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Rewetting Behaviour During Immersion Quenching

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Immersion quenching is a widely used technique in heat treatment, because this technique provides higher heat transfer coefficients than the most alternative gas quenching techniques. The disadvantage of immersion quenching in evaporating fluids is the complex heat transfer mechanism which consists of three phases, namely film boiling, nucleate boiling and convective cooling. Especially the transition from film to nucleate boiling – the rewetting of the sample surface – is a complicated process which leads to an extreme local dependence of the heat transfer coefficient. Therefore immersion quenching is very difficult to control and often leads to distortion of the quenched workpieces.

In the present paper the rewetting behaviour was investigated by means of hollow and solid cylinders. These workpieces offer the possibility to investigate different distributions of surface temperatures of samples with the same outer geometry/curvature. The observation of the rewetting process was done by means of video films. Additionally, the cooling curves at two positions near the surface were measured. From these data, heat transfer for the quenching simulation by the Finite Element Method was estimated and rewetting curves were calculated.

Vlaženje za vrijeme kaljenja u tekućem sredstvu

Izvornoznanstveni članak

Kaljenje u tekućem sredstvu je tehnika toplinske obrade koja se široko primjenjuje. Ta tehnika omogućava više koeficijente provođenja topline u odnosu na većinu alternativnih tehnika kaljenja na bazi plina. Nedostatak kaljenja u hlapljujućim fluidima je kompleksan mehanizam provođenja topline koji se sastoji od tri faze, redom filmsko ključanje, mjehurićasto ključanje i konveksno hlađenje. Posebno prijelaz s filmskog ključanja na mjehuričasto ključanje – vlaženje površine uzorka - je kompliciran proces koji dovodi do ekstremne lokalne ovisnosti koeficijenta provođenja topline. Zbog toga je kaljenje u tekućem sredstvu vrlo teško kontrolirati i često dovodi do distorzije zakaljenih uzoraka.

U radu je istraživano vlaženje sredstvima šupljeg i punog cilindra. Ovakvi uzorci nude mogućnost istraživanja distribucije temperature po površini uzoraka sa jednakom vanjskom geometrijom/zakrivljenosti. Procesa vlaženja promatrana je sredstvima video filma. Dodatno, mjerene su krivulje hlađenja na dvije pozicije blizu površine. Od dobivenih podataka, procijenjeno je provođenje topline za kaljenje simuliranjem metodom konačnih elemenata (FEM) i izračunate su krivulje vlaženja.

Keywords
Immersion quenching
Oil
Rewetting behaviour
Simulation

Ključne riječi
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1. Introduction

Immersion quenching is a widely used technique in hardening shops. The disadvantage of this quenching technique is the complicated local and time-dependent rewetting process and hence the complicated distribution of the heat transfer coefficient of the cooled workpieces. Therefore, controlling immersion quenching is very difficult and often leads to distortion. Even a slightly nonhomogeneous flow field surrounding thin shafts can result in a bending of these components since the rewetting will not be symmetrical with respect to the axis of the shafts [1]. The reason for this behaviour is the enormous increase of heat transfer coefficient (HTC) after passing of a rewetting front at a given position: On the non-rewetted side of the front the HTC is quite small because the vapor film acts as an insulator. Typical values of HTC in this phase are 300 to 700 W/(m²K) for quenching oils [2, 3]. On the rewetted side of the front the HTC increases at small temperature intervals to values of a few 1000 W/(m²K), which results from direct contact of the fluid with the hot surface.

Symbols/Oznake

HTC	- heat transfer coefficient - koeficijent prijelaza topline	α_1	- heat transfer coefficient of the regions of the surface - koeficijent prijelaza toplina površinskih dijelova
T_{Lcrit}	- local temperature - lokalna temperatura	α_2	- heat transfer coefficient of the other regions - koeficijent prijelaza toplina drugih dijelova
T_{L0}	- critical local temperature - kritična lokalna temperatura	α_3	- heat transfer coefficient during film boiling - koeficijent prijelaza toplina prilikom ključanja u tankom sloju
z_{crit}	- critical length - kritična duljina		

Because of the high heat transfer coefficient during the boiling phase, knowledge of the rewetting kinetic, which indicates the beginning of the boiling phase, is one of the most important points for prediction of heat transfer coefficients during immersion cooling. It is well known that the rewetting process depends on the kind of fluid, fluid temperature, fluid velocity, and workpiece properties such as roughness and cleanness of the surface [4].

