18th International Conference
ENGINEERING MECHANICS 2012
Svratka, Czech Republic, May 14 – 17, 2012
pp. 499–505
Paper #52

INFLUENCE OF WATER TEMPERATURE ON HEAT TRANSFER COEFFICIENT IN SPRAY COOLING OF STEEL SURFACES

M. Chabičovský, M. Raudenský, M. Hnízdil *

Abstract: *Cooling of stainless steel surfaces with flat fan nozzles was studied experimentally. Several configurations of jets and pressures were tested. Tests were done with variable coolant (water) temperatures (20 °C, 40 °C, 60 °C and 80 °C). The influence of coolant temperature on the heat transfer coefficient was investigated. An increase in coolant temperature caused a significant decrease of the Leidenfrost temperature (temperature at which the character of boiling is changed - the film boiling is changed into nucleate boiling). Changing the water temperature from 20 °C to 80 °C caused a change of the Leidenfrost temperature of about 140 °C. Furthermore it was observed that in a high temperature region (above Leidenfrost temperature) the heat transfer coefficient has the highest value for the lowest water temperature and for the high coolant temperature (80 °C) the cooling intensity is the lowest.*

Keywords: ***Spray cooling, Heat Transfer, Leidenfrost temperature, cooling with hot water***

1. Introduction

This article is based on an experimental study, which was conducted in the Heat Transfer and Fluid Flow Laboratory (Brno University of Technology). The cooling of stainless steel surfaces with flat fan nozzles and the influence of different factors on heat transfer coefficient (HTC) was studied. Because the water temperature in cooling processes in the metallurgical industry changes during the year, one of the goals was to find if the cooling intensity and the Leidenfrost temperature is influenced by the water temperature. The Leidenfrost temperature (Leidenfrost point) is defined as the temperature at which the character of boiling changes. Film boiling is changed into nucleate boiling (see Fig.1).

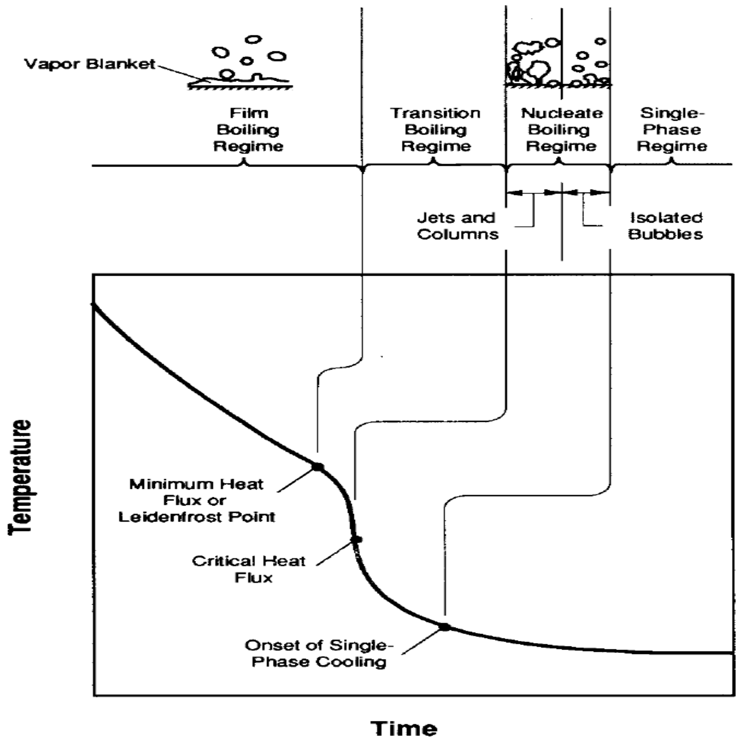

Fig. 1: Temperature-time history of a surface during quenching in bath of liquid (Bernardin & Mudawar, 2002)

The practical importance in the metallurgical industry of the Leidenfrost temperature is that above this temperature is a small heat flux and below is a large one. Water temperature can change the character of the heat transfer (boiling regime) and it can cause problems with process control.

