**MEASUREMENT OF SPRAY COOLING HEAT TRANSFER USING AN INFRARED-TECHNIQUE IN COMBINATION WITH THE PHASE-DOPPLER TECHNIQUE AND A PATTERNATOR**

F. Puschmann*, E. Specht*, J. Schmidt*

*Otto-von-Guericke-University Magdeburg, Institute of Fluid Dynamics and Thermodynamics, Universitätsplatz 2, D-39106 Magdeburg

**ABSTRACT**

A measurement setup-up to determine heat transfer and spray characteristics is presented. Spray properties are measured with a 2D-Phase-Doppler-Anemometer and a patternator, heat transfer is measured based on determining the surface temperature by means of infrared thermal imaging. The combination of these two measurement techniques makes it possible to determine heat transfer with high resolution in time and space and also to specify the influence of spray properties on the received heat transfer. Results from investigations in water spray quenching and evaporation quenching are presented to clarify the measurement procedure.

1. **INTRODUCTION**

In many heat treatment processes, metallic products must be quenched in a specified way. The aim of these quenching processes is to regulate material properties such as strength, hardness, machinability and so forth. At the same time, the quenching process must be carried out with defined precision, as only then the necessary quality can be achieved. In addition, using defined quenching, warping of a work piece can be reduced. During tempering, for example, steels are quenched quickly and defined from approx. 900°C to 400°C in order to achieve a certain degree of hardness.

To achieve high quenching speeds, liquid is used for cooling. As an example for a cooling process with water as liquid there is water spray quenching, used for example in continuous casting. Here, however, the so-called Leidenfrost problem arises. Above the Leidenfrost point a steam film forms between the hot surface and the cooling liquid. The steam film hinders direct contact between the surface and cooling liquid and as a result greatly reduces the heat transfer. If the process falls below the Leidenfrost temperature, the isolating steam film breaks down. The hot surface is in direct contact with the cooling liquid which leads to intense cooling and consequently leads to a greatly increased quenching speed. Besides the cooling conditions such as properties and flow of the liquid, the Leidenfrost temperature is also dependent on the body geometry, the surface roughness and the parameters of the material to be cooled.

Another quenching process using liquid is evaporation quenching with atomised sprays. Finely atomised water is sprayed on the surface to be cooled. The quantity of water must be limited to an extent that the individual drops on the heated surface completely evaporate and do not merge in a water film, as is the case in water spray cooling. In this quenching process the Leidenfrost problem does not arise and high quenching speeds can nevertheless be achieved. Investigations on this topic can benefit from results on investigations into the impact of single drops on hot surfaces [9-12].

**Figure 1. Experimental set-up**

The measurement setup sketched in Fig. 1 was designed to investigate both quenching methods. With this setup the parameters of the spray are determined using a 2D-Phase-Doppler-Anemometer. At the same time, heat transfer is measured with a measurement technique based on an infrared camera. The aim of measurements with this setup is to find out the influence of the main parameters such as
- impingement density,
- drop diameter,
- drop velocity and
- surface temperature

on heat transfer. In the case of producing the water spray with the help of compressed air, the impact of the air flow is another influencing parameter to be investigated.

2. EXPERIMENTAL SET-UP

The measuring set-up sketched in Fig. 1 was designed to investigate drop size and velocity at the same time as heat transfer. Thereby the spray characteristic is measured with a 2D-Phase-Doppler-Anemometer (PDA), the heat transfer is measured on the basis of determining the surface temperature by means of infrared thermal imaging. Impingement density is measured not only by PDA, but also by a patternator.

2.1 Drop Diameter and Velocity

The distribution of drop sizes and drop velocities of the water spray is measured by means of a PDA. The principle of this laser-based measurement system is sketched in Fig. 2. It is an optical measuring system which is able to perform non-contact and simultaneous measurements of the velocity and the diameter of spherical particles. The sensing volume of the PDA is fairly small, ensuring high resolution in terms of time and area. It is able to identify individual drops passing through the sensing volume. Due to its high laser power of 4 Watt it is an excellent device for performing measurements in misty and steamy environments.

