# Heat Transfer Modelling of Continuous Casting: Numerical Considerations, Laboratory Measurements and Plant Validation

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ABSTRACT: Accurate heat transfer models of continuous casting require accurate measurements to characterize the boundary conditions, temperature and alloy-dependent thermal properties, optimization of numerical errors caused by model discretization, and validation with plant measurements. Recent efforts of an international collaboration on all of these aspects are summarized, focusing on modelling of secondary cooling, spray cooling measurements, the effect of materials properties and analysis of the simulation results based on experimental and theoretical considerations. Spray cooling laboratory measurements are conducted using a collector system for the shape of spray water distribution and both transient and novel steady-state apparatus to obtain the corresponding heat transfer coefficients. The steady-state measurements indicate significantly higher values than the transient measurements.

## 1. Introduction

The ultimate goal of this research is to control spray conditions to optimize secondary cooling during the continuous casting of steel. This is being accomplished with the help of heat transfer models, which include both offline analysis tools and fully-online models which serve as “software-sensors” [1]. These different purposes require different considerations. The software sensor models must execute in fractions of a second, so must be simplified using coarse computational grids and efficient numerical methods. Every model requires accurate boundary conditions, which require both plant and laboratory measurements to characterize the heat transfer coefficients during spray cooling. Previous measurements with air-mist spray cooling are rare.

Plant trials are made to adjust the model coefficients such that the model predictions can accurately match the measurements for the entire range of operating conditions. After that, the model should be validated with an independent trial. After this calibration procedure, it should be possible to use the model as a tool to predict, optimize, and control the temperature distribution in the strand. Most plants routinely measure mould water temperature and flow rate (for mold heat flux) and use a single pyrometer located just after the end of the spray chamber. In addition, other possible plant measurements include other pyrometers located inside the spray chamber, other surface temperature measurements, and strand measurements such as with the “wedge test” to find the shell thickness at certain points down the caster [2].

Laboratory measurements are also necessary in order to find the nozzle water distribution, and heat transfer coefficients or directly-measured heat flux values that are obtained under controlled conditions. Such fundamental measurements enable more robust and accurate mathematical model predictions. Previous work has characterized this heat transfer using transient temperature measurements [3,4]. The present research also introduces laboratory spray-cooling measurements based on a novel induction-heating apparatus that are being applied to describe the heat transfer of both water-spray and air-mist nozzles.

## 2. Plant Trials

Pyrometer measurements are currently considered the most cost-effective and reliable method of measuring the strand surface temperature during continuous casting. This requires two-colour pyrometers that are less sensitive to the radiation absorption problems of steam and the emissivity problems of surface scale. Never-the-less, pyrometer measurements are usually noisy and averaging has to be used to find the surface temperatures. The reliability of these measurements can be estimated by using consecutive pyrometers and checking that temperature variations actually move down through the caster as expected with a known casting speed. An example of a typical pyrometer measurement during a casting trial is shown in Fig. 1. Other temperature measurement methods have not been reliably achieved yet in this project.

In the wedge test, a steel wedge is inserted between a roll and the strand. The mechanical bending stresses generate small cracks near the solidification front. After casting, this part of the strand is etched to reveal the cracks and to extract the nearby location of shell solidification front when the cracks formed. A more detailed description of the wedge method can be found from [2].

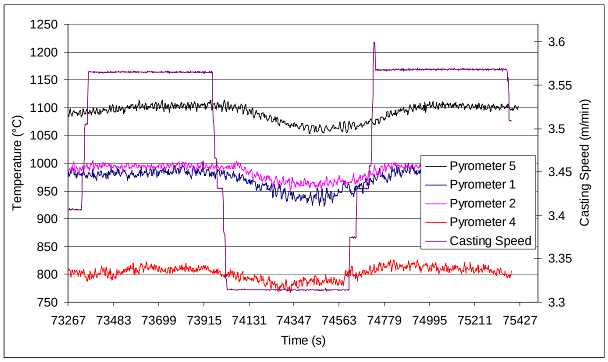


*Fig. 1: Transient temperature history measured by optical pyrometer during a plant trial.*

