WATER JET COOLING OF ALUMINUM ALLOY

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Abstract

Jet cooling is used in many industrial applications. A typical application is the ingot casting process. Cooling water flows into a mold, where it is distributed through a system of channels into holes that are spaced very closely together. For better homogenization, the water flows from the leading edge and then impacts the surface of an aluminum ingot [1]. To obtain realistic results from numerical simulations, it is necessary to know the boundary conditions for each cooling scenario. It is not possible to use analytic solutions or multiphysics simulation software to obtain realistic heat transfer coefficient (HTC) curves which represent the cooling intensity. Boundary conditions can be obtained by experimentally reproducing the same conditions in the laboratory and measuring temperature dependence over time. Evaluating the data is done using the inverse task, which calculates the surface temperature and HTC. Temperatures are measured using shielded thermocouples which are installed very close to the sample surface. The final goal of this work is to experimentally investigate the cooling intensity during the casting process of ingots. Two types of cooling regime - continuous and pulse and changing the amount of cooling water were studied. The HTC curves from the calculated surface temperature data are used as boundary conditions for a numerical model which can simulate temperature distribution inside the ingot during the cooling process.

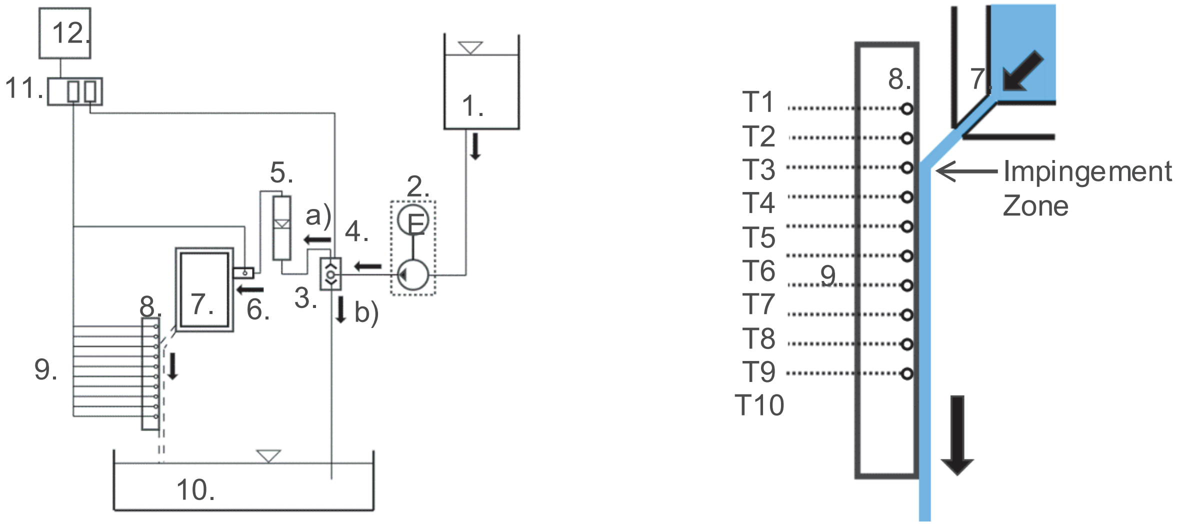
Keywords: Aluminum casting process, heat transfer coefficient, inverse task, thermocouples

1. INTRODUCTION

One of the most important considerations during the aluminum casting process is the capability of attaining defect-free ingots. The major influence on defect generation has a superheat extraction from the incoming liquid metal by the secondary water-cooling system due to direct water impingement on the ingot surface; typically, more than 80 % of the total heat is removed this way under steady-state conditions [2]. The casting process has two distinct stages - start-up and steady state. Considerable attention should be paid to the initial start-up stage, where defects are most likely to be initiated. Issues which reduce ingots quality include hot tearing, cold cracking and the butt curl effect caused by thermal stress generated during the transient start-up phase [3]. In order to avoid the appearance of structural defects in aluminum alloys ingots should be cooled with a low intensity. Decreasing at continuous regime can be achieved just by the reducing water flow rate. But to ensure the proper mold cooling function during the casting process the water flow rate can't be reduces below a certain minimum value. In other case cooling intensity will be non-uniform. Due to this the pulse cooling, which can decrease the cooling intensity in impingement zone (IZ) without reducing the water flow rate within the mold, is preferable in this casting phase. A solution is to find the optimal synergy of all main technological parameters (metal pouring temperature, casting speed, cooling regimes - continuous or pulse, and alloy composition) with the knowledge of the desired cooling intensity through a numerical simulation. A numerical model which can predict temperature distribution during the casting process should be based on boundary conditions reproducing a real cooling scenario. There is no available function which accurately describes cooling intensity using all of the aforementioned parameters, and so real measurement is the only way to determinate the cooling intensity [4]. Due to this fact, unique techniques utilizing the inverse computation of the HTC using a two dimensional transient model was developed in the Heat Transfer and Fluid Flow Laboratory (HeatLab), at Brno University of Technology.