It is assumed that for a given set of experimental parameters the rewetting process occurs when the surface temperature decreases below a given temperature. In literature this temperature is called the Leidenfrost temperature.

To investigate the rewetting behaviour of workpieces mostly spherical and cylindrical geometries were used. For example Majorek [3], Jeschar [5], and Maaß [6] carried out quenching experiments with such simple samples in water. They clearly pointed out the influence of fluid, type fluid temperature, radiation of the workpiece, and geometry of workpieces on the stability of the vapor phase.

The above-mentioned assumption concerning the start of the rewetting process was investigated in [7] by means of different kinds (seven types) of hollow and solid cylinders. These workpieces offer the possibility to investigate different distributions of surface temperatures at samples, with the same outer radius, by use of the same quenching conditions. The presented experimental results indicate that the assumption of a constant Leidenfrost temperature over the complete cylinder surface is in general not true and confirm similar findings in [3, 6]. Furthermore it was shown that screw threads can induce an additional rewetting front.

In this contribution, an improved evaluation of the rewetting behavior of a sample with a hollow and a solid region without a connection with a screw thread will be presented Moreover, two HTC models with different complexity were tested by means of quenching process simulation and compared to temperature and rewetting measurements.

2. Experimental setup

The heat treatment of the workpieces was done in a tube furnace with a nitrogen atmosphere. The samples were heated up to 850 °C. Beneath the tube furnace, an oil bath was placed (Figure 1), filled with Isorapid 277® (high speed oil). The quench tank had a width and height of 600 mm, and a depth of 400 mm. In total, 130 l of oil were used and heated up to 80 °C. The quenching was carried out without any additional agitation of the quenching oil. In the quench tank two windows (diameter 225 mm) were inserted for observing the rewetting process with a high resolution CMOS video camera, which provided 30 frames per second. To illuminate the workpiece in the oil bath a halogen lamp with 2000 W power was used. The positions of the rewetting fronts were measured directly from the pictures of the video film.

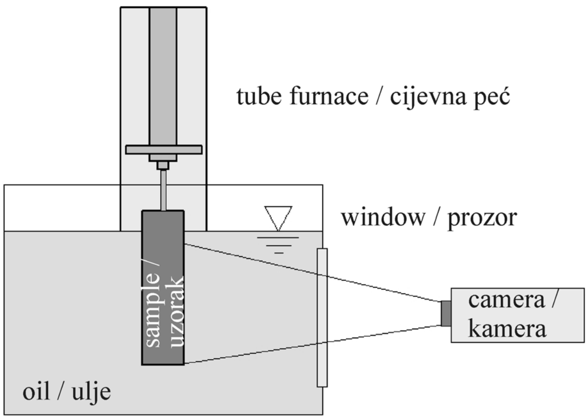


Figure 1. Schematic drawing of heat treating device with oil bath below the tube furnace

Slika 1. Shematski prikaz uređaja za grijanje s uljnom kupkom ispod cjevaste peći

For the investigations three types of cylindrical workpieces (50 mm Ø) were used (Figure 2). The sample material was an austenitic steel (AISI 30300). Sample "type a" is a solid cylinder with a length of 100 mm. "Type b" has a solid section with a length of 60 mm and a hollow one with a length of 140 mm and a wall thickness of 4 mm. This region of the sample will have a much faster cooling behaviour than the solid one and therefore, the influence of surface temperature on rewetting can be studied with a constant curvature of the heat transferring surface. Type a and b samples were not equipped with thermocouples.

