RESEARCH ON COOLING EFFICIENCIES OF WATER, EMULSIONS AND OIL

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There are many areas in the steel and metallurgy industry where pure water cannot be used as a coolant. Lubrication and corrosion are the two main factors why spray cooling has to use different cooling liquids. A typical example is cold rolling of steel where emulsions are used or rolling of some non-ferrous metals where pure oils are used. Other metallurgical processes use water polluted by oil or containing mineral salts. The spray cooling efficiency of these coolants is different from the cooling efficiency of pure water. This paper describes a research comparing the spray cooling by pure water to the cooling using water-base oil emulsions of different concentrations, cooling using oil, and cooling using polluted water. This comparison was done by the measurements of the cooling efficiency characterised by the heat transfer coefficient for identical pressure.

Keywords: spray cooling, water cooling, emulsion cooling, oil cooling, experimental

1. Introduction

The main goal of this paper is to give a quantitative overview how the cooling efficiency of water deteriorates when additives are added. These additives are either necessary for a technological reason (lubricants) or are water pollutants. Spray cooling using water emulsions and oils is compared to water cooling effectiveness. Nowadays, in addition to their primary function, industrial coolants must provide other technological benefits, such as lubrication, which can be provided by oil admixtures. This study focused on spray cooling and temperature of the cooled surface below 250 °C.

Technical literature devoted to cooling using additives concentrates mostly on a micro size approach of the problem. This paper considers small droplets with a very high velocity and the influence of various additives on cooling process, respectively impact process. King [1] describes the behaviour of diluted water when additives of acetates and sodium iodides in various concentrations are added. Those additives drastically increase the coolant viscosity and decrease the evaporation rate at a given temperature. A higher percentage of additives points up both effects.

Qiao and Chandra [2 and 3] present their investigations on water with surfactant cooling. An additional surfactant in water decreases the following parameters, surface tension, droplet diameter, and subsequently influences droplet diameter and impact angle. A mass of surfactant also affects evaporation time, but this, in addition, depends on surface tem-

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perature. Similar conclusions were found by Yang [4] for a wide range of surfactant types. Manzello and Yang have published a study [5], where they presented a liquid film diameter as a function of a water additive. Bertola and Sefine [6] described the behaviour of polymer additives impacting hot surfaces. This paper is focused to wider perspective of cooling. There is not only microscopic point of view (single droplets with cooling additives) and macroscopic approach has to be considered as well (spraying of mass). Study presents behaviour of different coolants and their influence to total heat transfer.

The complete experimental plan was performed on a test rig (see Fig. 1) developed at the Brno University of Technology. The rig is predominantly used for determining cooling intensity in a wide range of applications. The rig consists of a muffle furnace in order to heat samples, a rig frame, a pool and cooling section including the nozzle, a cooling circuit which allows diverse coolant utilization and control unit. The nozzle used in all of the tests is a common industrial full cone nozzle (60° spray angle) with an impingement density of $12.751 \text{m}^{-2} \text{s}^{-1}$ at 5 bars. A test sample from an austenitic steel plate ($80 \times 80 \times 30 \text{ mm}$) is located 150 mm from the nozzle outlet. The sample is equipped with thermal sensors consisting of thermocouple in a prescribed depth below the surface (varies within 0.2-2.7 mm).

Measured temperature data from the sensors is used as input to inverse problem calculation that results in surface temperature and heat transfer coefficient (HTC). Inverse task in contrast with direct problem is not looking for temperature distribution in time, which is known from experiment, but is trying to find unknown boundary condition (HTC). Beck's method in combination with optimization method [7] was used. Simplified Beck's approach is described on Fig. 2, showing the metal plate equipped by thermal sensor exposed by unknown HTC. The scheme shows an algorithm minimizing the difference between the computed and measured temperature for varying boundary condition. To determine the unknown HTC a sequential estimation formula is used (see Fig. 2), where h^* is unknown value of HTC, h_i are estimations of HTC, $(T_{exp}^i - T_h^i)$ is temperature difference between experimentally measured and calculated temperature, D^i is derivation of T_h^i by h_i .

