range of 50, partly 66 µs, to capture the high temporal dynamics of the spray. The usage of a small class size leads to high number of classes, so it is necessary to smooth the mean value profiles, which is done with a 30 point Savitzky-Golay smoothing filter. To characterise the droplet size the diameter d_{10} is chosen and is defined out of Eq. (1) [7, 8].

$$d_{ab}^{(a-b)} = \frac{\sum n_i \cdot d_i^{\,a}}{\sum n_i \cdot d_i^{\,b}} \qquad (1)$$

According to that, the d_{10} diameter is the arithmetic mean value of the droplets.

Patternator

This measuring system consists of eleven parallel tubes with a diameter d_R. These tubes are connected with glass containers through hoses with a certain coating so that water can directly drop in. The injector is placed above these tubes with the adjusted distance of 150 and 200 mm. After a certain period of measuring time the collected water masses of each glass container is determined through weighing. This procedure is done repeatedly to get a significant result. Afterwards a mean value is formed. The whole Patternator-system is traversed and shifted in steps with the value of the tube diameter. The duty cycles are adjusted to 2.5 and 5 %. Figure 2 shows the schematic experimental setup of the Patternator.

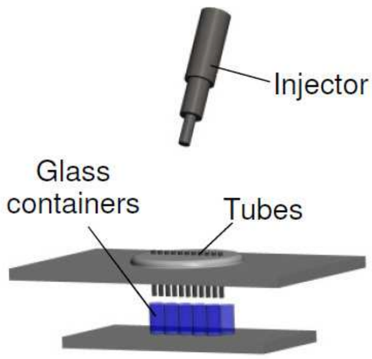

Figure 2: schematic experimental setup of the Patternator

Based on the weighed mass of water and the known geometric dimensions of the tubes, the local mass flux can be calculated from Eq. (2).

$$\dot{m} = \frac{M}{A_{tube} \cdot \Delta t_{inj}} = \frac{M}{\frac{\pi}{4} \cdot d_R \cdot \Delta t_{inj}} \qquad (2)$$

Infrared thermography

To detect the surface temperature of the nickel alloy sheet, infrared thermography (IR) measurements are conducted. The IR-camera is placed on the dry side below the sheet, which has a black coat on the bottom side. The schematic experimental setup is shown in Figure 3. There is a certain temperature difference between wet and dry side, especially in the transition and nucleate boiling regime. In further investigations an inverse algorithm will be created to calculate the heat transfer coefficient of the wet side using the raw temperature signal of the bottom side.

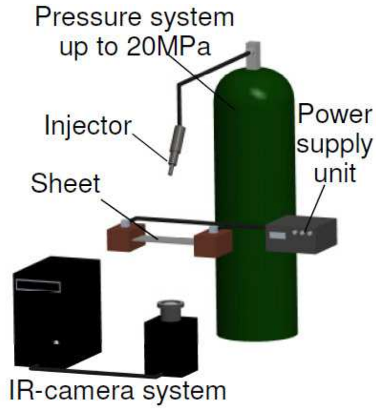

Figure 3: schematic experimental setup of the IR-measuring-system

The applied infrared camera was the Infratec ImageIR® 8300. The used resolution is 640 x 515 Px with 50 Hz uptake rate. The recorded section of the sheet is limited to the impact area of a single spray jet. In an evaluation routine the mean value of the 100 lowest temperatures is calculated to get temperature versus time profiles. The evaluated section is shown in figure 4 with an arbitrary view of an IR-recording. For the temperature profiles, there is another analysis routine to detect the Leidenfrost temperature and a turning point temperature. These two points of the curves are defined as turning points and can be calculated.

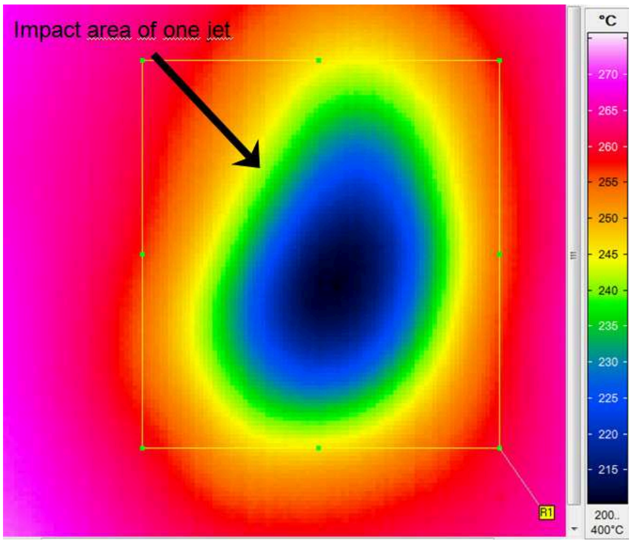

Figure 4: evaluation section of the impact area of the investigated spray jet

RESULTS AND DISCUSSION

The experimental results can be considered in two main categories. On the one hand the spray characterisation with the determination of the droplet properties (velocity and diameter) and the local mass flux, on the other hand the temperature profiles.