2. DESIGN OF THE EXPERIMENTS

The goal of the experimental measurement was to reproduce real casting conditions in the laboratory and show the influence of parameters on cooling intensity which are typically used in casting plants, including: water flow rate, cooling regime (continuous or pulse) and on/off time for pulsating water. The experimental rig is illustrated in **Fig. 1**. It consists of a test sample with built-in thermocouples which is heated to approx. 475 °C. Cooling is performed with a mold segment positioned in front of the sample. The flow rate is adjusted to the desired values (from 5 l/min to 15 l/min) with the help of a control valve and flow meter. A pulsation unit is used for pulse cooling, along with a pneumatic valve for switching between two ducts a) and b) (see **Fig. 1**) and to deliver on/off water pulses. All pulse periods last for 1.5 sec and can be programmed via PC. The readings from the embedded thermocouples were recorded by a data acquisition unit to a PC with a frequency of 100 Hz.



(a) All components

(b) Position of the thermocouple due to the water flow

Fig. 1 Experimental rig

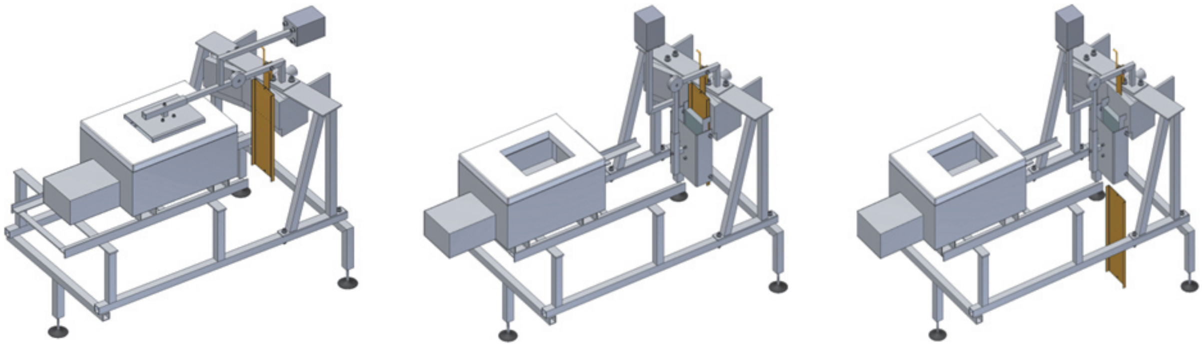
1. Tank with cooling water. 2. Electric motor with hydro-generator. 3. Valve (providing pulse cooling). 4. Valve pulse controlling connection. 5. Flow meter. 6. Thermocouple for cooling water temperature measurement. 7. Mold segment. 8. Test sample. 9. Thermocouples for data collection from sample. 10. Tank for used water. 11. Data acquisition system. 12. Computer

Table 1 Experiments setup

Continuous Cooling		Pulse Cooling			
Experiment	Flow rate [l·min^{-1}]	**Experiment**	Flow rate [l·min^{-1}]	ON time [s]	OFF time [s]
E1	5.79	**E5**	5.94	0.6	0.9
E2	6.42	**E6**	5.94	0.9	0.6
E3	10.7	**E7**	6.42	0.9	0.6
E4	14.98	**E8**	6.38	1.35	0.15

2.1. The experimental device

The design's main function is to ensure that the position of the mold and the sample during measurement is as it would be during the real casting process. The design allows for the vertical position of the sample to be changed before experiment by raising or lowering it, thus changing the IZ position of the thermocouples. Due to this change the place of impingement zone on the sample surface. The experimental procedure is as follows and is illustrated in **Fig. 2**: The sample was placed into a furnace to warm it to a temperature of 475 °C. Next, data recording was started at the computer, the desired water flow rate was set (if pulse cooling was required, the periods of pulses were set as well) and the sample was placed in the cooling position. The last step was to let water impact the sample surface by removing the deflector.



