Proceedings of the 8th World Congress on Mechanical, Chemical, and Material Engineering (MCM'22)
Prague, Czech Republic – July 31, 2022 - August 02, 2022
Paper No. HTFF 190
DOI: 10.11159/htff22.190

Heat Transfer Study for Oil-in-Water Emulsion Jets Impinging onto hot Metal Surface

K. Nabbout[1,*], L. Pasternak[1], M. Sommerfeld[1], B. Bock-Marbach[2], J. Kuhnert[2], E. Barth[3] and E. Uhlmann[3,4]
[1]Institute of Process Engineering, Otto-von-Guericke-University Magdeburg,
Universitätsplatz 2, 39106 Magdeburg, Germany
[2]Fraunhofer Institute for Industrial Mathematics (ITWM)
Fraunhofer-Platz 1, 67633 Kaiserslautern, Germany
[3]Institute for Machine Tools and Factory Management (IWF), Technische Universität Berlin
Pascalstr. 8-9, 10587 Berlin, Germany
[4]Fraunhofer Institute for Production Systems and Design Technology (IPK)
Pascalstr. 8-9, 10587 Berlin, Germany
Corresponding author: kaissar.deoliveira@ovgu.de

Abstract – The purpose of this work is to analyse numerically as well as experimentally liquid jets impinging at different angles (30°, 60° and 90°) and different velocities (4.7 m/s, 7.0 m/s and 9.7 m/s) onto a hot circular plate made of Inconel 718. Liquids used in the experiments are water and oil-in-water emulsion with 8% concentration of the mineral oil Adrana AY 401 from Houghton Deutschland GmbH. An infrared camera is used to measure the black-coated rear face of the plate during the jet cooling process. The temperature field obtained is then used as input to estimate the heat transfer coefficient. The heat transfer coefficient is estimated by solving an Inverse Heat Transfer Problem (IHTP). In addition, the transient growth of the wetting area is also shown for both liquids. The heat transfer coefficient obtained from the experiments are utilised as input in numerical simulations with the Finite-Pointset-Method (FPM). Comparison between experiments and simulations is done to validate the recently implemented evaporation modelling in the MESHFREE software.

***Keywords*:** Jet cooling, inverse heat transfer, experimental studies, heat transfer coefficient, Finite-Pointset-Method

1. Introduction

High temperatures can be reached in the tool-workpiece contact area during metal cutting due to friction and plastic deformation. Therefore, cutting fluids are often applied to reduce these temperatures and consequently increase tool life [1]. Liquid jets may be necessary to remove dissipating thermal energy resulting from machining processes. However, the cooling mechanism during wet cutting is not fundamentally understood today. Thus, an economical as well as ecological adjustment of the cooling strategy and its respective parameters poses a scientific and industrial challenge.

When a liquid jet impinges onto a hot surface, for instance, a chip produced during machining, a vapor film can be formed between liquid and hot surface preventing a direct interaction between them. Consequently, the heat transfer is reduced [2]. The present work focuses on two main objectives. Firstly, the cooling behaviour of an oil-in-water emulsion with 8% concentration of mineral oil Adrana AY 401 from Houghton Deutschland GmbH is experimentally analysed. Thereby, a comparison between emulsion and water is also performed. Heat transfer coefficient and wetting front development are used as comparison parameters. The heat transfer coefficient for a liquid jet impinging onto a hot surface is estimated by solving an inverse heat transfer problem (IHTP). Secondly, the obtained results for the heat transfer coefficient are applied as input in numerical simulations with the Finite-Pointset-Method (FPM) present in the MESHFREE software. Numerical results are then compared to experiments to validate the accuracy of the recently implemented evaporation model within the MESHFREE software.

IHTP involves the use of measured internal or surface temperatures in order to estimate any unknown quantity of interest, as for example, boundary conditions [3] or thermophysical properties [4]. Due to its classification as mathematically ill-posed, IHTP are usually very unstable and, therefore, require a stabilization technique. Several methods have been proposed to solve IHTP such as: function specification, Tikhonov regularization (TR), conjugate gradient (CG), and singular value decomposition. A comparison between these methods can be found in [5]. Depending on the time domain used from the measurements, the methods can be classified as whole-time domain methods and sequential methods [6]. Sequential methods have the advantage of demanding less computation resources when compared to whole-time domain methods, but they are also extremely sensitive to measurement errors. Hybrid methods have also been proposed [7]. The authors combined the CG method, which is a typical whole time domain method, with sequential functions specification method.