The experiment starts by heating the sample to an initial temperature of $250 \,^{\circ}$ C. The sample is then shifted to the cooling section, where is protected from the coolant by a deflector until it is sprayed. During the experiments all data received from sensors is stored in a data logger for later inverse calculation and analysis. Temperature of $250 \,^{\circ}$ C was chosen because of the Leidenfrost point effect even if it is substantially below the ordinary metallurgical operating temperatures. Leidenfrost phenomenon is widely known as a massive change



Fig.1: Scheme of experimental rig (left); sample cooling provided by full cone nozzle

in cooling performance. Outstanding increase of heat transfer below the Leidenfrost point is caused by breaking of vapour layer that is formed upon the surface at high temperature regions. Unfortunately wide range of Leidenfrost temperature occurrence (400–1000 °C) and problematic starting point determination, pushes our experimental plan to safety temperatures below 250 °C. This test procedure allows clearly quantify effect of each coolant type to HTC.

Since there are tens and maybe hundreds of industrial used coolants, the typical species, seen Tab. 1, were chosen for the purposes of this study. The most widespread coolant liquid is still water, so the cooling intensity and effectiveness under various circumstances, e.g. coolant pressures and flow rates. Oil 1 as an essential Al-plate rolling coolant was treated in similar conditions as pure water. Oil Emulsion number 1 involves a mixture of water and commonly used mineral oil, while Emulsion 2 is a mixture of water with polymers and organic salts. In addition, the paper indicates the influence of water total hardness on the cooling process. For those purposes the experiments with salt solution 1, including $CaCl * 2H_2O + MgSO_4 * 7H_2O$, were performed.

Coolant type	Experiment parameters	Experiment name
Pure Water	pressure of $1, 3, 5, 7$ and 10 bar	A1, A2, A3, A4, A5
Oil	pressure of $1, 3$ and 5 bar	B1, B2, B3
Oil Emulsion 1	concentration 2 and 4% in water; pressure of 5 bar	C1, C2
Emulsion 2	concentration $0.1, 1, 5, 10, 20$ and 50% in water; 5 bar	D1, D2, D3, D4, D5, D6
Salt Solution	total hardiness 16.55 and 30.10 ; pressure of 5 bar	E1, E2

Tab.1 List of used coolants and experimental parameters set up





Fig.2: Scheme of Inverse task (left), Beck's algorithm (right) and sequential estimation formula (below)

$$h^* = \frac{\sum_{i=1}^r h_i D^{i^2} + \sum_{i=1}^r (T_{\exp}^i - T_{h}^i) D^i}{\sum_{i=1}^r D^{i^2}}$$

2. Cooling results analyses

2.1. Reference cooling tests with pure water

The graph in Fig.3 shows results for pure water at 5 bar pressure (exp. A3). Surface temperature history and computed HTC has been plotted. Since the cooling is applied in

time 0 sec. surface temperature, computed by the inverse problem, it rapidly falls down from the initial temperature. At the same time HTC is drastically increased. With increasing time, the surface temperature is closer to coolant temperature and HTC slowly decreases. In Fig. 4 the dependence of HTC on water circuit pressure can be seen. It also shows that water with a pressure of 1 bar has a 3 times lower cooling effect in comparison to 10 bars. Average HTC values were computed for further evaluations.



Fig.3: Surface temperature and HTC history for pure water, reference experiment, pressure 5 bar



Fig.4: HTC records for pure water and growing pressure, 1, 3, 5, 7 and 10 bar

2.2. Tests with oil

The experiments for Oil (B1, B2 and B3) used pressures of 1, 3 and 5 bar. It should be stressed that the viscosity and density of the oil used is different from the viscosity and density of water. Although the pressure of the water and oil was exactly the same, the flow rate of oil through the nozzle was by 15% higher. Figs. 5 and 6 present a comparison of HTC for pure water and oil. Pressure dependence of the average HTC values is shown in Fig. 5. The cooling intensity of oil is significantly lower. Fig. 6 shows a direct comparison of the cooling intensity of water and oil based on coolant impingement density. The average HTC value in spray cooling is 3–6 times higher for water than for the tested oil.