(a) Heating position

(b) Preparation position before cooling

(c) Cooling position

Fig. 2 Experimental device

2.2. Design of the sample

The aluminum sample had a machined surface with a height of 200 mm and thickness of 20 mm. It was equipped with 10 shielded, ungrounded, K-type thermocouples with a diameter of 1 mm. Holes for thermocouples were drilled from the side surface of the sample parallel to the horizontal axis at a distance of 3 mm from the cooling surface. The distance between thermocouples was equal to 10 mm. First, two thermocouples were placed above the impingement zone, the axis of the third thermocouple coincided with the IZ and the rest of the thermocouples were placed under the IZ (see **Fig. 1b**).

2.3. Calculating of boundary conditions

Measured data in the form of temperature dependence on time was taken as inputs for the calculation of the temperature dependent boundary conditions (HTC on the surface temperature). The inverse heat conduction problem (IHCP) based on a modified 2D method of Beck's sequential approach was used for solving. The two-dimensional model was used because the high thermal conductivity of aluminum leads generates large lateral heat fluxes in the material during the cooling process which must be accounted for. The basic idea of the sequential approach was to solve the entire task step by step in time [5, 6]. First, the sum of squares error was computed using *f* future time steps when the measured temperatures T_i^* are compared with the computed temperatures T_i at the current time *m*:

$$SSE = \sum_{i=m+1}^{m+f} \left(T_i^* - T_i\right)^2 \qquad (1)$$

Temperatures T_i are temperatures calculated by direct calculation for a constant heat flux. Then, the surface heat flux *q* at time *m* was calculated by minimizing equation (1) using the linear minimization theory

$$q_m = \frac{\sum_{i=m+1}^{m+f} \left(T_i^* - T_i \,|_{q^m=0} \right) \zeta_i}{\sum_{i=m+1}^{m+f} (\zeta_i)^2} \tag{2}$$

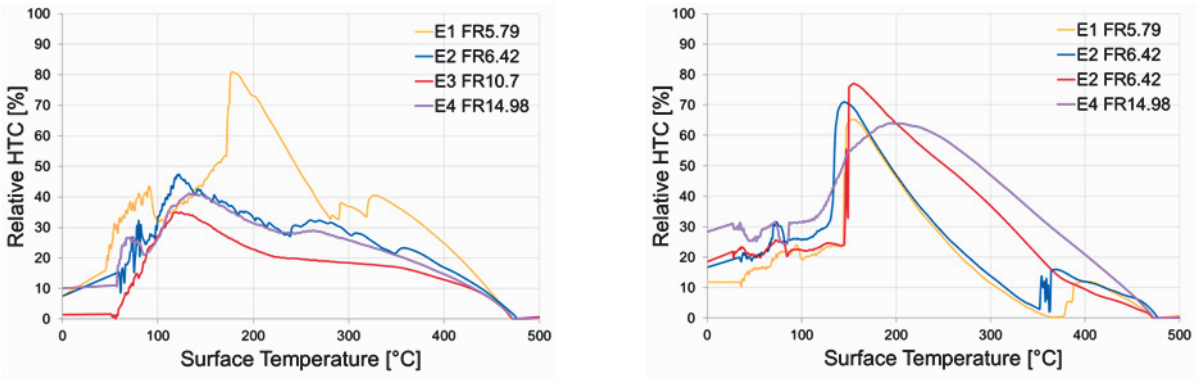
where ${}^{T_i}\big| q^m = 0$ are the temperatures of the thermocouples, which have been embedded in the test sample, and computed from the forward solver using all previously computed heat fluxes without q_m. ζ_i is the sensitivity coefficient at time index i to the heat flux pulse at time m. These sensitivity coefficients physically indicate an increase of the temperature in the thermocouple per unit of heat flux at the surface. The heat transfer coefficient can be computed when surface temperatures T_0^m and surface heat fluxes q_m are known.

$$HTC_m = \frac{q_m}{T_\infty^m - \left(T_0^m + T_0^{m-1} \right) / 2} \tag{3}$$

T_∞^m is ambient temperature.