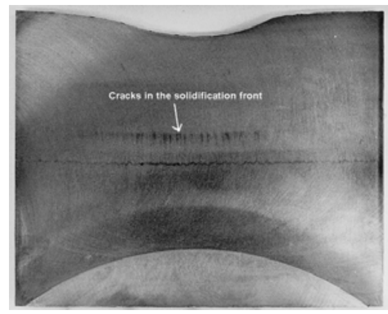


*Fig. 2: A figure of the formed cracks in the solidification front [2]*

## 3. Heat Transfer Modelling of Continuous Casting

Fundamental heat transfer models developed for continuous casting are based on solving the transient heat-conduction equation and the accuracy of the predictions is governed by numerical accuracy, the boundary conditions, and the material properties. Of particular importance is the choice and sensitivity to numerical parameters such as the mesh refinement and time-step size. After finding the limits after which the results do not change (within a selected tolerance limit), the software is ready to be used for optimization, development, research, and designing purposes. This sometimes means that the model is too slow to be run online. To run a model online requires simplifications, such as assuming one-dimensional heat conduction through the strand centerline, or using a coarse grid. The implications of these simplifications should be known.

Most of the heat in continuous casting process is extracted in the secondary cooling zone. The secondary cooling consists of several cooling segments and within a segment there can be found four different zones that are repeated: I roll contact, II dry or low water zone, III spray, and IV flowing/water pool zone.

The roll absorbs heat from strand surface radiation and conduction. Both have major contribution to the roll cooling water [5]. In reality, the contact area is complicated to know, and in the models, this heat removal is usually simplified to only the estimated contact area.

Between the roll and the spray only air convection and radiation is taken into account. This is probably not a completely right assumption but the heat removal is small compared to spray and roll contact areas. Below the spray region, the water is flowing and building up on the roll causing a pool of water to form. There, the convection is considered to be that of the flowing water. In curved portions of the caster, the spray on the upper surface of the strand can accumulate, while the droplets tend to bounce off the lower surface. This leads to a difference in effective heat transfer coefficient between the upper and lower strand surfaces.

Most of the heat is removed in zone III by the sprays. Over the years, many experimental correlations have been proposed that mathematically describe the spray heat transfer coefficient in the secondary cooling zone. [6] Most of the models are of the same form as Eq. (1) where $h$ is heat transfer coefficient, $a$ an adjustment parameter, $Q$ the water flux, $n$ a fitting parameter for the water flux and $c(T)$ a term to take the effect of the Leidenfrost effect into account. The Leidenfrost temperature is where the heat flux is the lowest in the end of the film boiling regime. Below this temperature, the heat flux increases with a decrease in temperature, within a certain range.

$$h = a * Q^n * c(T) \tag{1}$$

These models can be accurate as long as the water on the surface is in the film boiling regime where the water forms two layers: water and underneath the water a thin layer of steam. When the heat transfer is within this regime, the heat transfer coefficient is relatively constant. At lower temperatures, the models should include the Leidenfrost effect. This is difficult because the Leidenfrost temperature is dynamic and is a complex function of droplet momentum, surface roughness, and surface temperature. [3]

Today air-mist nozzles are commonly used in which the water is driven out of the nozzle orifice using compressed air. This practice may increase the Leidenfrost temperature to such a high value that heat transfer is always in the transient boiling regime [2,3]. As can be seen, Eq. (1) does not contain a term to take into account water droplet size or velocity. In [8] a more sophisticated correlation Eq. (2) is presented where the droplets are considered but again the model is only valid above the Leidenfrost temperature. In Eq. (2) $D_P$ is the droplet diameter, $v_0$ the impingement velocity, and $N$ the droplet number density.

$$h = 1.90 D_P^{1.1} v_0^{1.1} N^{0.65} \tag{2}$$

A fundamental relation based on Eq. 2 has not yet been validated with plant measurements for the nozzles and conditions of interest to continuous casting. Thus, further lab measurements and empirical adjustments based on plant experiments are still required. This means that measurements have to be made on all of the nozzles in a caster for several spraying conditions (air and water flow rates) and the results have to be analyzed and set as boundary conditions into the models as a function of spraying condition.