* Ing. Martin Chabičovský, Prof. Ing. Miroslav Raudenský, CSc, Ing. Milan Hnízdil: Heat Transfer and Fluid Flow Laboratory, Brno University of Technology, Technická 2896/2; 616 69, Brno; CZ, e-mail: chabicovsky@lptap.fme.vutbr.cz

Many articles about cooling in metallurgical industry and factors which have the biggest influence on heat transfer have been written in technical journals. Only a small number of them deal with the influence of coolant temperature. Some authors studied, both in theory and practice, the parameters of water droplets (including their temperature) and their influence on cooling and the Leidenfrost point (Bernardin & Mudawar, 1999), (Raudenský & Boháček, 2009). A generalization of models for a single droplet to spray does not lead to results that are measurable in industry (Raudenský & Boháček, 2009). In the experimental study in the Heat Transfer and Fluid Flow Laboratory (Raudenský et al., 2011) the influence of water temperature on cooling with mist nozzles for an austenitic steel plate was measured. In addition the research at the University of British Columbia in Canada (Xu & Gadala, 2006) showed the influence of coolant temperature on cooling in spray cooling for 7 mm thin carbon plates.

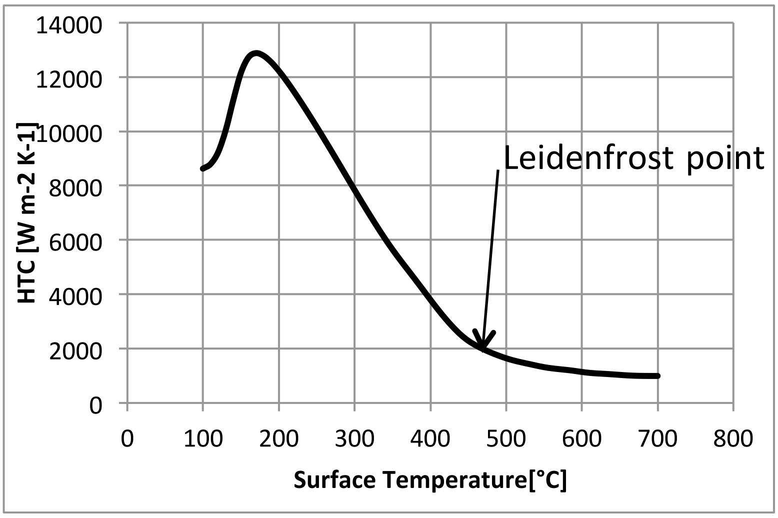

Fig. 2: Typical dependence of HTC on surface temperature in spray cooling

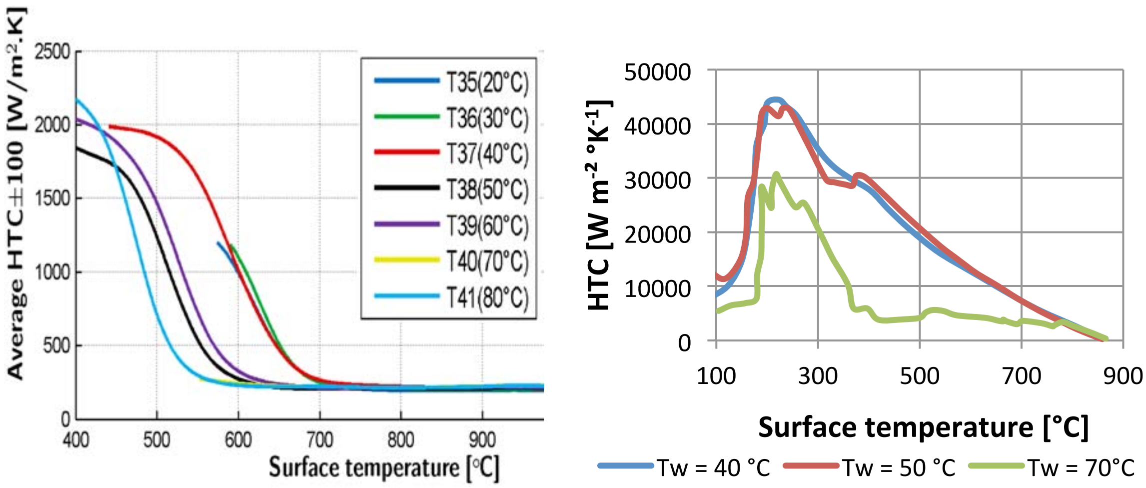

Fig. 3: Influence of water temperature on heat transfer coefficient. Left graph adapted from paper (Raudenský et al., 2011). Right adapted from paper (Xu & Gadala, 2006).