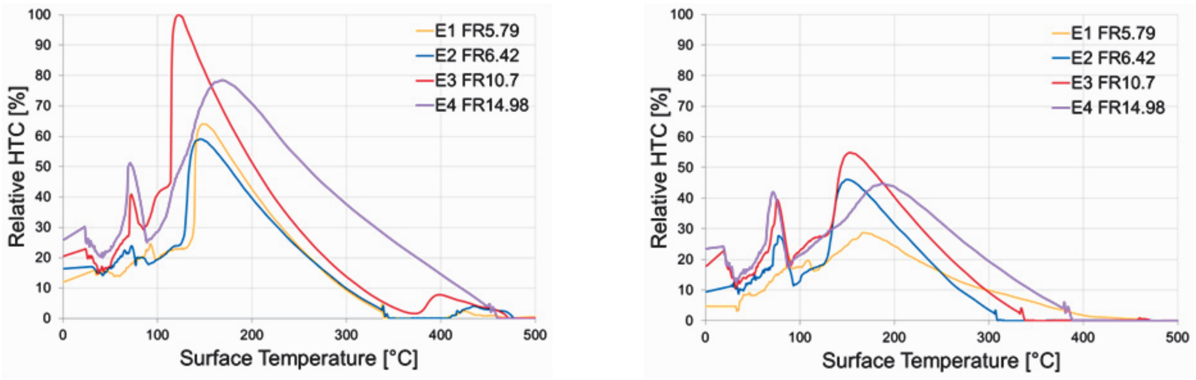
3. RESULTS OF THE JET COOLING INTENSITY MEASUREMENTS

The following charts were calculated via the model which is described in the previous section. All obtained boundary conditions had been verified using the commercial software ANSYS 15.0. These HTC curves were used as boundary conditions for cooling. This data aligns to measured temperatures quite well. All deviations are within acceptable values.



(a) 0 mm from IZ

(b) 20 mm from IZ



(c) 30 mm from IZ

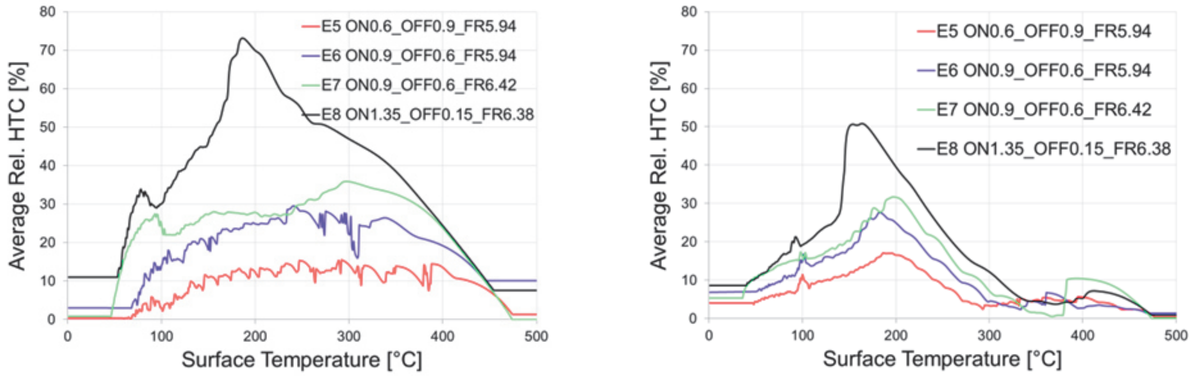
(d) 50 mm from IZ

Fig. 3 Influence of distance from IZ on the HTC curves for continuous cooling experiments

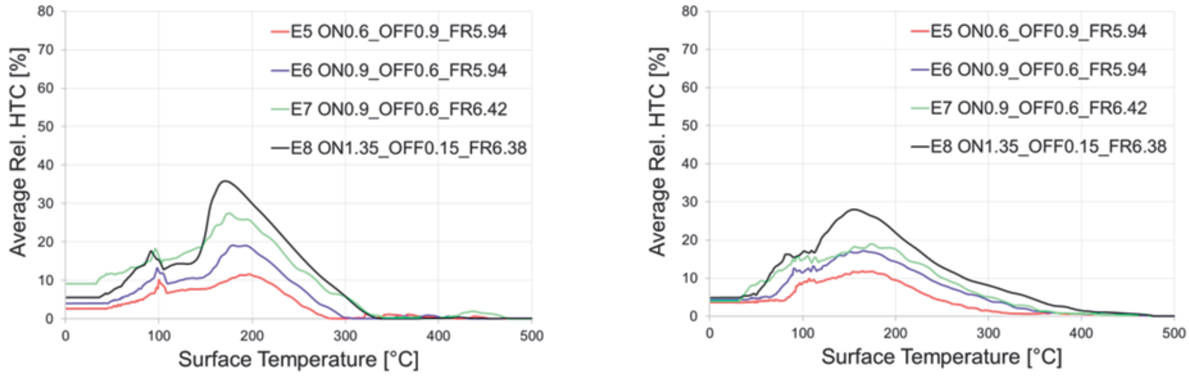
The HTC loops were formed during pulse cooling as a result of switching between time periods with and without cooling. These loops cannot be described by mathematical functions and therefore were averaged according to the following equation (4). The following four charts in **Fig. 4** are average values of relative HTC.

$$HTC_{ave} = \frac{\sum_{i=t}^{t+n} HTC_i}{n} \tag{4}$$

Where *t* is the time index for the beginning of a pulse and *n* is the sample number collected in one pulse. The time period of each pulse is 1.5 sec and the sampling frequency during the experiments was 100 Hz, as described in the beginning of section 2.