When the wall temperature is high enough, the liquid jet may not have immediate contact with the wall due to a thin vapour layer formed between them. This is called Leidenfrost effect. But once the jet hits the surface, a wetting region is formed and further grows. The growth speed depends on many factors, such as, liquid properties, liquid subcooling, wall temperature, and wall properties [8]. Estimating the rewetting temperature is not straightforward once it depends on flow conditions and can be very sensitive to measurement errors [9]. Although the exact value of the temperature is difficult to determine, the position of the wetting front is known to be in the region of maximum heat flux [2].

2. Experimental setup and procedure

A simplified scheme of the experimental setup used for the experimentsis depicted in Fig. 1. The circular plate, made of Inconel 718, has a diameter of d_{plate} =140 mm and a thickness H = 5 mm. An Inducta IH-25 induction heating system is first heating the plate up to a certain temperature, higher than the temperature of interest. The heater is then turned off and moved aside while the plate cools down in ambient temperature until the desired initial temperature is reached. By that time, a homogenous temperature field is obtained. The temperature field of the rear surface of the plate is recorded by an Infratec PIR uc 605 infrared camera at a frame rate of f = 25 Hz. The jet nozzle has a diameter of d_{nozzle} = 3 mm and is connected to a pressurized vessel. The nozzle can move vertically by a linear rail system connected with stepper motors and controlled by an Arduino board. It is also mounted on a high precision rotating stage which allows using different jet impingement angles.

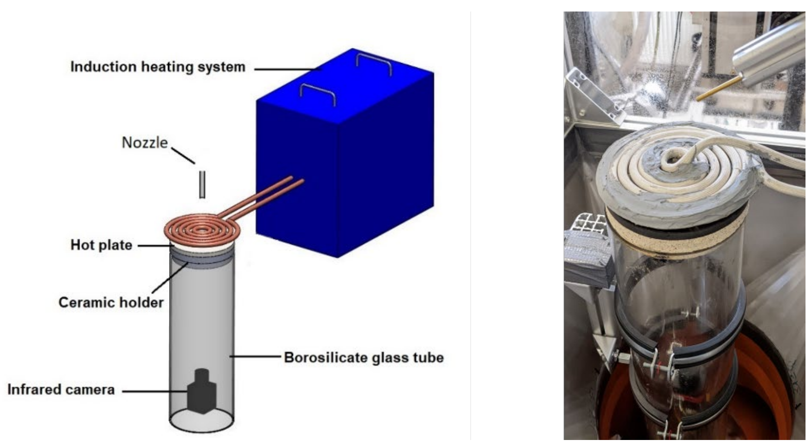


Fig. 1: Schematic of experimental setup (left) and a picture of the real facility (right).

3. Solution of IHTP

The solution of IHTP is obtained by reformulating it as an optimization problem with some stabilization technique that gives it a well-posed characteristic [10]. The CG method with sensitivity and adjoint problem for function estimation [6] is used in this work to estimate the heat transfer coefficient h(t) due to the cooling by a liquid jet impinging onto a hot surface. The computational algorithm of this method can be seen in Fig. 2. The method starts by solving, with an initial guess for h(t), a simple 1D heat conduction problem which represents the temperature distribution of the plate through its thickness H. The plate is considered insulated at the bottom (y=0) and subject to a convection boundary condition on the top side (y = H). To solve the direct problem the thermophysical properties are all considered constant with change in temperature, so α is the thermal diffusivity of the plate, k is its thermal conductivity and T_∞ is the temperature of the liquid jet.

