Dynamic Quenching Tests of Steels and their Evaluation by Inverse Task

J. Horský & M. Raudenský
Technical University of Brno, Technická 2, 616 69 Brno, Czech Republic
E-mail: raud@kinf.fme.vutbr.cz

Abstract

The paper presents an experimental work carried out while studying the cooling of hot steel surfaces by spray nozzles. Links between the experiment and its evaluation are discussed. A relative movement of the quenched surface in relation to the nozzle is typical for all experiments. Two experiments with different configuration are used, speeds are discussed. The first type - experiment on a rotating roll cooled by water nozzles - applies a circumferential velocity of the roll within a range from 1 to 5 m/s. The second experiment studies a situation where a flat cooled surface moves linearly in relation to a twin fluid nozzle. The speed applied here varies from 1 to 3 m/min. Experimental results of the first experiment find their application usually in rolling and those of the second one in continuous casting.

Measured temperature histories, calculated heat transfer coefficients (HTC) and also methods for evaluating the HTC from the recorded temperatures are presented in the paper. A dynamic behaviour of the thermocouples is considered for calculating the HTC. The temperature histories obtained from the experiments are evaluated by an inverse task. The paper describes the principles of a 3D inverse heat conduction model.

1 Introduction

Comprehensive quantitative information regarding the heat transfer conditions for the quenching of hot moving surfaces is not available. Authors of this paper studied cooling of steel surfaces [1], [2], [3] but these experiments do not include any movement of the surface in relation to the nozzle(s). A comprehensive theoretical study of two-phase cooling was done by Hatta [4] but his work is more interesting for the academic audience rather than for the industrial people. The research discussed here links to early heat transfer tests conducted by Tseng [5, 6] on a rotating roll heated by burned gas. These
experiments compared with previous static ones show that the influence of movement even for low speeds is enormous.

The first type of experiment described here was designed with respect to the demand to cover all typical cooling arrangements and roll speeds, commonly used in rolling. Adjustable factors are as follows: speed of rotation, temperature range of experiment, nozzle type and configuration and coolant type, pressure and temperature.

The case study presented here dealt with the influence of water pressure on the magnitude and distribution of the heat transfer coefficient along the circumference of the roll.

The second example is aimed at an experimental investigation of cooling characteristics of water and air-water nozzles quenching hot moving surfaces. The arrangement of the experiment enables to simulate conditions during secondary cooling in the process of continuous casting. The influence of the nozzle type, water-air pressure and speed of motion is investigated. The measured data are evaluated by the inverse task and they are used in a numerical simulation of the thermal problems in continuous casting.

2 Experiments

2.1 Cooling of rotating cylindrical surface

The arrangement of the experimental apparatus is obvious from Fig. 1.

![Figure 1 Stand with rotating cylinder](image)

Figure 1 Stand with rotating cylinder (A - roll, B - test plate, C - nozzle, D - motor, E - tank, F - pump, G - throttle)

A roll of a diameter of 650 mm and a width of 600 mm is fixed in bearings of the stand. The roll has two rigid faces where a jacket made of stainless steel is
wound on. A hole was made in a part of the jacket and the measuring plate embedded with thermocouples was fastened there. The plate has a thickness of 20 mm and is made of austenitic steel. The surface of the plate has been ground. The thermocouples are of the sheathed type with an insulated measuring tip, type K, 0.5 mm in diameter, and are soldered parallel with the surface of the plate placing the measuring tip 0.45 mm under the outer surface of the plate. A cross-section of the thermocouple embedded into the surface is presented in Fig. 2.

![Cross-section of thermocouple embedded in plate (1 - plate, 2 - solder, 3 - thermocouple)](image)

The thickness of the shell is 0.07 mm (Alloy 600), the diameter of the thermocouple wire is 0.07 mm and the insulation is made of MgO. Seven thermocouples in one row with a mutual distance of 75 mm are used. The wiring of the thermocouples is lead through a hollow shaft to the outer side of the stand where it is connected to a measuring system - data-logger. A battery, self-containedly working device with 12 channels is used. It enables to record up to 500 000 samples with a sampling frequency of up to 50 kHz. After the measurement, the measured data, stored in a data memory, are transferred to a PC using a serial line RS 232.