(a) 0 mm from IZ (b) 20 mm from IZ



(c) 30 mm from IZ (d) 50 mm from IZ

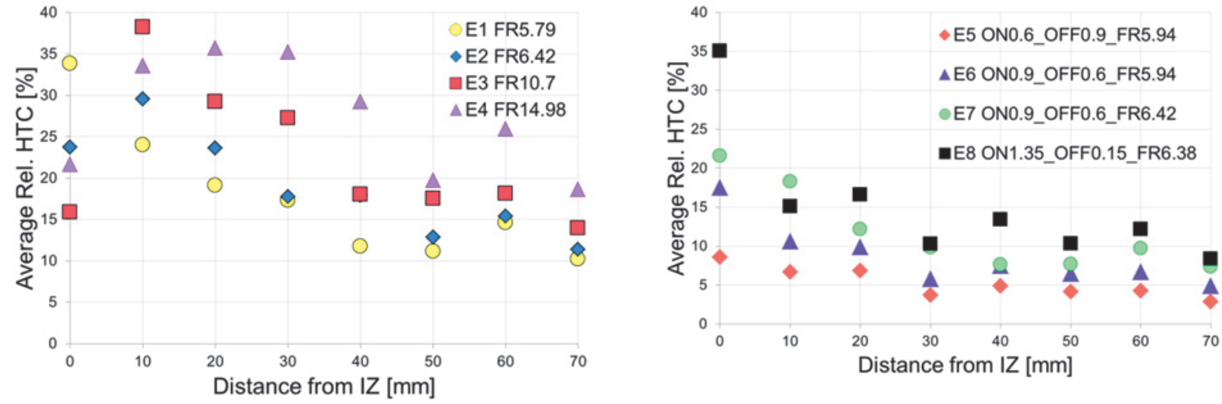
Fig. 4 Influence of distance from IZ on the HTC curves for pulse cooling experiments

4. ANALYSIS OF THE RESULTS

One important property of aluminum is its high thermal conductivity. Due to this fact, it is capable of supplying the surface layer with sufficient heat energy by internal and lateral heat fluxes. Therefore the vapor layer can resist the water flow much longer (see **Figs. 3** and **4**).

Figs. 3 and **4** show that the HTC curves have two modes. In the first mode (see **Fig. 3a**, **3b**, **4a** and **4b**), with a distance within 20 mm from the IZ, there is not a visible Leidenfrost point neither film boiling regime. The kinetic energy of the water flow has enough energy to break through the vapor layer immediately after it hits the sample surface. In the second mode (see **Fig. 3c**, **3d**, **4c** and **4d**), with a distance of 30 mm and further from the IZ, the water flow is separated from the surface by the steam layer, which acts as insulation. Above the Leidenfrost temperature (about 320 °C), the HTC is close to zero compared to maximum values.

During the experiments were observed an unstable behavior of the water stream for a very short period of time. This effect was occurred at the moment when water impacts the sample. Due to this fact is the maximum of average HTC located between 0 mm and 10 mm from the IZ (see **Fig. 5**).



(a) Continuous cooling

(b) Pulse cooling

Fig. 5 Variation of average HTC [%] for different distance from IZ and different types of cooling

When comparing both cooling types (see **Fig. 5**) it is clear that pulse cooling has a lower intensity. For the start-up phase of the casting process this cooling type is more suitable because it generates less thermal shell strain.

5. CONCLUSION

This article summarizes the results from an experimental determination of heat transfer coefficient. It also compares the influence of two different types of cooling, pulsation and continuous, on cooling intensity. During this work was established that a pulsing cooling regime of ingots provides a lower intensity. At pulse cooling regime the lowest HTC were received when the period of cooling (ON time) was the shortest and not-cooling period (OFF time) was the longest. This cooling type is more suitable for the start-up phase of the casting process because it generates less thermal shell strains.

ACKNOWLEDGEMENTS

This work is an output of research and scientific activities of this project LO1202 with financial support from the MEYS under the programme NPU I

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