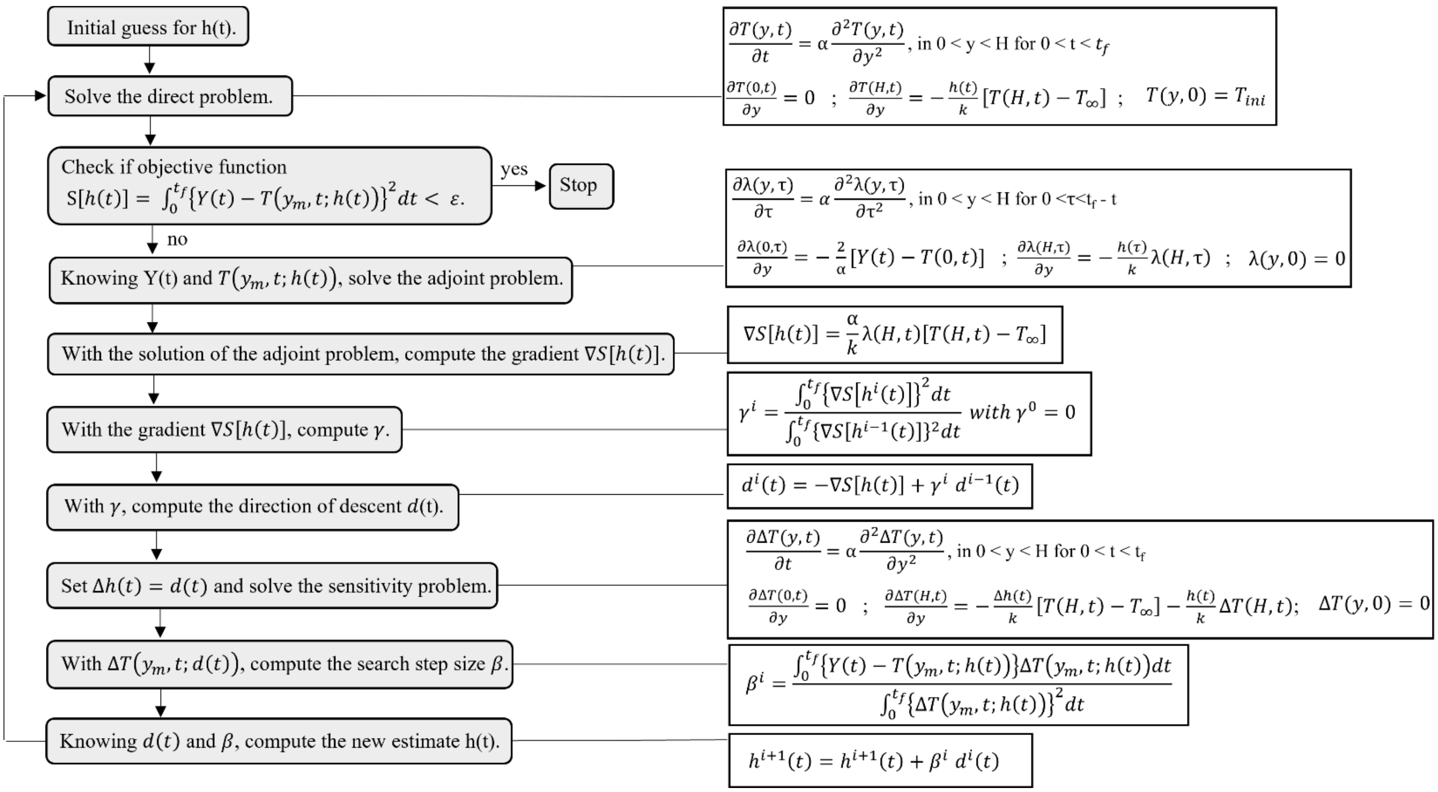


Fig. 2: Computational algorithm for the CG method with sensitivity and adjoint problem for function estimation.

After solving the direct problem, the objective function S[h(t)] is evaluated, where $Y(t)$ are the measured values obtained by the infrared camera and $T(y_m, t; h(t))$ is the estimated temperature obtained from the solution of the direct problem at the same position of the experimental measurements. If the objective function is smaller than the stopping (convergence) criterion, then the code stops. The stopping criterion plays a very important role in the CG method since it is responsible for its stabilization. If the algorithm does not stop at the right moment and keeps running, the results will probably diverge. Also, if the code stops too early, then the results will not be accurate. The most common stopping criterion used in the literature is based on the discrepancy principle [11]. If the stopping criterion is not satisfied, the next step is to solve the adjoint problem, where λ(y,τ) is the Lagrangian multiplier. The solution of the adjoint problem is used then to calculate the gradient ∇S[h(t)]. With the gradient, γ can be calculated. Here, the Fletcher-Reeves version of the CG method is used to calculate γ, which is then used to calculate the direction of descent d(t). With d(t), the sensitivity problem can be solved which is developed by assuming that when h(t) undergoes a variation Δh(t), the temperature T(y,t) varies by an amount ΔT(y,t). With the solution of the sensitivity problem, the search step size β can be calculated and, finally, a new heat transfer coefficient is estimated, so the procedure can restart. More details of the formulation can be found in [6].

4. Simulation setup

The experimental data presented here offer the opportunity for validating the vaporization simulation using the MESHFREE software and its recently implemented monolithic vapor modelling. Therefore, experimental data and simulation of a water-cooling jet impinging onto a hot surface are compared. MESHFREE solves the balance of mass, momentum and energy in partial differential equation form based on the FPM, a generalized finite difference method. The FPM utilizes points which move in Lagrangian framework as carriers of information. The generalized form allows flexible mesh adaptation. Hence, the numerical solution of a large variety of simulations regarding flow and solid mechanic problems is feasible [12][13][14][15]. A more detailed description of the FPM and the modelling of vapor as a monolithic phase can be seen in [16].