It can be inferred from the dependence of heat flux on the surface temperature and the knowledge of eq. (1)

$$\dot{q} = HTC(T_S - T_W) \tag{1}$$

that the change of cooling intensity is caused only by the difference between the surface temperature T_S and the water temperature T_w and it is not connected with the shape of the HTC curve. It is not true. The change of cooling intensity is mainly caused by changing the type of boiling. As it was shown in Raudenský et al. (2011) and Xu & Gadala (2006), the increase of coolant temperature caused the decrease of the Leidenfrost temperature, which is connected with changing of type of boiling.

2. Experimental measurements

2.1 Experimental apparatus

An experimental apparatus developed for linear moving of the hot test sheet under nozzles was used in experiments. The nozzles were located above or under the hot sheet. The movement of the holder with the test plate was provided by an electric engine, which was connected to the holder by a steel wire. The girder was rotatable. It allowed upper, bottom and side cooling. The collector with nozzles was connected to a manometer and a water tank. The water tank was equipped with a heater. It allowed adjusting of the water temperature from 20 °C to 90 °C. The water from the water tank was pumped to the collector. The sheet holder was equipped with a position sensor. Thermocouples were welded on the underside of the test sheet (see Fig. 4). Information about the temperature of the test sheet, water temperature and position of the test sheet was recorded in a data acquisition system (datalogger). The information was transferred from the datalogger into the computer after the experiment.