## 4. Laboratory Measurements

In the laboratory, it is possible to characterize nozzles and get valuable information for adjusting the heat transfer models in addition to practical information on how the nozzles behave in the steel plant. These measurements include operating diagrams, water distribution of the nozzle and heat transfer measurements to quantify the nozzle's heat removal. The operating diagrams are graphs that show the relationship between water and air flow rates at different pressures. During this project, it was noticed that operating windows for some nozzles are very small and special attention should be paid at the plant to minimize pressure variations in the secondary cooling air and water, to avoid problems.

In this project, water distribution was measured using a collector shown in Fig. 3. From these measurements dimensions and water impact flux values were obtained and input into the heat transfer model. An example of the results is shown in Fig. 4.

*Fig. 3: Water collector used in the distribution measurements*

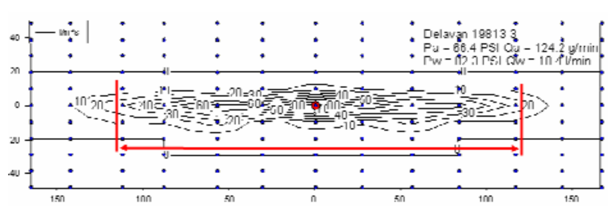


*Fig.4: Example of a distribution obtained by the measurement*

Spray heat transfer research can be divided into two principal methods: transient and steady state measurements. It is most likely that conditions in the actual caster are a combination of both of these experimental conditions and both types of measurements are required in developing realistic and accurate mathematical models for spray cooling. In the transient method, a piece of metal is heated to a desired temperature and after that it is spray cooled down to room temperature and the temperatures are recorded with thermocouples. Usually a 1-dimensional inverse heat transfer model is used to calculate the heat flux as a function of both surface temperature and time. To use these results in a spray heat transfer model, each thermocouple location can be associated with an impact flux of water. This can be accomplished by measuring the water flux distribution using a collector, as shown in Fig. 3. A potential problem with this method is that the independent variations of heat transfer with time and with surface temperature cannot be distinguished, as temperature is coupled with time and most of the experiment is over in just a few seconds. To overcome this problem requires maintaining the strand surface temperature using steady-state experiments.

A few previous articles have been published about steady state measurements e.g. [9,10,11,12]. In [9] a blowtorch and for smaller specimens electrical heating is used but no results are given. In [10,11] a blowtorch is used for heating a round steel plate. The problem with a blowtorch is to quantify the heat input into the plate. Another problem of accuracy is that spray characteristics i.e. droplet size and velocity, are a strong function of position in the spray, the blow torch sample is very large and the sample is exposed to the entire spray area. This means that a relationship between local spray parameters and measured heat fluxes can not be established. In the novel method developed in this project, an induction based heating system is used with a small sample (diameter 8 mm). It was selected because of the possibility to accurately monitor the power consumption, and to use a small sample, having an accurate, variable position and a fast response time. A schematic of the apparatus is shown in Fig. 5 and a picture of the experiment is shown in Fig. 6.

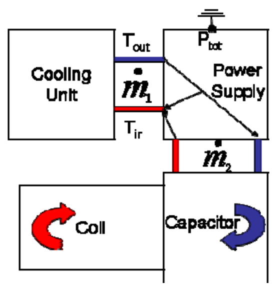


*Fig. 5: Steady state measurement apparatus.*

*Fig. 6: A hot sample ready for a spray experiment*

The apparatus is still under development but preliminary results look promising. In Fig. 7, some new steady-state results are given and compared to transient measurements.