![Figure 2. Principle of the PDA system](image)

Fig. 3 depicts the distribution of drop size and drop velocity for a flat-spray nozzle as used in continuous casting. The mean volumetric diameter is presented as a function of the measuring position. The measuring plane was located at a distance of 200 mm in front of the nozzle. The measuring position was the distance measured across the length of the flat jet from its centreline. A pressure of 5 bar was applied to the nozzle resulting in a water flow rate of 318 kg/h. The mean volumetric diameter was about 110 µm in the centre of the spray jet. The drop size increased towards the border. Reducing towards the border, the mean drop velocity was about 6.4 m/s. It should be noted that the aperture angle of the flat-jet nozzle was 105° and, hence, the overall length of the spray jet in the measuring plane was about 520 mm. The figure shows a section of the centre exhibiting a width of 200 mm.

![Figure 3. Drop Size and Velocity](image)

2.2 Impingement Density

A patternator as depicted in Fig. 4 was used to measure the water impingement density. The water drops of a spray were collected by means of collecting tubes which were arranged in the spray jet and exhibited a diameter of $D_{in}=10$ mm, over a period $\Delta t$. The amount of water $M_w$ collected can be used in the equation

$$\dot{m}_w = \frac{4 \cdot M_w}{\Delta t \cdot \pi \cdot D_{in}} \tag{1}$$

to compute the water impingement density. The water impingement density can be also measured by means of the PDA, but due to the high error rate it is necessary to employ another measuring system, i.e. a patternator as in this case [1].

![Figure 4. Patternator system](image)
Fig. 5a shows the distribution of water impingement density obtained with the flat-spray nozzle as a function of the measuring position. As can be seen, the mean impingement density amounting to 4.5 kg/m²s is fairly constant under the operating conditions described above, forming individual skeins at the nozzle. The results of two measurements are shown to document the reproducibility of the measuring results obtained with this measuring procedure.

![Figure 5a. Impingement Density flat-spray nozzle](image)

Fig. 5b shows the distribution of water impingement density obtained with an internal-mixing air-assist atomizer as a function of the patternator tube. The air pressure at the nozzle serves as parameter. As can be seen, the impingement density is greatest in the centre of the spray, decreasing to its border. The impingement density decreases with increasing air pressure.

![Figure 5b. Impingement Density](image)

### 2.3 Heat Transfer

The measuring procedure to determine the heat transfer within a fairly short period of time and with locally high resolution is presented in Fig. 1 [2,3,4]. It is based on determining the surface temperature by means of infrared thermal imaging. To determine heat transfer, a thin metal sheet was arranged in front of the spray-generating nozzles and supplied with a constant electric current. The water leads

the heat away from the hot metal sheet surface. In a stationary measuring process the metal sheet temperature assumed to be a value of a function of the local heat transfer coefficient. The higher this coefficient, the lower was the local metal sheet temperature. In a non-stationary measuring process the metal sheet was heated to an initial temperature without being cooled by water spray. Subsequently, the spray jet was released cooling down the sheet. Due to the small thickness of the metal sheet between 0.1 mm and 0.3 mm, both measuring procedures yielded an almost identical temperature distribution on the side sprayed on and the side not sprayed on. The local distribution, and time distribution in the non-stationary case, of the surface temperature of the non-impinged side were recorded by means of an infrared camera. On the relevant side, the sheet exhibited a specific coating with an emission capability that had been determined before as a function of temperature. A local temperature resolution of up to 0.2 mm/pixel can be achieved by using a telephoto lens with a supplementary lens. The local distribution of the heat transfer coefficient can be calculated from the temperature distribution. The difference between the surface temperature distribution measured on the rear side and the required surface temperature distribution can be determined using a numerical solution of the problem of thermal conduction. Thereby the multidimensional conduction of heat within the sheet was taken into account.