Spray characterisation

As an example, the distribution of the droplet velocity versus time shows figure 5, even the unsmoothed and smoothed mean value profile. Complementary, it illustrates the droplet number distribution to get more information about the dominant droplet speed. The same is illustrated for the droplet diameter, it is merely abstained from the unsmoothed profile versus time. This measurement is done in the spray centre with a liquid pressure of 200 bar, an injection duration of 5 ms and a distance of 150 mm. The first droplets which arrive at the measured volume are larger ones than the following. Smaller droplets are slowed down and influenced by the air resistance. Accordingly some droplets reaches a size of about 40 µm, but also very small ones are already measured. The bandwidth of the arriving spray has a wide range with a Δd of nearly 35 µm. The following droplets are predominant small with a size of less than 5 µm. This is shown very clearly in the histogram. Concerning to the velocity, there is a wide range, especially around the time when the spray arrives. The first droplets are consequently faster as the following spray particles. Its velocity ranges from slow ones with 5 m/s up to very fast ones with over 40 m/s. Afterwards the value decreases and settles to round about 5 m/s.

This effect is illustrated in some high-speed-recordings in figure 6. The first droplets which arrives at the sheet are isolated and large compared to the rest of the particles. The spray reaches the sheet subsequent of these drops. It is clearly shows a higher density and the droplets are smaller.