Fig.5: Average HTC values for pure water and oil



Fig.6: Average HTC values for water and oil, comparison for coolant impingement density

2.3. Tests with oil emulsions

Two types of emulsions were tested. All of these tests were done with a coolant pressure of 5 bar (see Tab. 1). The first emulsion is commonly used for cooling rolls and lubricating the rolling gap in cold rolling. Oil Emulsion 1 (C1 and C2 in Tab. 1), was applied in a concentration of 2% and 4% mixture. This concentration is typical for cold rolling application. Hence, Emulsion 2 (D1–D6), consisting of water and Lubrodal 192 with a concentration varying from 0.1% up to 50%, was examined. The results obtained from this investigation are shown in Figs. 7 and 8. Obviously the average HTC of such oil emulsion does not, in general, reach the same values as pure water for the same conditions. The results show another

conclusion, plotted in Fig. 7 where an HTC slumping trend for increasing oil percentage is evident. The first five columns show the HTC trend as a function of water pressure. This is important as it gives us an idea of the range of HTC due to pressure and coolant changes. Variation of water pressure can cause a 43% increase (10 bar) or a 47% drop (1 bar) in cooling intensity, while changing the oil and varying the concentration brings a much lower impact, see Fig. 8. Oil shows similar pressure and HTC behaviour to pure water – increasing pressure raises the average HTC significantly.



Fig.7: Comparison of average HTC values for all of the test cases



point is cooling intensity of water at 5 bar

Both oil emulsions show a decrease in average HTC value in comparison to a reference point (pure water at 5 bar). This decrease is proportional to the increasing oil additives. Oil Emulsion 1 with concentrations of 2% and 4% perform only 84 and 79% of water cooling under the same pressure conditions. Applying Emulsion 2 and higher admixture percentages, the cooling becomes even worse. Using the following concentrations of 0.1, 1, 5, 10, 20 and 50% caused the following HTC drops: 7.8%, 17.7%, 19.6%, 22.7%, 27.4% and 35.6%. It is a very interesting fact that the main portion of HTC decrease comes at low

oil concentration. For example, the concentration change from 0 to 0.1 % caused a decrease of $-3000 \,\mathrm{W \,m^{-2} \, K^{-1}}$ in absolute numbers, while the change from 20 to 50 % caused only a decrease of $-2500 \,\mathrm{W \,m^{-2} \, K^{-1}}$.



Fig.9: Average HTC values for Emulsion 2 depending to water-oil concentration

The fact that a low oil concentration had a drastic influence was surprising and therefore further detailed examinations of oil in using a larger concentration scale were done. This was a starting point for a more precise investigation of Emulsion 2. The concentration was investigated in a range of 0.1% up to 10% in order to check the previous results. These new experiments confirmed the conclusions already drawn – oil additives have a negative impact on the cooling process already at low concentrations. The trend seems to be of a logarithmic character.

2.4. Tests with high water hardness

Last batch of experiments covers the investigation of aqueous salt solutions. It is obvious that even ôpure waterö contains a small number of solutes. The level of salt contamination is related to water total hardness (TH). To find a relationship between TH and cooling efficiency, $CaCl * 2H_2O + MgSO_4 * 7H_2O$ admixture was introduced into the cooling water circuit. The cooling intensity was measured and compared to pure water (same reference point with a 5 bar pressure) for two solutions with TH equal to 16.55 and 30.10. As shown in Figs. 7 and 8, the difference between pure and salt solution is not large. Although TH 16.55 reaches 101% (random statistical error) the salt additives are expected to slightly decrease HTC value.