**Stationary measuring procedure.** In the case of stationary measuring of surface temperature distribution a constant value under cooling conditions was assumed and which was recorded by means of an infrared camera. This surface temperature distribution can be used to compute the distribution of the heat transfer coefficient. The heat flux resulting from the current flow through the metal sheet and, hence, from the source of heat applied, is calculated by means of the electric power $P_o$ supplied and the area $A$ of the metal sheet as follows

$$\dot{q}_H(\theta_H) = \frac{P_o}{A} = \frac{I^2}{b \cdot l} \cdot \rho \cdot \frac{s}{s} \cdot \left(\theta_H - \theta_l\right) \cdot \frac{I^2}{b^2},$$  \hspace{1cm} (2)

where $\theta_H$ is the corrected metal sheet temperature, $I$ the electric current passed through the metal sheet, $R$ the electrical resistance of the metal sheet, $(\rho \cdot s)$ the temperature-dependent specific resistance of the metal with reference to the sheet thickness $s$, and $b$ the width of the sheet. The specific resistance of the metal sheet was established in special measurements as a function of temperature. Since the specific resistance of the used metal is slight temperature dependent, it is assumed that the specific resistance is constant at an investigated temperature level. If the temperature difference over the metal sheet area is wide, heat conduction in the metal sheet plane must be taken into account.

During the measurement the sheet was not only cooled by the spray jet. Radiation of energy and a convective heat transfer must also be considered under the conditions of high temperatures. This heat transfer is included as the heat loss. The model to calculate the heat loss is verified by measurements where the metal sheet is heated up and only cooled by the heat loss. The heat flux $\dot{q}_{sp}$ ($\theta_H$) led away by the spray jet is calculated by
\[ \dot{q}_{SP}(\theta_H) = \dot{q}_V(\theta_H) - \dot{q}_V(\theta_H), \]  
(3)

where \( \dot{q}_V(\theta_H) \) is the temperature-dependent heat loss. Hence, the obtained heat transfer coefficient \( \alpha_{SP} \) can be calculated by using the corrected surface temperature \( \theta_H \) and the spray jet temperature \( \theta_{SP} \), using the following equation:

\[ \alpha_{SP}(x, y) = \frac{\dot{q}_{SP}(\theta_H(x, y))}{\theta_H(x, y) - \theta_{SP}}. \]  
(4)

Non-stationary measuring procedure. Under the conditions of high heat transfer coefficients and high surface temperatures it is difficult to obtain and keep a stationary operating point and in some cases this is even impossible due to the limits of the electric power available. Hence, heat transfer coefficients were determined by means of non-stationary techniques under the conditions of high heat flux. To this end, the metal sheet was heated to an initial temperature supplying a constant current and, subsequently, cooled down using a spray jet. The time-dependent distribution of temperature on the metal sheet surface was measured.

For calculating the total heat transfer coefficients \( \alpha \) neglecting conduction, the differential equation

\[ \rho_M \cdot V \cdot c_M \cdot \frac{d\theta_H}{dt} - P_e = \alpha \cdot A \cdot (\theta_{SP} - \theta_H) \]  
(5)

can be established using an energy balance at the metal sheet. Here, \( \rho_M \) is the density of the metal sheet, \( V \) its volume, and \( c_M \) its specific thermal capacity. Dividing by the area of the metal sheet and converting the ratio \( P_e/A \) as described in Eq. (2), we obtain

\[ \rho_M \cdot s \cdot c_M \cdot \frac{d\theta_H}{dt} - \frac{I^2}{b^2} \left( \frac{\rho_e}{s} \right) = \alpha \cdot (\theta_{SP} - \theta_H). \]  
(6)

With the well known time-dependent surface temperature it is possible to compute the total heat transfer coefficient. This coefficient is corrected by heat losses. The IR camera operates in line-scan mode with a data rate of 2500 Hz. In this case a high resolution in time of surface temperature is obtained.

### 3. RESULTS ON NON-STATIONARY MEASURING PROCEDURE

In the following the evaluation of the non-stationary measuring procedure is demonstrated.