The impinging jet is simulated with an angle of $\theta = 30°$ and with a uniform velocity profile of $V_j = 7$ m/s (i.e. plug flow). In order to save simulation time, the inlet of the jet is placed closer to the plate with a distance of z = 5mm to the plate. No significant change on the global jet and especially on the vaporization zones and cooling areas is expected. The phase change takes place within the vaporization interval of $\Delta T^* = 5$ °C around the boiling point of $T_p^* = 100$ °C, while the pressure dependence of the boiling point is neglected. The physical properties for liquid and vapor phase are shown in Table 1. The latent heat of vaporization is $\Delta H_p^{vap} = 2501$ kJ/(kg.K).

In order to avoid abrupt changes of density which would affect the performance of the simulation, a vapor density of $\rho_{vapor} = 100$ kg/m³ was used in the simulation. This can potentially lead to a thinner vapor layer. However, it is not expected to alter the general properties of the water flow and distribution. This is based on the assumption that the time scales of the expansion due to vaporization are much smaller than time scales of convection. Thus, the scaling of the density only affects one direction of the extent of the vapor layer, i. e., the layer thickness. To counteract effects on the heat transfer, a decreased value of the heat conductivity of the vapor was applied in order to account for the heat conduction through a thicker vapor layer than simulated. The factor for the used heat conductivity is based on the ratio between used and real (0.50489 kg/m³) vapor density.

Table 1: Physical properties of liquid and vapor phase.

Phase	Density kg/m³	Surface tension 10^{-3} N/m	Dynamic Viscosity 10^{-3} Pa s	Specific heat capacity J/(kgK)	Heat conductivity W/(mK)
Liquid	998	72.86	1	4185	0.59801
Vapor	100	-	0.13	2059	0.00012405

4. Results and discussion

The experiments were conducted for three different jet angles (30°, 60° and 90°) and three different jet velocities (4.7 m/s, 7.0 m/s and 9.7 m/s). These are mean velocities obtained by measuring the liquid jet flow rate. The heat transfer coefficients h(t) estimated by solving the IHTP are shown in Fig. 3 for all configurations and for both liquids: water (left column) and 8% oil-in-water emulsion (right column). By analysing each graph separately, it is noticeable that the heat transfer coefficient is greatly affected by the jet velocity. The greater the velocity, the greater the heat transfer coefficient. These results are expected since higher velocities result from higher flow rates which means that more liquid is being used to cool down the plate. In addition, higher velocities also contribute to the evolution of the wetting front. Thus, leading to a faster growth of the wetting area which is the most important area for heat exchange.

By analysing the left and right columns separately, there is also a perceptible influence of the jet angle on the heat transfer coefficient. Lower values of h were obtained for smaller angles, except in the case of the emulsion with jet angles of 60° and 90°, which presented similar values of h. The increase of heat transfer coefficient with increasing angles up to 90° are assumed to result from a faster growth of the wetting area. When comparing the heat transfer coefficient, the emulsion jets had a better performance than the water jets for the angles $\theta = 30°$ and $\theta = 60°$. For $\theta = 90°$, water performed better for $V_j = 7.0$ m/s and $V_j = 9.7$ m/s. It is important to highlight that the results can be more accurate if temperature measurements closer to the impingement surface are possible.

As mentioned before, the accurate determination of the rewetting temperature poses challenge. However, its position can be related to the maximum heat flux. Therefore, in the present work, the rewetting temperature was considered to be the Nukiyama temperature (T_N), also known as critical heat flux temperature. By setting T_N as threshold in the images obtained by the IR camera, the wetting area could be obtained in the software Fiji. This temperature was determined, together with the Leidenfrost temperature (T_L), for both liquids by using the droplet evaporation method in a previous work [17]. The comparison between the growth of the wetting front for water and emulsion are shown in Fig. 4. For all cases, the emulsion had a higher growth rate, which agrees with the findings from [18]. The reason why this happens is yet not fully understood and further experiments are necessary.