Two heating bodies of a total power of 1500 W are placed in a removable box on the outer side of the plate. They are used for a radiation heating of the plate. To move the roll, an asynchronous motor fed by a frequency converter is used. Its revolutions can be continuously set within a range from 0.1 to 10 rev./sec. The cooling nozzles can be directed to any point and at any incidence angle. It is supplied by water from a storage tank using a pump. The output pressure is set by a throttle.
2.1.1 Procedure of the experiment:
- The roll is rotated so that the measuring plate is in the most upper position and the heater is placed above the plate.
- The heating supply is connected and the plate is heated up to the prescribed temperature. This one is maintained by a controller until a thermal steady state is reached.
- The heating supply is disconnected, the heater is removed and the measuring system is switched on.
- The roll starts rotating with the chosen speed and in a certain time instant, the pump is switched on and the spraying begins.
- After the experiment, the measured data are transferred from the inner memory of the data-logger to a computer.

2.1 Cooling of linearly moving flat surface

An experimental stand was built to enable the study of the following factors influencing the cooling intensity:
- type of nozzle,
- water/(air) pressures,
- speed of motion.

An austenitic steel plate represents the basic part of the stand. The size of the plate is 600 x 320 mm, its thickness is 26 mm. Eighteen pieces of thermocouple (1.5 mm in diameter, type K) are built in the plate in regular 3 x 6 grid points.

The thermocouple set measures temperature at a depth of 2.5 mm (measured from the quenched surface). The front view of the stand with the test plate and the nozzle is presented in Fig. 3. The upper surface of the plate is insulated. The bottom side of the plate is cooled. Nozzles with a flat jet typical for continuous casting are applied in the tests. The spray is restricted by two cylindrical surfaces in the same way as by rolls in continuous casting. Both the nozzle and the cylindrical bodies are placed on a movable bed. This enables to move the nozzle parallel with the plate in the direction of the longitudinal axis of the test plate.

The steel plate with the thermocouple set is placed into a holder. The plate is electrically heated. The holder enables to lift the plate into the horizontal heating position and to remove the heater after the heating. The space between the heater and the plate is filled with inert gas - argon. The argon flow is constant during the whole process of heating. The reason for using the inert gas is to have the same conditions for all experiments and to prevent the oxidation of the plate. The surface of the test plate is of "rolled" quality and is covered by a thin layer of oxides arisen during the spray period. The oxides are removed before each new heating but the surface is not polished.
In the quenching position, the plate is directed towards the manifold with the nozzle (the heater was removed). During the experiment, water is pumped from a tank by a pump through a flow-meter to the nozzles. The water pressure is measured in the manifold. The temperature of water and that inside the plate is monitored by a data acquisition system.

2.2.1 The experimental procedure can be described as follows:

The heater is fastened onto the stand and the plate is moved down to the heating position. The plate is electro-radiatelly heated up to a temperature of 1200°C. The whole process of heating and cooling is monitored by a computer. As soon as the prescribed temperature is reached the plate is lifted, the heater is removed and a mechanism driving the nozzle during the experiment is put into the quenching position.

After replacing the heater with the nozzle driving unit, the temperature starts falling down due to the radiation and natural convection. The computer is checking the prescribed starting temperature of quenching. When this temperature is reached the computer removes the deflector in order to start quenching and it switches on an engine driving the nozzle. The nozzle moves...
from the left (position -170 mm) to the right (position 170 mm) with an open deflector and with a closed one in the opposite direction. The speed is the same in both directions. The spraying lasts 1100 seconds.

The temperature history records and information on the nozzle position in relation to the plate axis are stored in digital form. These data are used as the input information to the inverse task evaluating the heat transfer conditions.

3 Experimental data and its numerical evaluation by inverse task

The experimental procedure described in the above paragraph gives temperature histories in the measured points, temperature of the coolant and a signal for finding the relative position of the thermocouple in relation to the nozzle. An example of the temperature record from the first experiment is presented in Fig. 4.