2.5. Comparison to published results

Despite the fact that oil cooling is a widely used technique, there are not many published results on this topic. Wallis [9] presents optimized cooling for nickel super-alloys and titanium forgings. This study compares water-air mist, oil quenching and fan water cooling in range 100–1100 °C. Oil shows lower HTC of $250 \text{ Wm}^{-2} \text{ K}^{-1}$ for temperature intervals of 100–400 °C and above 1000 °C, while during transition boiling regime it exceed to $2700 \text{ Wm}^{-2} \text{ K}^{-1}$. Air-mist and water-fan cooling shows a different behaviour. A high peak at lower temperature can be observed ($4000 \text{ Wm}^{-2} \text{ K}^{-1}$ for 150 °C) and lower HTC values at high temperature region $(200-300 \,\mathrm{W \,m^{-2} \, K^{-1}}$ above 500 °C). Fan cooling (forced convection) shows slow, but continuous increase of HTC with raising surface temperature.

Japanese authors [9,10 and 11] focus on glass and ceramic cooling applications. Their studies present cooling performances for water and a wide range of oil types (mineral, silicone, spindle, turbine, compressor and machine) in a temperature range of 10-1000 °C. Although neither flow rates nor cooling system are described, findings similar to ours are given. At low temperature water performs very well (max. HTC $12000 \text{ Wm}^{-2} \text{ K}^{-1}$ for 150 °C), while at high temperature range less than $500 \text{ Wm}^{-2} \text{ K}^{-1}$. Oil cooling efficiency is reversely very low below 500 °C ($200-300 \text{ Wm}^{-2} \text{ K}^{-1}$) and with growing temperature HTC reaches $1000-2000 \text{ Wm}^{-2} \text{ K}^{-1}$ for 700 °C. There were found differences among different oil types (max. peaks at different temperature).

Considering the fact of different quenching parameters (cooling devices, flow rates, etc.) those studies are in good agreement with our results. Whatever oil type has several times lower average HTC below 250 °C and even water-oil mixtures are not performing well [9]. Not knowing spraying parameters Tachibana's [10] water data are corresponding to HTC for pure water at 1 bar (experiment A1), while Shin'ichi's [9] machine oil measurement corresponds to B2 oil experiment results at 3 bars.

3. Conclusions

A wide range of experiments with various industrial coolant types has been conducted at the Brno University of Technology. Pure water, oil and oil emulsions, as well as salt dilutions were investigated under various conditions, e.g. coolant pressure, concentration and coolant total hardness. This was done to determine the influence of coolant and cooling parameters to heat transfer coefficient. All experiments were conducted at temperatures of 25-250 °C. The investigations lead to the following conclusions:

- Spray cooling is significantly influenced by the coolant type used.
- Pure oils with a low viscosity used for the spray cooling, for example in aluminium rolling, have about a 3–5 times smaller cooling intensity than water with the equivalent impingement density.
- Water total hardness level does not greatly influence the cooling intensity. HTC decreases slightly (by a few percents) probably due to the surface layer of crystallized salts created during the evaporation process.
- Oil admixtures and emulsions cause a significant drop in cooling intensity (even as much as 40%) compared to pure water under the same conditions.
- The most important finding is that water-based emulsions showed a significant decrease in cooling intensity even for 0.1% of the oil content in water. The cooling intensity dropped by 7.8% for oil content of 0.1% and by 17.7% for oil content of 1%. Low concentrations can be found in polluted cooling water in industrial plants. A significant decrease in cooling efficiency should be taken into consideration when designing spray cooling with emulsions and also when water spray cooling systems need to be rebuilt for another coolant.
- Surface sediments and burning-on oil residues create additional thermal resistance which can greatly reduce the intensity of heat transfer. Laboratory experiments showed that these thermal barriers are of unpredictable thickness and can cause an overheating of the spray cooled surface.

- Results of this experimental study support further investigations of combined lubrication and cooling systems in a steel plant where cooling water and lubrication oil are sprayed separately. The oil layer at the cooled surface can be expected to deteriorate heat transfer.

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