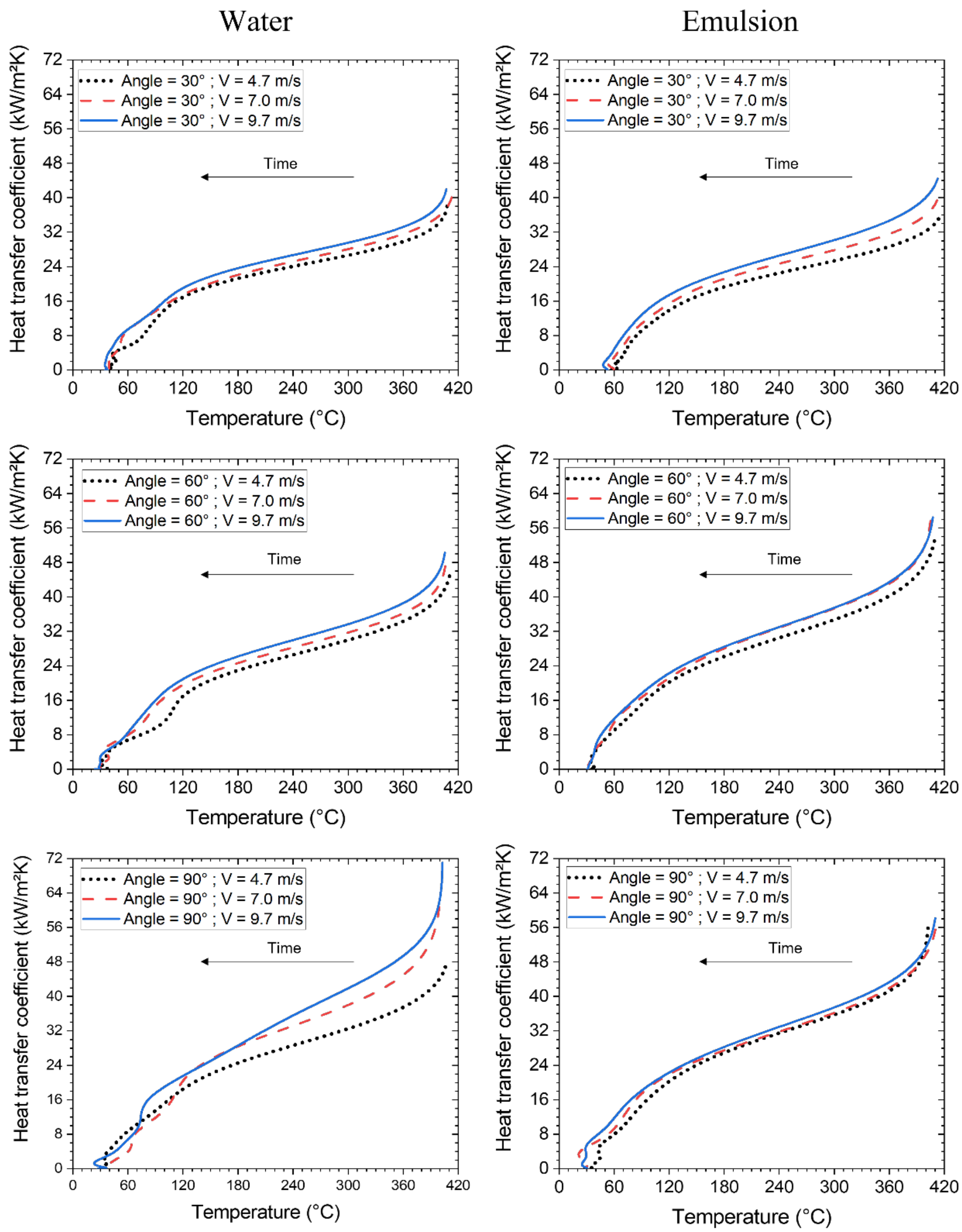


Fig. 3: Comparison between heat transfer coefficients obtained by solving the IHTP for different jet angles and velocities. On the left column are the results for water and on the right for the oil-in-water emulsion.