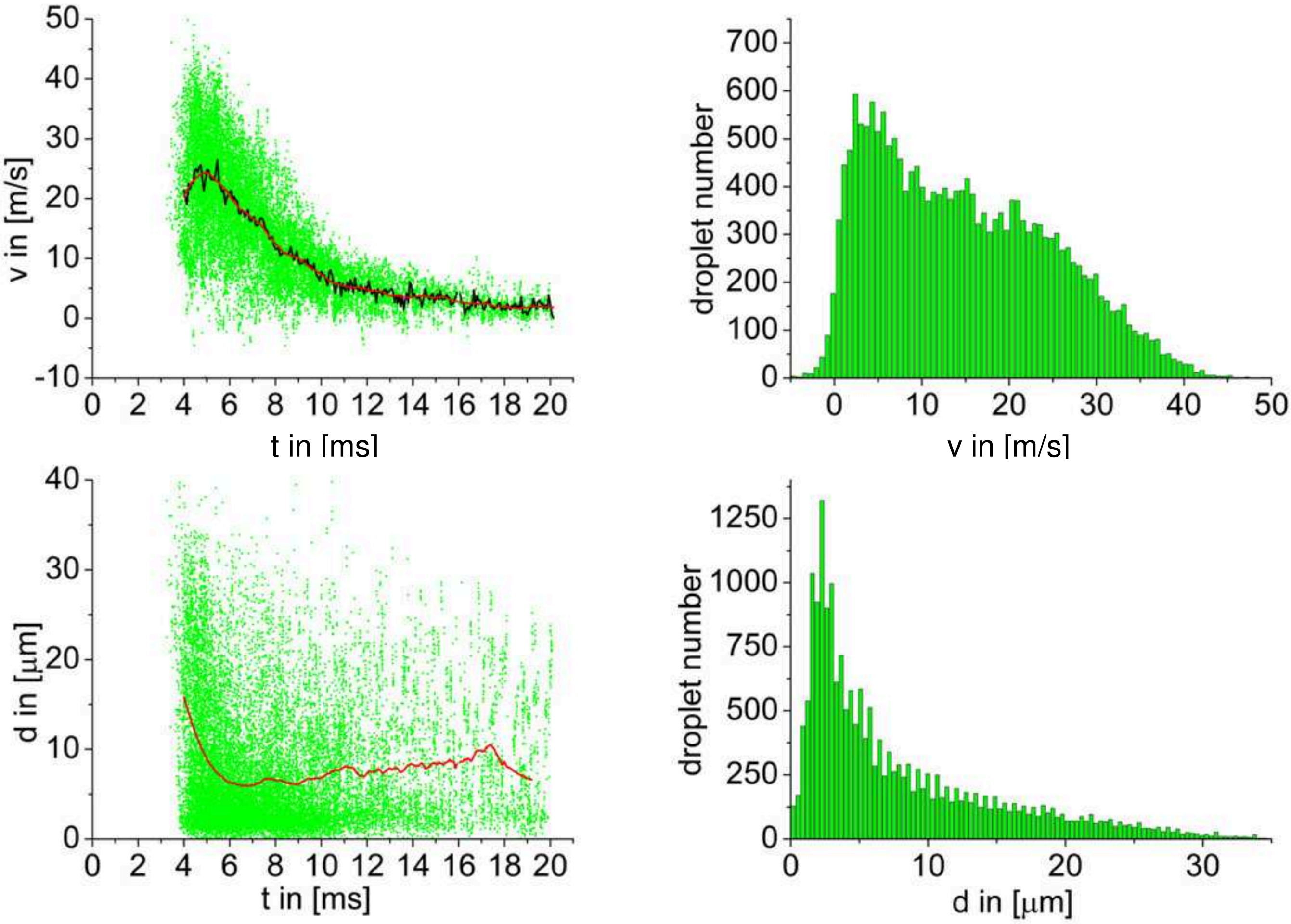

Figure 5: Illustration of the droplet velocity and diameter distribution

They also has to be slower, because they arrive with a certain offset.

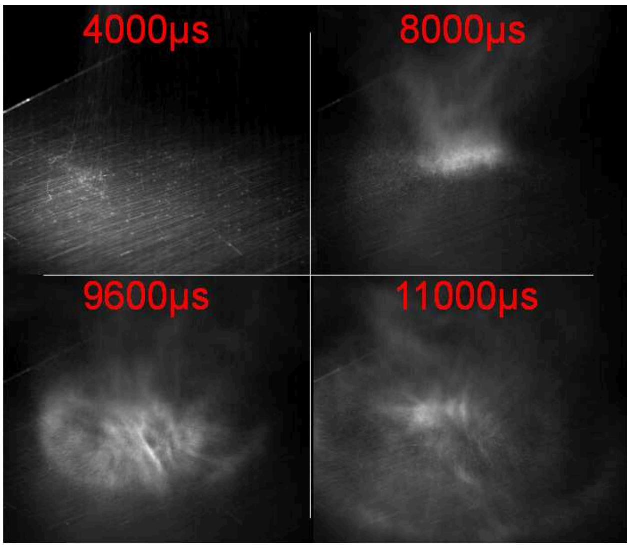

Figure 6: High-speed image sequence at certain points of time of a spray impact

Figure 7 illustrates some comparisons between parameter settings and their influence on the main droplet size (d_{10}). Increasing the distance between nozzle and nickel alloy sheet only the arrival time of the spray changes. The applied injection pressure is constantly 200 bar. With doubling the distance from 100 to 200 mm the spray takes three times as much time to get the range. But the droplet diameters are still similar, just the first arriving ones are insignificant smaller at bigger distances.

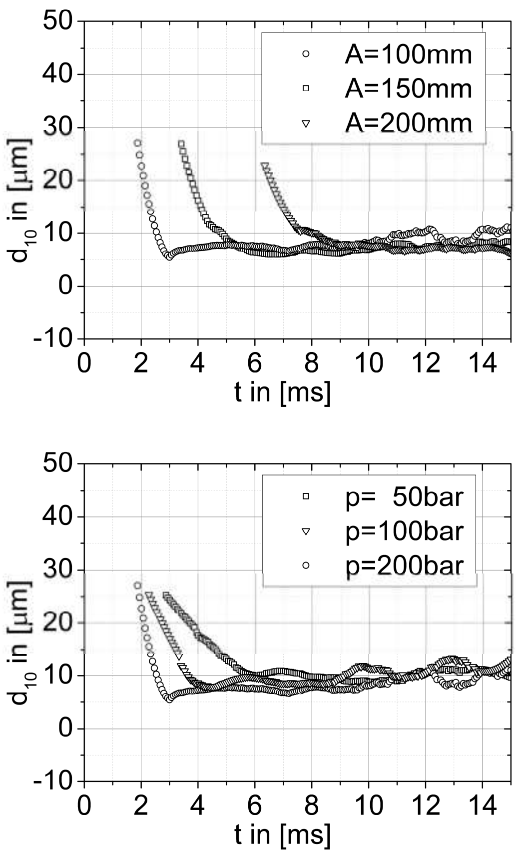

Figure 7: Influence of distance A and injection pressure p of the mean droplet diameter d_{10}

Increasing the injection pressure results in smaller droplet diameters. The spray also arrives earlier at the sheet and gets faster smaller droplets than with less liquid pressure. Following the spray front, the d_{10} droplet diameter settles to a certain value, which is from approximately 7 µm at 200 bar up to 10 µm at 50 bar. These experiments are performed in a distance between nozzle and sheet of 100 mm.

The local mass flux is illustrated in figure 8 for a distance of 150 mm, a liquid pressure of 200 bar, an injection time of 10 ms and a duty cycle of 5 %. In relation to the impact area of one jet in comparison with the results of [2], the local mass flux is about twice as high in this experiment. This is mainly due to the higher injection pressure used.