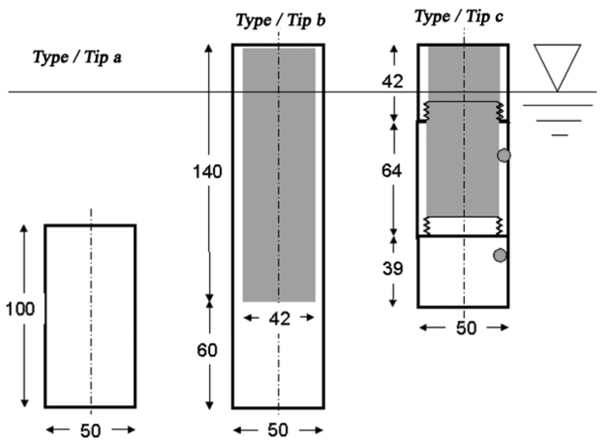


Figure 2. Geometry, dimensions and thermo-couple positions (circles) of the investigated samples

Slika 2. Geometrija, dimenzije i pozicija termo parova istraživanog uzorka

The "type e" specimen was used to measure cooling curves (Figure 2). It consists of one solid and two hollow parts which were connected by screw threads. This technique was used to avoid the very expensive insertion of thin and long bore holes (Ø 0,6 mm, length 120 mm) for thermocouples into cylinders of "type a" and "type b". The temperature measurements were done with sheathed Ni-CrNi thermocouples with diameters of 0,5 mm and with an insulation between sheath and weld of thermo wires. The measuring position was 1 mm below the outer surface.

Samples from "type b" and "type e" were dipped into the oil bath but not fully immersed, otherwise the hollow parts of the workpieces would have been filled with oil (cf Figure 2). This must be avoided, because an additional rewetting front inside the workpieces would make the quenching process more uncontrolled and more difficult to simulate. "Type a" sample was completely immersed.

3. Experimental results

3.1. Rewetting kinetic

Figures 3 and 4 show the results of the rewetting behaviour of the samples a and b. About 1 – 2 s after dipping the samples into the oil a rewetting front starts at the bottom of both sample types. After 3 s a second front starts at the completely immersed cylinder of "type a" from the top and moves downward with a lower velocity. After nearly 16 s both fronts meet at a distance of 78 mm from the bottom (Figure 3) and the rewetting is completed.

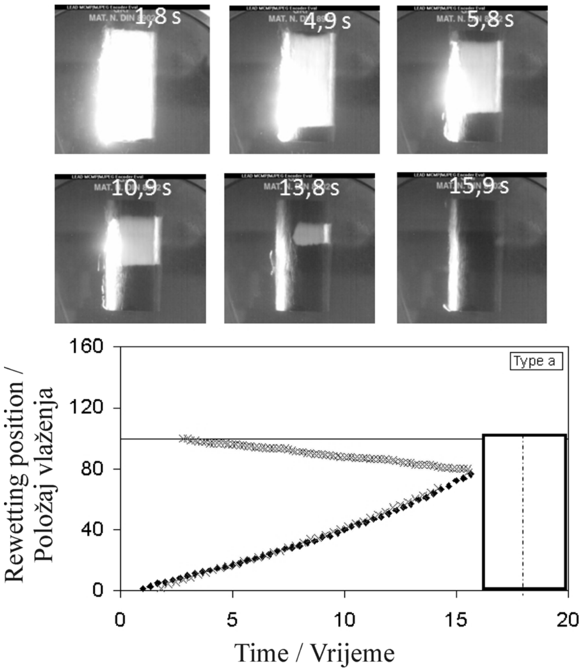


Figure 3. Rewetting of sample "type a" (two eperiments)

Slika 3. Vlaženje uzorka 'tipa a' (dva ekperimenta)