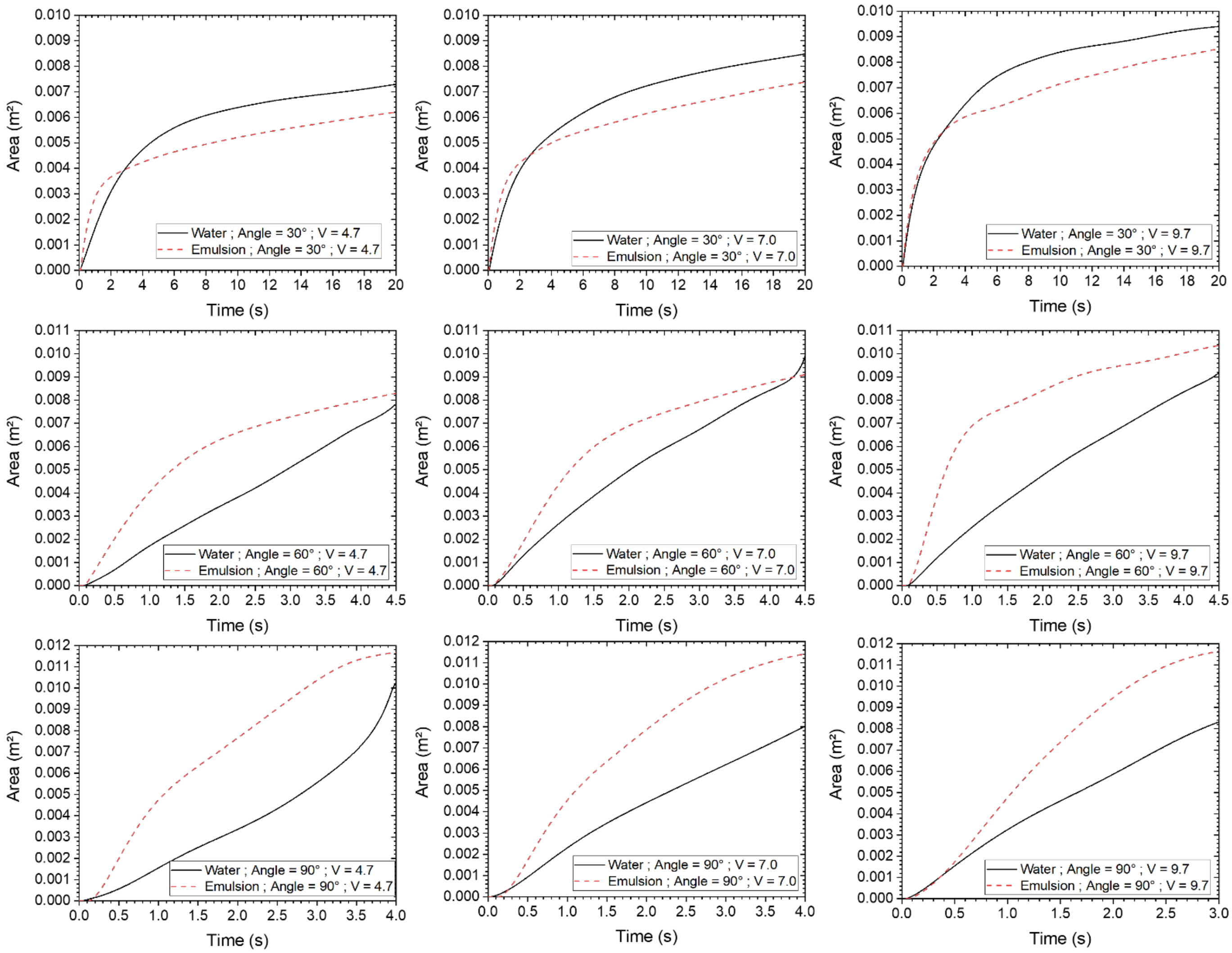
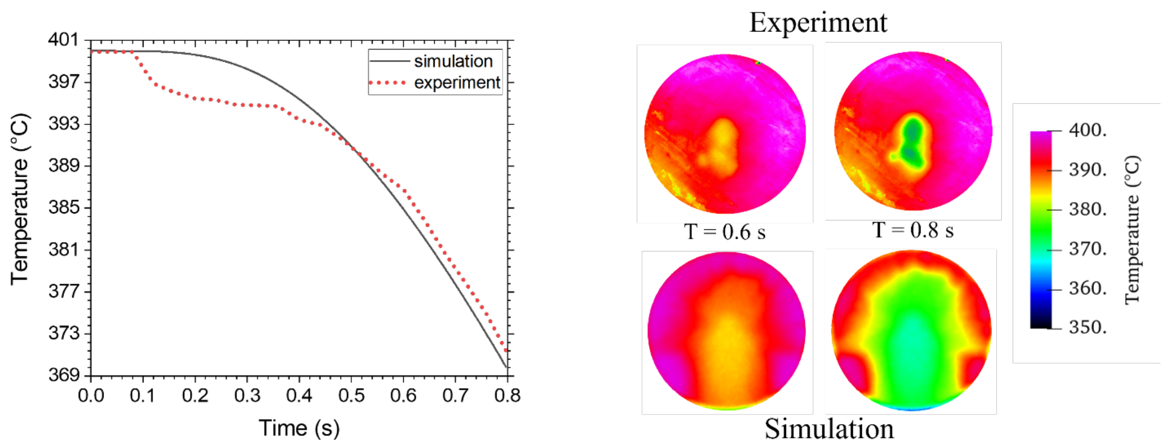


Fig. 4: Evolution of the wetting area over time for different jet impingement angles (upper 30°, middle 60° and lower 90°) for water and emulsion jet at different bulk impingement velocities (left 4.7 m/s, middle 7.0 m/s and right 9.7 m/s).