![Temperature history in sensor location - rotational stand](image)

It can be seen that the initial temperature of the test plate is close to 300°C. Each wave on the temperature history curve refers to one revolution of the roll. A sharp decrease of temperature occurs in a position where the thermocouple location passes through the sprayed area.

An example of the temperature record from the second experiment is presented in Fig. 5.
The initial temperature of experiment is close to 1200°C. A thermal wave can be observed in the sensor location. It is caused by the fact that the nozzle is moving with the open deflector in one direction and with the closed one in the opposite direction.

3.1 Thermocouple dynamics

When calculating the heat transfer coefficient from the temperature histories, the dynamic behaviour of the thermocouple has to be considered [7]. Neglecting the dynamic features of the sensors causes time lag and signal distortion, which generates serious errors in the computed heat fluxes and heat transfer coefficients. This is, in our opinion, the major source of data deviations found in literature. Therefore, the inner structure of thermocouple and the non-homogeneity in material of the plate caused by the usage of solder or another way of embedding must be included in the inverse numerical model.

3.2 Inverse task

The temperature history records are stored in digital form. These data are used as the input to the inverse task evaluating the heat transfer conditions. The basic part of the inverse task is a 3D model of the plate and thermocouples. A classical inverse method based on Beck's minimisation procedure [8] is used. A detailed description of the method can be found in [9]. The distribution of the heat transfer coefficient and heat flux on the studied surface is the result of the
evaluation procedure. Examples of the results shown in Figs. 6 and 7 correspond with the temperature histories in Figs. 4 and 5.

Figure 6 Heat Transfer Coefficient history - rotational stand

Figure 7 Heat Transfer Coefficient history - linear stand
Fig. 6 is for the HTC distribution on the cooled cylindrical surface. A first glimpse proves a serious influence of the boiling phenomena on the heat transfer. A closer observation can show that, in the area of direct water impingement, there are less changes in the HTC due to surface temperature whereas, in the area outside the spray where water flows or sticks on the surface, the HTC is seriously influenced by the surface temperature.

A different conclusion would have to be drawn looking at Fig. 7 which presents results of the second experiment conducted for much higher surface temperatures. The Liedenfrost temperature plays the most important role here. This surface temperature divides the temperature range to an upper area where the vapour layer is sufficiently stable and does not allow for penetrating the droplets to the surface and the lower area where the droplets are wetting the surface. The differences in heat transfer intensity are obvious from Fig. 7.

4 Conclusions

The experiments on cooling the rotating roll show essential differences in the cooling intensity caused by the relative motion of the surface and the water spray. An illustrative example is presented in Fig. 8. Results from four separate tests show the heat transfer from the cylindrical surface moving with a circumferential velocity of 1, 2, 3 and 4 m/s. The peak in HTC is close to the central impingement point. The influence of the speed is obvious.

![Figure 8 Influence of circumferential velocity on HTC (one revolution of the roll is shown)](image-url)
A comparison of the newly obtained data with those from previous studies [10] shows that results valid for a case where the surface is not moving in relation to the nozzle cannot be easily applied to cases with high relative mutual speeds.

A simple increase in the coolant pressure can only influence the area of direct water impingement and this way is not economic and efficient for an improvement in the cooling technology. A better way is to estimate experimentally the influence of the factors concerned: nozzle type, spray angle, distance of nozzle from the surface and mutual interference of several sprays.

It is impossible to formulate common correlation describing the influence of various cooling parameters. A numerical test was used to quantify various parameters investigated experimentally. It can be stated that the most important factor for spraying of surfaces above the Liedenfrost temperature is the kinetic energy of droplets. For surface temperatures under the Liedenfrost temperature, the coolant impingement density is the most important feature.

Results of this work can be used for modelling cooling processes where the precision of the boundary conditions predominantly influences the precision of the model. Experiments are necessary for the design and control models.

ACKNOWLEDGEMENT
Theoretical and experimental work was supported by the Grant Agency of Czech Republic, grant contract 106/97/0328.

References