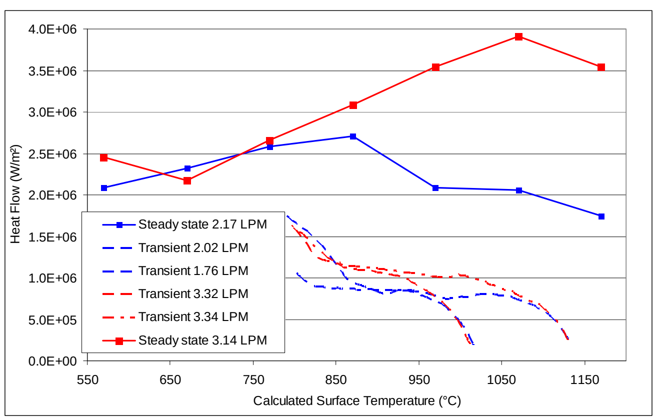


*Fig. 7: Steady state and transient heat transfer measurements of a water nozzle*

It is difficult to draw firm conclusions from this experiment, owing to the difficulties in avoiding sample oxidation, measuring thermal efficiencies, extracting accurate temperatures and obtaining repeatable results. However, the preliminary results in Fig. 7 suggest that the transient experiment produces much lower heat transfer coefficients than the steady state experiment. This might be due to the time needed to establish the boundary layers, or due to thermocouple delays. The initial portion of each transient experiment is similar. After several seconds, the transient measurements start to approach the steady-state predictions, as indicated by the similarity between the heat fluxes at 700°C and lower.

Future improvements to the experimental procedure and heat balance calculations are planned to improve the ability to measure heat extraction. At the same time, another project is investigating the effects of droplet dynamics in the spray [13]. The goal is to combine the results of these projects together into a mathematical model that accurately describes the heat transfer in actual continuous caster conditions.

## 5. Effect Of Material Data

It is often difficult to obtain material property data and it is tempting to use data close to the desired composition. The effect of materials data is illustrated by comparing examples. Figs. 8 and 9 compare the results for plain carbon and stainless steels and show the large difference in shell thickness profiles produced by the same cooling conditions. [14]

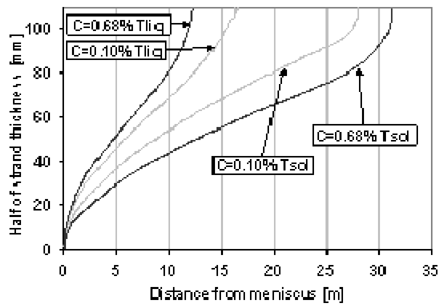


*Fig. 8: Liquidus and solidus isotherms of the steels C=0.10% and C=0.68% [14]*

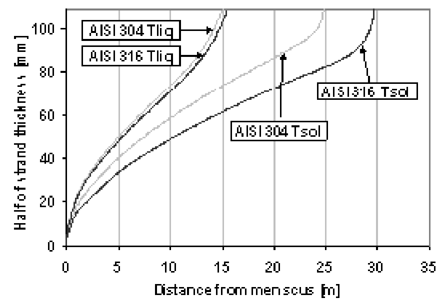


*Fig. 9: Liquidus and solidus isotherms of stainless steels AISI 304 and AISI 316. [14]*

## 6. Results

Simulations were conducted using TEMPSIMU2D software [15]. The data from water distribution measurements was input to the secondary cooling water distribution and industrial data was obtained from the Nucor, Decatur, Alabama steel plant. The secondary cooling boundary conditions in the spray zone are modelled using Eq. (1) and the parameters were fitted to obtain the best agreement with the last pyrometer in the caster. The last pyrometer is a permanent pyrometer and is used for monitoring the casting process. Other three pyrometers were installed just for these experiments. Results of the simulation are shown in Figs. 10 and 11.