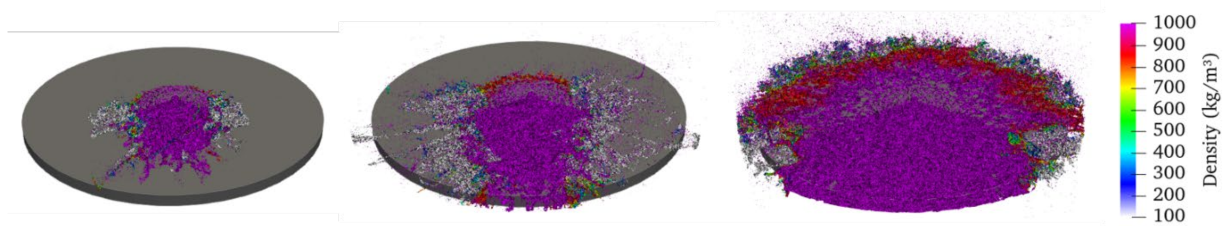
A comparison between experimental and numerical results for the temperature change over time for a point located in the center of the rear surface of the specimen plate can be seen in Fig. 5(a). The experiment presented an oscillation in the first moments when a temperature drop is detected, but it stabilizes afterwards and both curves follow the same trend. The temperature distribution of the rear surface can be seen in Fig. 5(b) for two different time steps. The heat transfer coefficient used in the simulations was $h = 50000$ W/(m²K). The growth of the wetting area is more pronounced in the simulations if compared to the experiments. One possible reason for this, is the absence of a model in the simulations to predict the Leidenfrost effect, which would completely change the heat transfer between liquid and solid in the wetting front.

The wetting area can also be identified in the simulations, as shown in Fig. 6. The plate (shown in grey) acts as rigid boundary on the liquid and they are thermally coupled. The represented points illustrate the vaporization front with the ascending vaporized fluid of lower density. The wetting areas from the simulation for bottom and top surfaces can be considered comparable, but with a time delay due to conduction. It is also important to mention that the thicker the plate, the greater will be the difference between the areas.



(a) (b)

Fig. 5: Comparison between experimental and numerical results for the temperature change over time for a point located on the middle of the rear surface (a) and the rear surface temperature distribution for two different times (b). The jet angle and jet velocity were θ = 30° and V_j = 7.0 m/s, respectively. A heat transfer coefficient h = 50000 W/m²K was used in the simulations.



(a) (b) (c)

Fig. 6: Liquid cooling jet simulation with impact angle θ = 30°, V_j = 7.0 m/s and h = 50000 W/(m²K) for 0.01 s (a), 0.02s (b) and 0.6 s (c). Colors showing the density are thereby the vaporization front.

5. Conclusion

The heat transfer coefficient for the jet cooling of a hot plate made of Inconel 718 was obtained by solving an Inverse Heat Transfer Problem (IHTP). Water and 8% oil-in-water emulsion were used as cooling liquid. It was shown that the emulsion performed better for the angles θ = 30° and θ = 60° in terms of heat transfer coefficient. Different jet velocities and jet angles were also compared. Higher velocities led to higher heat transfer coefficients, what is expected since higher velocity means more flow rate. Jet angles of 30°, 60° and 90° were used. The results show that the heat transfer coefficient is higher for 90° impinging jet when compared to the 60°, which is also higher than the 30°.

It was shown that the growth rate of the wetting area is remarkably higher for the emulsion when compared to the water. The reason why it happens is still not clear and further research is necessary to answer this issue. Simulations using the MESHFREE software with a heat transfer coefficient close to the one found in the experiments showed good agreement for the temperature change over time for a point located in the centre of the rear surface. However, the numerical simulation presented a much higher growth of the wetting area when compared to the experiments.

The heat transfer coefficients obtained by the experiments are considered to be representative conditions for the wet cutting processes. In the future, the temperature dependent heat transfer coefficients will be implemented in wet cutting simulations to improve the modelling of cooling capability.