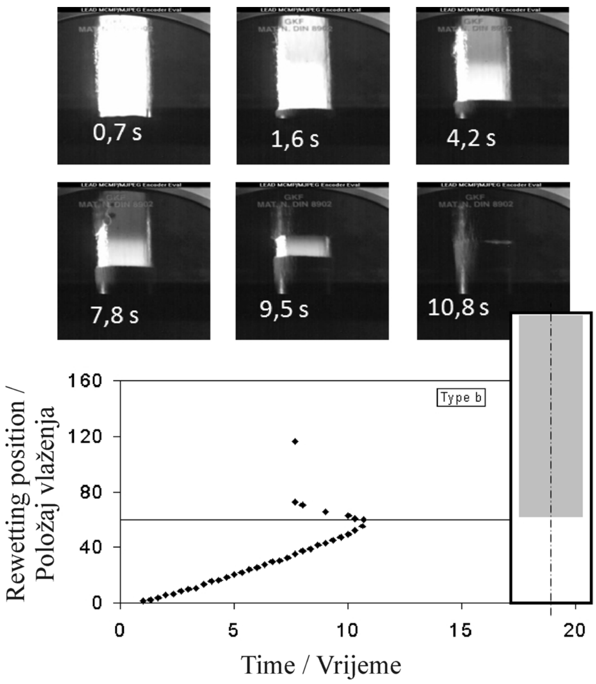


Figure 4. Rewetting of sample "type b"

Slika 4. Vlaženje uzorka 'tipa b'

A large region of the hollow part of sample b was rewetted instantaneously 7.8 s after dipping the workpiece in the quenching oil. Close by the transition to the solid part a second front started moving downward and met the first front exactly at the transition from hollow to massive. After 10.7 s the rewetting was completed.

3.2. Corresponding cooling curves

In Figure 5 the resulting cooling curves of sample e are shown. As expected the hollow part cools faster than the solid one. The increase of the cooling rates marks the transition from film boiling to nucleate boiling and can therefore be assumed as estimation of the Leidenfrost temperature. It can be seen that this temperature differs at the two measuring positions: about 740 °C in the solid part and 650 °C in the hollow one.

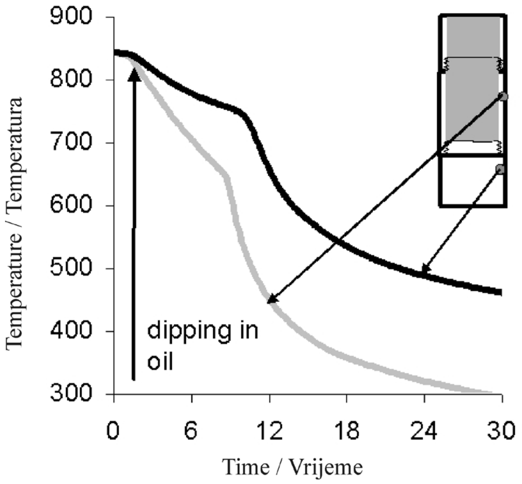


Figure 5. Cooling curves of sample "type e"

Slika 5. Krivulje ohlađivanja uzorka 'tipa e'

Figure 6 shows that the rewetting kinetics of the samples b and e differs because the screw thread induces a second rewetting front [7]. Consequently the cooling curves of sample e cannot be directly compared to sample b. But they can be used to estimate the parameters of heat transfer during film boiling.

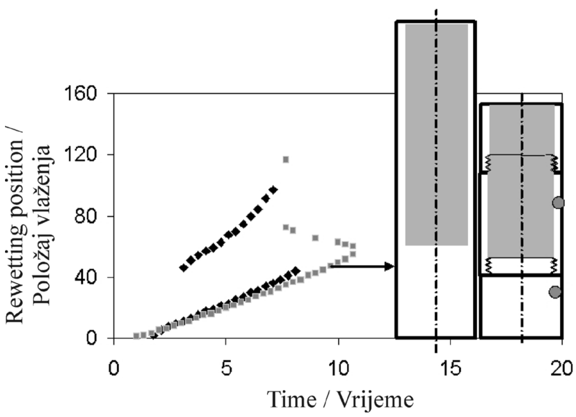


Figure 6. Rewetting kinetics of sample "type e" compared to "type b"