#### 3.1 IR Sequence

Fig. 6 shows a thermographic picture of an IR Sequence, in which the temperature distribution of the metal sheet is recognizable. In this test the metal sheet was cooled with a water spray, which was sprayed perpendicularly onto the surface of the test metal sheet. The spray was produced using an internal-mixing air-assisted atomizer. The cooling effect decreases radially. The results then obtained can be applied to the entire sprayed surface, if the properties of the atomised stream only depend on the radial position in the spray cone and on the distance from the nozzle. As an example the heat transfer coefficient is determined by using the non-stationary measuring procedure.

#### 3.2 Run of temperature

For calculating the heat transfer coefficient from the non-stationary measuring procedure the test metal sheet is heated up to an initial temperature and then abruptly cooled down by the water spray. This process is recorded in a sequence of pictures by the IR camera. From three sequences the run of temperature with time during the cooling down process is plotted in Fig. 7 for the three different water flows 5.7 kg/h, 9.9 kg/h and 13.1 kg/h. In Fig. 7 every plotted point of one curve is a measured temperature value from one picture of a taken sequence. The measured point on the metal sheet surface is in the centre of the spray, 24 mm on the x-coordinate of Fig. 6. The air flow used for atomisation remains constant for all three experiments. It can be seen that the higher the water flow is, the faster the metal sheet is cooled down and the steeper the gradient of the temperature curves is. For very faster cooling down processes the IR camera resolution in time is not sufficient. In this case sequences have to be taken in line-scan mode with a resolution in time of 2500 Hz.
3.3 Heat flux

From the time-dependent surface temperature plotted in Fig. 7 the heat flux is calculated using Eq. (6). Thereby, the heat flux is equal to the right side of Eq. (6), whereas the heat losses are taken into account. In Fig. 8 the surface temperature dependent heat flux is plotted for the three water flows from Fig. 7. It can be seen that for a constant surface temperature the higher the water flow is, the higher the heat flux is. For a constant water flow the heat flux increases with increasing surface temperature. In the investigated area the gradient of the increase of heat flux with increasing surface temperature is nearly independent of the water flow.

![Figure 8. Heat flux](image1)

3.4 Heat transfer coefficient

From the time-dependent surface temperature plotted in Fig. 7 the heat transfer coefficient is calculated using Eq. (6) by taking the heat losses into account. In Fig. 9 the surface temperature dependent heat transfer coefficient is plotted for the three water flows from Fig. 7. It can be seen that for a constant surface temperature the higher the water flow is, the higher the heat transfer coefficient is. For a constant water flow the lower the surface temperature is, the higher the heat transfer coefficient is. The dependence of the heat transfer coefficient on surface temperature increases with increasing water flow.

The results are taken from experiments on evaporation quenching, that means although surface temperature is above Leidenfrost temperature, there is no water film on the hot surface.

4. RESULTS ON STATIONARY MEASURING PROCEDURE

In past investigations the heat transfer in water spray quenching was investigated [4,7,8]. The results of these investigations are shown in Fig. 10 in comparison to other researchers (Fujimoto [5] and Müller/Jeschar [6]). Our own investigations were carried out with the stationary measuring procedure at a surface temperature of 550°C, a drop velocity of 8 m/s and a mean volumetric drop diameter of 60 µm. It can be seen that the water impingement density exerts a major influence on the heat transfer coefficients achieved. When the water impingement density increases, the obtained heat transfer coefficient also increases. Our own examinations result in higher heat transfer coefficients for constant impingement density, but the same gradient of heat transfer coefficient with increasing impingement density as Fujimoto. The curve of Müller/Jeschar has a lower gradient. In order to compare the results of other researchers with our own results it has to be taken into account that the measurement set-up of other researchers measure the heat transfer over a more or less large area. In most publications only the impingement density is investigated as an influencing parameter. But as mentioned before [4], also drop parameters have an influence on the heat transfer achieved.

![Figure 10. Heat transfer coefficient](image2)

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6. REFERENCES