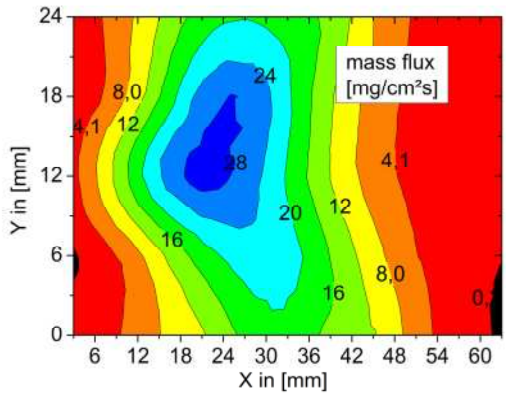

Figure 8: Local mass flux $\dot{m}$ of one vertically down directed spray jet

A cooling sequence reaching over all boiling regimes is illustrated in figure 9. The parameter setting for this example is a distance of 100 mm, an injection pressure of 50 bar, a frequency of 5 Hz and a duty cycle of 0.625 %. The different ranges and temperatures are marked. The Leidenfrost temperature acts as the transition between the boiling regimes.

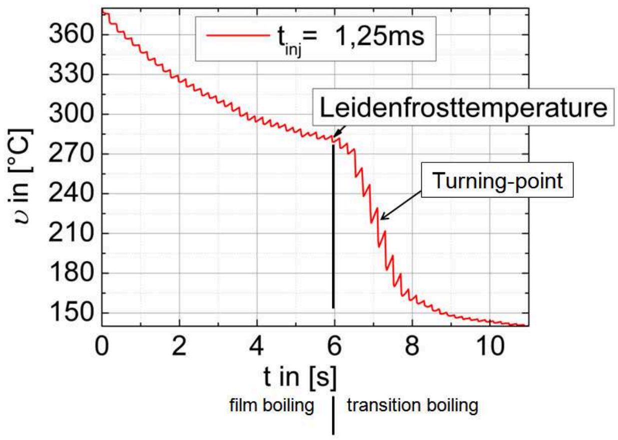

Figure 9: Temperature profile during a cooling process versus time

The difference of the temperature drops during an injection between film- and transition boiling regime are very significant. The process of cooling down 100 K takes roughly just one second after exceeding the Leidenfrost-temperature. In contrast to that this process takes six times longer in the film boiling regime. Due to these large differences in the cooling velocities it is not trivial to calculate heat transfer coefficient of the wet side out of the temperature signal of the dry side of the sheet. In this boiling range it is no longer permitted to neglect the heat conduction in the sheet in reference to the heat transfer (Bi>0.1). Therefore this results in an inverse problem, which will be solved in future works.

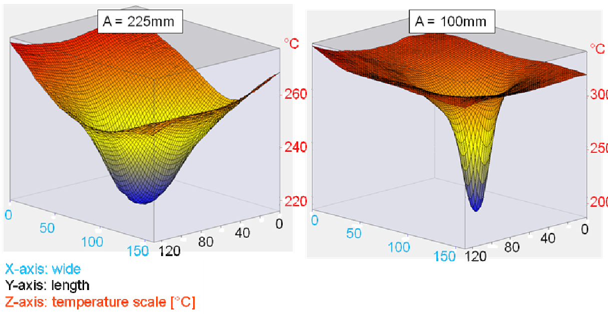

Figure 10: Temperature distribution of the spray impact area at the turning point time

In the investigation of the parameter variation for the IR-measurements a larger and more homogenous temperature field is aimed. Figure 10 illustrates the field at the turning point time for two different distances between sheet and injector. The used injection pressure is 100 bar and the duty cycle is 0.625 % with a injection time of 1.25 ms. The larger distance leads to a more uniform distribution of the spray and as a consequence a more uniform temperature distribution. This is very important for the evaluation and also for the avoidance of mechanical stresses.

CONCLUSION

This paper reports experimental studies to characterise the spray of an gasoline direct injector used with water and shows its potential for intermittent spray cooling. The possibility to work with high injection pressure leads to predominantly very small droplets. It also influences the mass flux, so that very short injection times are possible. The local mass flux has a big influence on the heat flux, especially in the transition boiling regime. High pressure and larger distances create a larger impact area, which provides a more uniform temperature distribution on the sheet.

However, the dry surface temperature profiles are shown for all boiling regimes. Large differences in the cooling behaviour make it impossible to determine the temperature or the heat transfer coefficient of the wet side in a trivial way.

Future work will include an inverse algorithm to calculate the additional information of the wet side of the sheet. Final infrared measurements with a certain parameter setting will be used as a basis for this calculation.

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