Slika 6. Kinetika vlaženja uzorka 'tipa e' u usporedbi s 'tipom b'

3.3. Summary of experimental results

The investigations of oil quenching from hollow and solid cylinders and study of literature for water quenching [e. g. 3-7] have shown that:

- corners at the lower end of samples and components induce a rewetting front
- spheres show an instantaneous rewetting
- a second front may start at
  - the upper end
  - screw threads or any geometrical disturbances
- regions of a sample, which cool down much faster than the lower end, can show an nearly instantaneous rewetting
- instantaneous rewetting may generate an additional front
- screw threads or any geometrical disturbances can initiate additional rewetting fronts
- Leidenfrost temperature depends on position.

Analyzing these results two questions appear:

- Why does a second rewetting front not appear in all cases?
- Why can an instantaneous rewetting occur in regions with higher cooling rates?

The answer to these questions could be the existence of a critical surface temperature below which no vapour film can exist. Such a behaviour would lead to a second rewetting front at the top of a sample when this region cools down faster to this critical temperature than the first front needs to reach this position. The same explanation can be given to the second question.

4. Quenching simulation

To check the hypothesis of a critical temperature the HTC was modelled with two different degrees of complexity. These models are purely phenomenological and were used as boundary conditions for the simulation of the quenching process of samples from "type a" and "type b". The simulations were done with the commercial Finite-Element-code SYSWELD®. For the simulation the temperature dependent thermo-physical properties of the steel AISI 30300 as published in [8] were used. The meshes and boundary conditions are given in Figure 7. The sample "type a" was completely immersed. So it was assumed that the HTC can be described on the whole surface with a function α_1. Sample b is only partially immersed. Therefore, it was assumed that HTC of the regions of the surface, with direct contact to the quenching oil, can be described by the same function α_1. The other regions were assumed to have a HTC α_2 which was taken as 50 W/(m²K) as a typical value for air cooling.

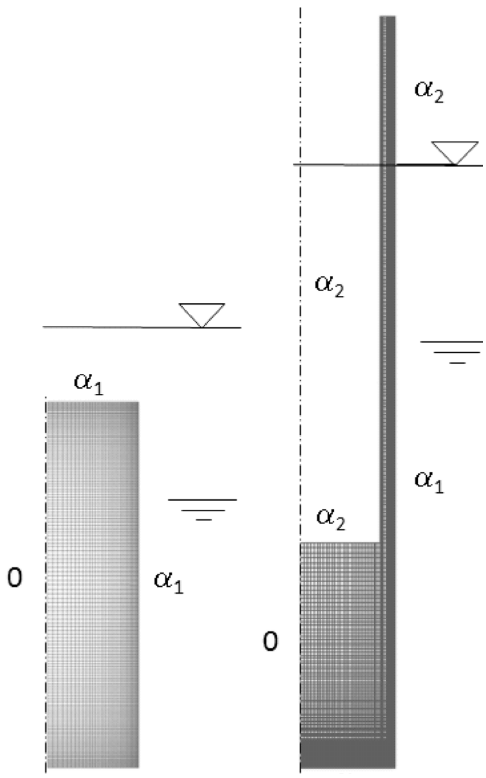


Figure 7. Meshes and boundary conditions: α_1 see Figure 8, α_2 = 50 W/(m²K)

Slika 7. Mreže i granični uvjeti: α_1 vidi sliku 8. α_2 = 50 W/(m²K)

4.1. HTC depends only on temperature – constant Leidenfrost temperature

The simplest approach for predicting the rewetting behaviour is the assumption of a constant Leidenfrost temperature. In this approach it is assumed that the vapour film is stable until the temperature decreases locally below the Leidenfrost temperature. In that case the rewetting will start simultaneously at the upper and lower corner of the cylinder. The corresponding HTC depends only on temperature. Figure 8 shows this function, as it was derived from experiments with the quenching oil Isorapid 277®. The Leidenfrost temperature in this figure equals 700 °C.