Acknowledgements

The authors would like to thank the German Research Foundation (DFG) for financial support of this research. This work is related to the project "Multiphasen-Modellierungen von Kühlschmierstoff und dessen Aerosolen in der Zerspanungssimulation mit der Finite-Pointset-Methode zur Untersuchung der Wirkungsmechanismen" (439626733).

References

[1] P. Yan, Y. Ron and G. Wang, "The effect of cutting fluids applied in metal cutting process." *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,*" vol. 230, no. 1, pp. 19-37, 2016.

[2] A. K. Sharma, M. Modak and S. K. Sahu, "The heat transfer characteristics and rewetting behavior of hot horizontal downward facing surface by round water jet impingement," *Applied Thermal Engineering*, vol. 138, pp. 603-617, 2016.

[3] J. Bohacek, J. Kominek, A. Vakrushev, E. Karimi-Sibaki and T. Lee, "A Sequential Inverse Heat Conduction Problem in OpenFOAM," *OpenFOAM®*, vol. 1, pp. 27-46, 2021.

[4] F. Mohebbi, "Explicit sensitivity coefficients for estimation of temperature-dependent thermophysical properties in inverse transient heat conduction problems," *Computation*, vol. 8, no. 4, p. 95, 2020.

[5] J. V. Beck, and K. A. Woodbury, "Inverse heat conduction problem: Sensitivity coefficient insights, filter coefficients, and intrinsic verification," *International Journal of Heat and Mass Transfer*, vol. 97, pp. 578-588, 2016.

[6] M. N. Özisik and H. R. B. Orlande, *Inverse heat transfer: fundamentals and applications*, Routledge, 2018.

[7] P. Xiong, J. Deng, T. Lu, Q. Lu, Y. Liu and Y. Zhang, "A sequential conjugate gradient method to estimate heat flux for nonlinear inverse heat conduction problem," *Annals of Nuclear Energy*, vol. 149, p. 107798, 2020.

[8] A. K. Mozumder, M. Monde and P. L. Woodfield, "Delay of wetting propagation during jet impingement quenching for a high temperature surface," *Internation Journal of Heat and Mass Transfer*, vol. 48, no. 25-26, pp. 5395-5407, 2005.

[9] N. Karwa, "Experimental study of water jet impingement cooling of hot steel plates," Ph.D. dissertation, Dept. Mechanical Engineering, Technical University of Darmstadt.

[10] M. Colaco and H. R. B. Orlande, "Comparison of different versions of the conjugate gradient method of function estimation," *Numerical Heat Transfer: Part A: Applications*, vol. 36, no. 2, pp. 229-249, 1999.

[11] O. M. Alifanov, "Solution of an inverse problem of heat conduction by iteration methods", *Journal of Engineering Physics*, vol. 26, no. 4, pp. 471-476, 1974.

[12] P. Suchde, J. Kuhnert and S. Tiwari, "On meshfree GFDM solvers for the incompressible Navier-Stokes equations," *Computers & Fluids*, vol. 165, pp. 1-12, 2018.

[13] P. Suchde and J. Kuhnert. "A fully Lagrangian meshfree framework for PDEs on evolving surfaces," *Journal of Computations Physics*, vol. 395, pp. 38-59, 2019.

[14] J. Bender and J. Kuhnert, "Solid-fluid coupling in a fully Lagrangian framework," *PAMM*, vol. 19, no. 1, e201900240, 2019.

[15] I. Machel, I. Bathaeian, J. Kuhnert, D. Kolymbas, CH. Chen, I. Polymerou, C. Vrettos and A. Becker, "Meshfree generalized finite difference methods in soil mechanics – part II: numerical results," *International Journal of Geomath*, vol. 8, no. 2, pp. 191-227, 2017.

[16] P. Suchde, H. Kraus, B. Bock-Marbach and J. Kuhnert, "Meshfree One-Fluid Modelling of Liquid-Vapor Phase Transitions," *arXiv preprint*, arXiv: 2203.10383, 2022.

[17] K. Nabbout, M. Sommerfeld, E. Uhlmann, E. Barth and J. Kuhnert, "Interaction of Cooling Lubricant Droplets with Hot Metal Surfaces," in *Proceedings of the 7th World Congress of Momentum, Heat and Mass Transfer (MHMT'22)*, p. 154, 2022.

[18] M. Gradeck, A. Ouattara, D. Maillet, P. Gardin and M. Lebouché, "Heat transfer associated to a hot surface quenched by a jet of oil-in-water emulsion", *Experimental thermal and fluid science*, vol. 35, no. 5, pp. 841-847, 2011.