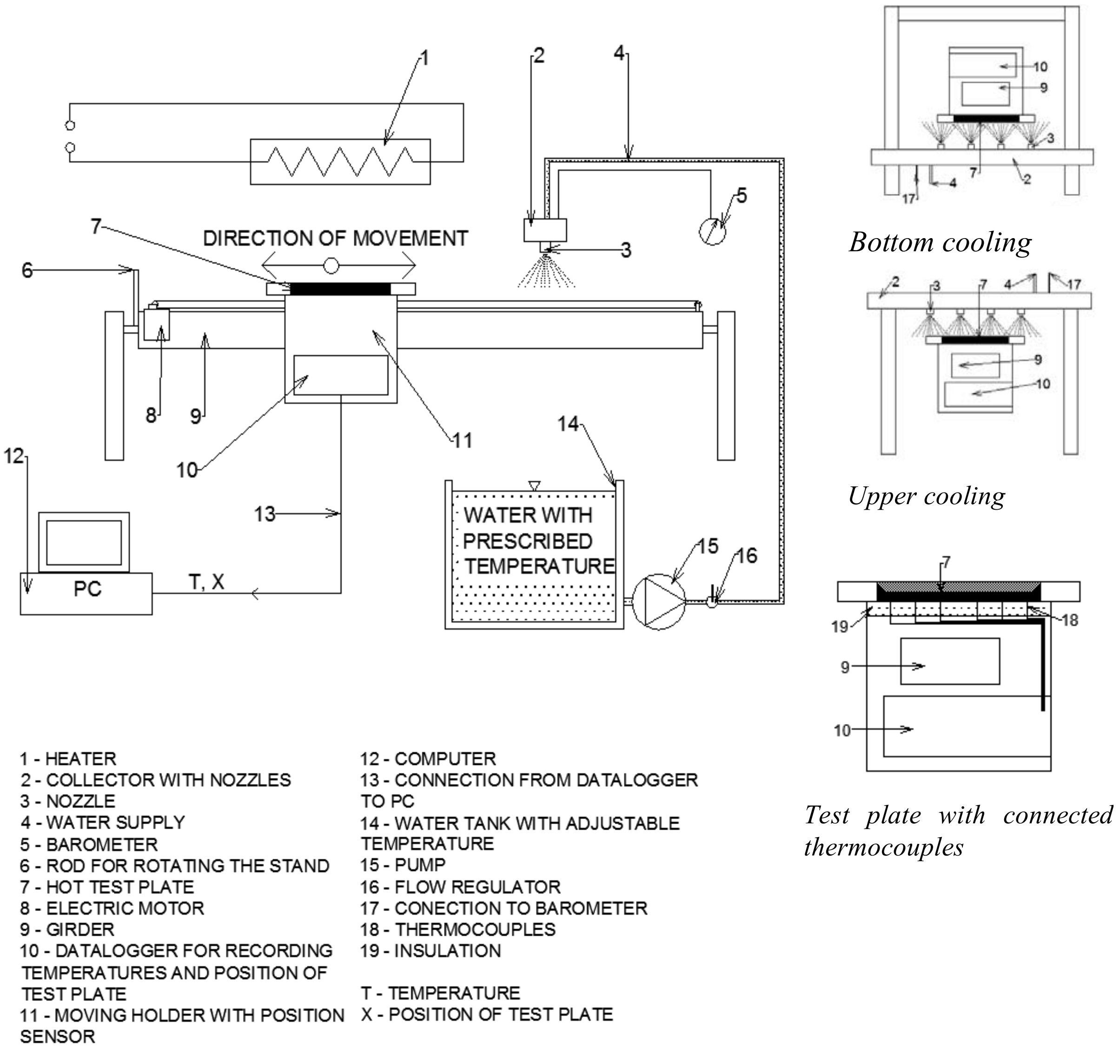

Fig. 4: Schematic diagram of experimental apparatus

2.2 Experimental procedure

First the cooling section and the test sheet were prepared. A predetermined number and type of the nozzles was connected to the supporting frame. The thermocouples were connected on the test sheet. The test sheet was placed into the furnace and heated. The experiment started after reaching the target temperature 900 °C. The datalogger started recording information about the temperature and location of the test sheet. The pump was switched on and the flow rate was adjusted. Heating was stopped. The test sheet was removed from the furnace and repeatedly passed through the cooling section with prescribed velocity (see Fig. 5). When the test sheet was sufficiently cooled, the pump was switched off and the movement of the test sheet was stopped. Data recording was stopped and the obtained data were transferred into the computer. This was followed by subsequent data processing and numerical computation of surface temperature and HTC using inverse task (Raudenský, 1993).

Fig. 5: Example of upper cooling experiment

2.3 Program of experiments

Commercially available flat fan nozzles were used for experiments with different water temperatures. The initial temperature of stainless steel sheet was 900 °C. All experiments were conducted with water pressure 3 bar and velocity of the test sheet 0.8 ms^{-1}. Some experiments were conducted with upper cooling and others with bottom cooling. Each experiment was conducted with a different temperature. The temperatures tested in the experiments were 20 °C, 40 °C, 60 °C and 80 °C for upper cooling and 40 °C and 60 °C for bottom cooling. Experiments TEMP20U, …, TEMP80U indicate upper cooling experiments and TEMP40B, TEMP60B indicate bottom cooling experiments (Tab. 1).

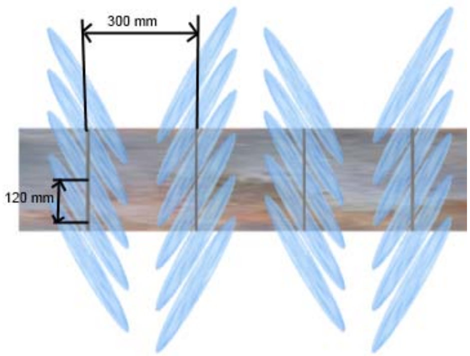

Fig. 6: Illustration of nozzles position above sheet

Tab. 1 Table of testing parameters

Experiment	Step between nozzle widthwise	Velocity	Water Pressure [bar]	Water Temperature [°C]
TEMP20U				20
TEMP40U	120 mm	0.8 m/s		40
TEMP60U			3	60
TEMP80U				80
TEMP40B				40
TEMP60B	120 mm	0.8 m/s	3	60

3. Results

The measured temperatures were recomputed to the surface temperatures and the heat transfer coefficient was computed by the inverse task (Raudenský, 1993). The dependence of the heat transfer coefficient on the surface temperature for various water temperatures in top cooling experiments is shown in Fig. 7. This graph shows the shift of the Leidenfrost temperature to lower temperatures with increase of the coolant temperature. The change of water temperature from 20 °C to 80 °C caused the change of about 140 °C of the Leidenfrost temperature. A similar result was obtained for bottom cooling experiments (Fig. 8). These results match results for austenitic plate presented in Raudenský et al. (2011) and for carbon steel in Xu & Gadala (2006).

Furthermore it was observed that in a high temperature region the heat transfer coefficient decreases with increasing coolant temperature (Fig. 9 and Fig. 10). It is interesting that the value of the heat transfer coefficient is nearly the same for water temperatures 40 °C and 60 °C (Fig. 9). These results can be expected, but are inconsistent with results presented in Raudenský et al. (2011) for mist nozzles. This could be caused by different type of nozzles (mist nozzles) and the general experiment configuration.