For both types of sample a systematic variation of the Leidenfrost temperature and the HTC during film boiling (α_F) was done until agreement between resulting cooling curve and corresponding measurement was acceptable. The results are shown in Figure 9. The curves were achieved by a Leidenfrost temperature of 745 °C and α_F =440 W/(m²K) ("type a") respectively 640 °C and α_F =580 W/(m²K) ("type b").

The related rewetting curves are presented in Figure 10. In the solid region of the samples the measured curves differ significantly from the calculations. Only in the hollow region of sample b can the rewetting curve be predicted quite well with this simple model. This last result is one indication that the hypothesis of a critical temperature could be correct.

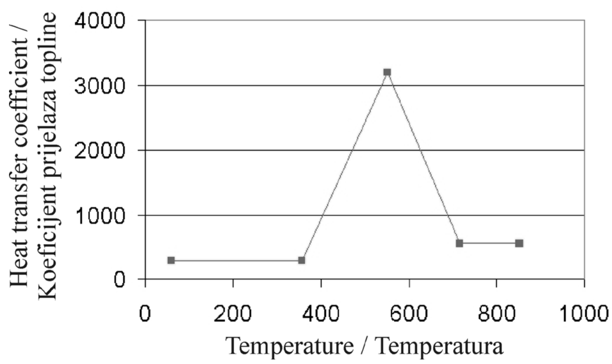
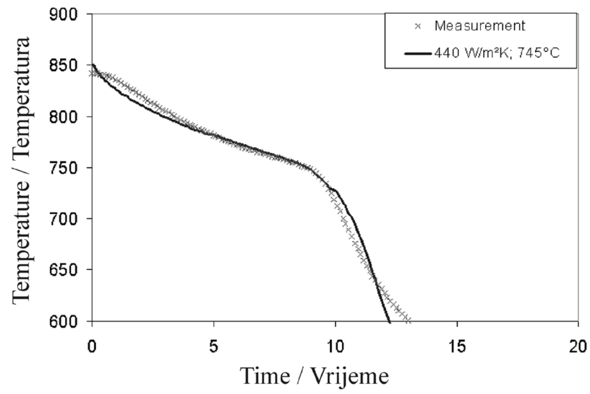


Figure 8. Temperature dependency of α_1, oil temperature: 80 °C

Slika 8. Ovisnost α_1 o temperature, temperature ulja: 80 °C



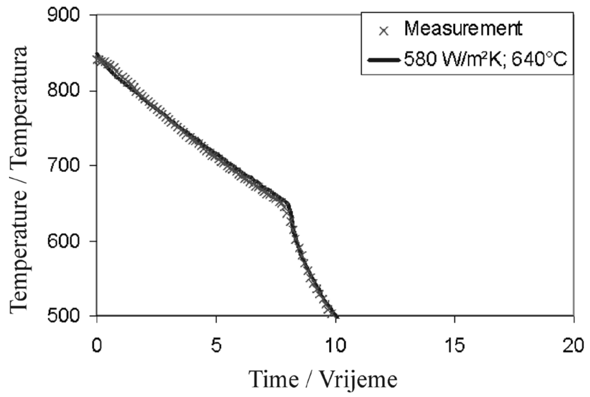


Figure 9. Comparison of measured and calculated cooling curves (α_1=α_1(T)): left: simulation of sample "type a" and measurement of "type e", mass.part, right: simulation of sample "type b" and measurement of "type e", hollow part

Slika 9. Usporedba izmjerenih i izračunatih krivulja ohlađivanja (α_1=α_1(T)): lijevo: simulacija uzorka 'tipa a'i mjerenje 'tipa e', puni komad, desno: simulacija uzorka 'tipa b'i mjerenje 'tipa e', šuplji komad