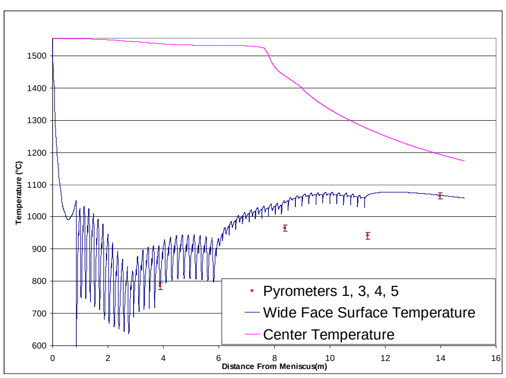


*Fig. 10: Comparison of simulation results pyrometer measurements.*

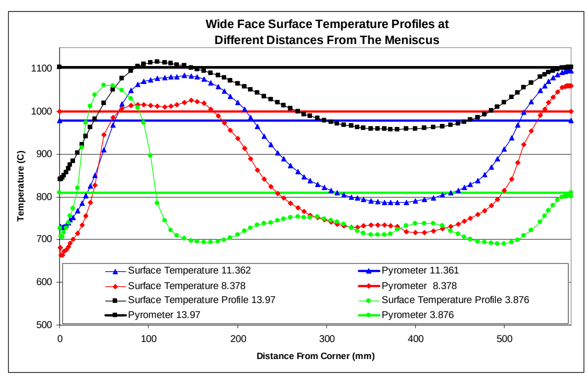


*Fig.11: Temperature distribution in simulation results over the width of the strand.*

It can be noted that it is impossible to fit the pyrometer results using Eq. (1). If pyrometers 1-4 have matching temperatures, the last temperature (5) will fall far from measured temperature. This suggests that heat removal across the strand width might be different at the pyrometer location, or that the Leidenfrost temperature is dynamic.

According to simulation results, temperature distribution across the width of the strand exhibits steep gradients. During the casting trials, tilting of the pyrometers was investigated. As can be seen in Figs. 12 and 13, tilting has only a minor effect on temperature and is practically lost in the measurement noise. This suggests that the disagreement between calculated and measured data might be due to water scattering after hitting the surface.

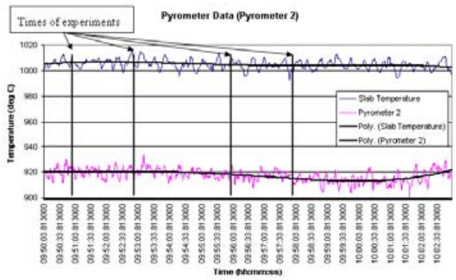


*Fig. 12: Pyrometer reading during tilting experiment of pyrometer 2 between segments.*

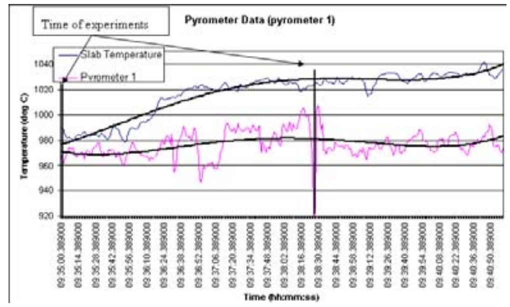


*Fig. 13: Pyrometer reading during tilting experiment of pyrometer 1 at the end of the last segment.*

## 7. CONCLUSIONS

A complete procedure for optimizing a heat transfer model to be used for simulating a continuous casting machine is considered. There are some plant measurements that have to be made in order to tune the heat transfer model to match a particular caster. Laboratory experiments have to be made to describe the spray cooling. A novel apparatus has been developed to measure heat fluxes under steady state conditions to complement transient measurements. This will contribute to understand the complex phenomena occurring during spray and air-mist cooling and to develop a model that would better describe heat removal of the industrial sprays used in cooling of continuous casting.

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