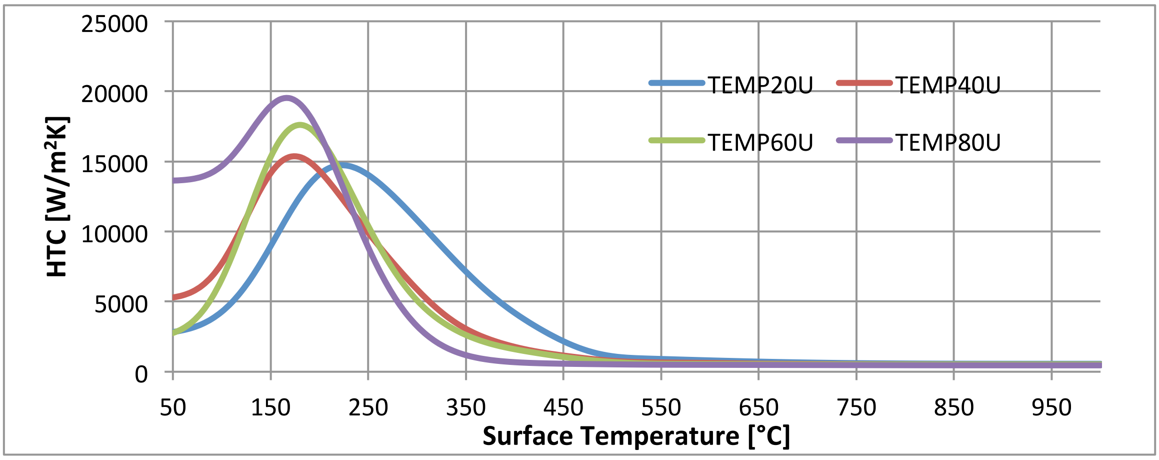

Fig. 7: Upper cooling

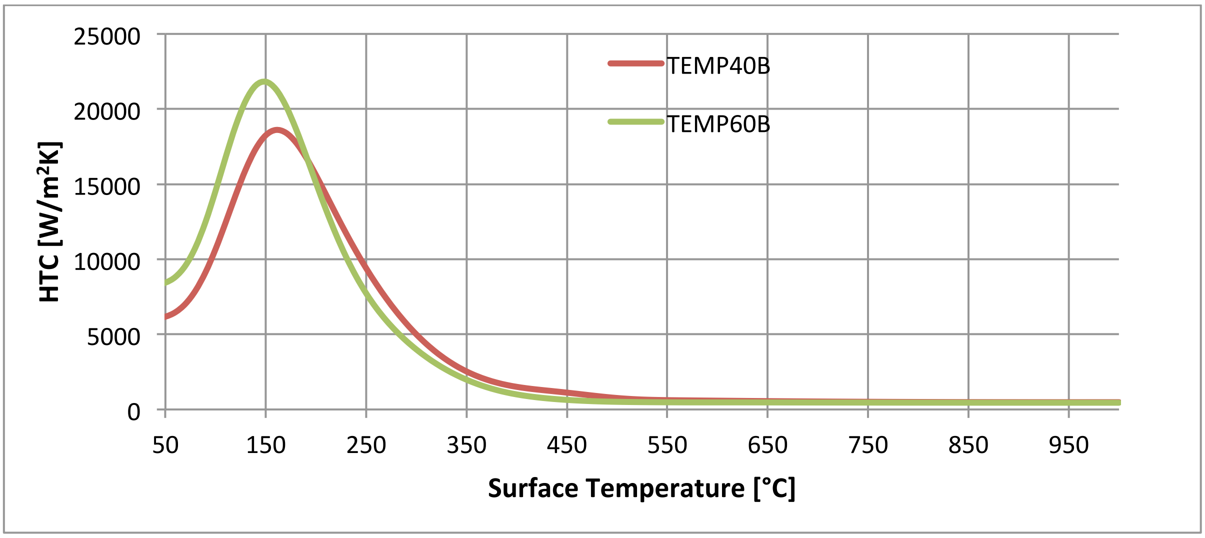

Fig. 8: Bottom cooling

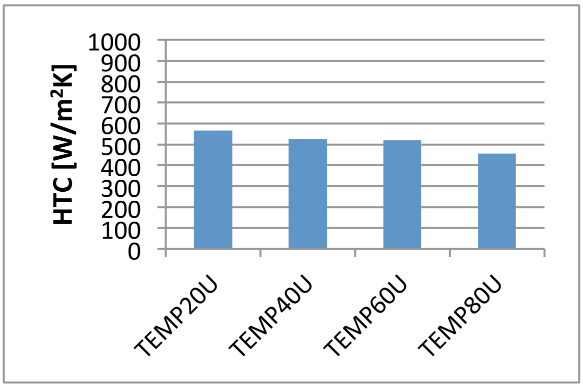

Fig. 9: Upper cooling in high temperature area

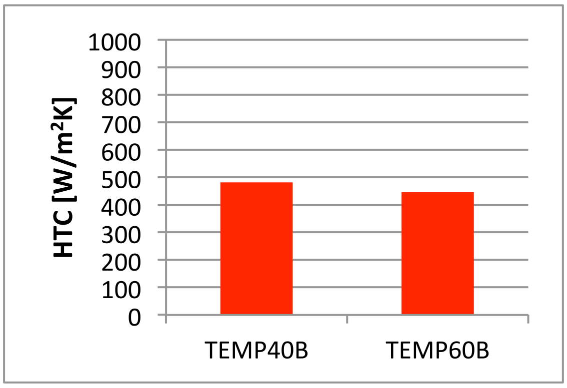

Fig. 10: Bottom cooling in high temperature area

A simple explanation of the shift of the Leidenfrost temperature may be as follows. Hot water does not need as much heat as cold water to reach the boiling temperature. Heat needed to heat water to boiling temperature is small compared with the heat required to change phase from liquid to gas. The time required to heat warmer water is a bit shorter than for colder water. This small shorten of the time needed to heat water can cause a decrease of Leidenfrost temperature. There is no need to supply so much heat from the surface to incoming water and so a steam layer can be formed even at lower surface temperatures. Another thing which may cause a shift of the Leidenfrost temperature could be decrease of water viscosity with increasing water temperature. Proper justification would require further research.

4. Conclusion

Experimental investigation showed the influence of coolant temperature on Leidenfrost temperature in cooling stainless steel sheets. The change of water temperature from 20 °C to 80 °C caused the change of 140 °C of the Leidenfrost temperature. This result is in agreement with results for austenitic steel (Raudensky et al., 2011) and for carbon steel (Xu & Gadala, 2006). This result has applications in the metallurgical industry, where the temperature of cooling water changes during the year. This change of coolant temperature causes a change of cooling intensity and it leads to undesirable material properties. Furthermore it was observed, that in the high temperature region the heat transfer coefficient decreases with increasing coolant temperature and the value of the heat transfer coefficient is nearly same for water temperatures 40 °C and 60 °C.

Acknowledgement

The paper presented has been supported by the internal grant of the Brno University of Technology No. FSI-S-11-20.

References

Bernardin, J. D. & Mudawar, I. (1999). The leidenfrost point: Experimental study and assessment of existing models. *Journal of Heat Transfer*, 121(4), pp. 894-903.

Bernardin, J. D. & Mudawar, I. (2002) A cavity activation and bubble growth model of the leidenfrost point. *Journal of Heat Transfer*, 124(5), pp. 864-874.

Bernardin, J. D. & Mudawar, I. (2004) A leidenfrost point model for impinging droplets and sprays. *Journal of Heat Transfer*, 126(2), pp.272-278.

Bernardin, J. D., & Mudawar, I. (2005) Transition boiling heat transfer of droplet streams and sprays. *Paper presented at the American Society of Mechanical Engineers, Heat Transfer Division, (Publication) HTD*, 376 HTD(2), pp. 201-210.

Horský, J. & Raudenský, M. & Tseng, A. (2005) Heat Transfer Study of Secondary Cooling in Continuous Casting. *AISTech 2005*. Ohio, pp. 1-11.

Raudenský, M. (1993) Heat transfer coefficient estimation by inverse conduction algorithm. *International Journal of Numerical Methods for Heat and Fluid Flow*, 3(3), pp. 257-266.

Raudenský, M. & Boháček, J. (2009) Leidenfrost Phenomena at Hot Sprayed Surface. *In 7th ECI International Conference on Boiling Heat Transfer.* pp. 1-9.

Raudenský, M. & Hnízdil, M. & Lee, S. & Kim, S. & Hwang, J. (2011) Influence of Water Temperature on Cooling Intensity of Mist Nozzles in Continuous Casting. *In 19th Conference on Materials and Technology. Ljubljana 2011*. pp. 60-70.

Xu, F & Gadala, M. S. (2006) Heat transfer behavior in the impingement zone under circular water jet. International Journal of Heat and Mass Transfer, Volume 49, Issues 21–22, pp. 3785-3799, ISSN 0017-9310.