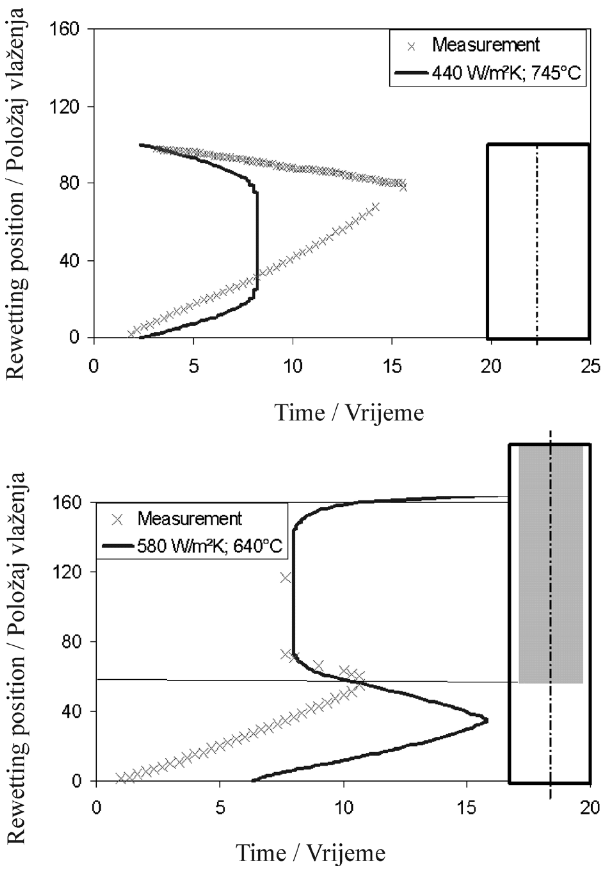


Figure 10. Comparison of measured and calculated rewetting kinetic ($\alpha_1=\alpha_1(T)$)

Slika 10. Usporedba izmjerene i izračunate kinetike vlaženja ($\alpha_1=\alpha_1(T)$)

4.2. Position dependent Leidenfrost temperature

To improve the calculations of rewetting, according to [3] a position dependent Leidenfrost temperature was used. The model is given in Figure 11, its parameter in Table 1. The rewetting at the top of the samples will start when the local temperature falls below the critical one.

The value of T_{Lcrit} was taken from the fit of the rewetting of the hollow region of sample b. But in this model it will be used for both types of sample. The same is true for T_{L0}. The value of this parameter was chosen in such a way that the start of the rewetting at the bottom of the sample corresponds to the measurements.

The influence of geometry consists of different values for the length and z_{crit}. The value for "type a" equals the measured position of the rewetting completion (Figure 10). For "type b" the length of the solid part was taken.

Majorek reported a position dependent HTC during film boiling too [3]. Due to the lack of sufficient cooling curve measurements this effect was neglected for the moment. But to have an idea about the influence, a variation of the parameter α_F was done. With increasing α_F the quality of the predicted cooling curve of "type a" degrades but the quality of rewetting simulation is improved (Figure 12). But none of the used values for αF results in the measured rewetting velocity in the upper part of the sample. All values are systematically too high.

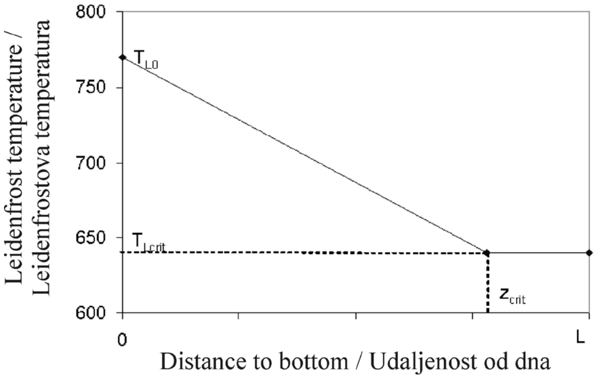


Figure 11. Position dependent Leidenfrost temperature – model

Slika 11. Model Leidenfrostove temperature ovisan o položaju

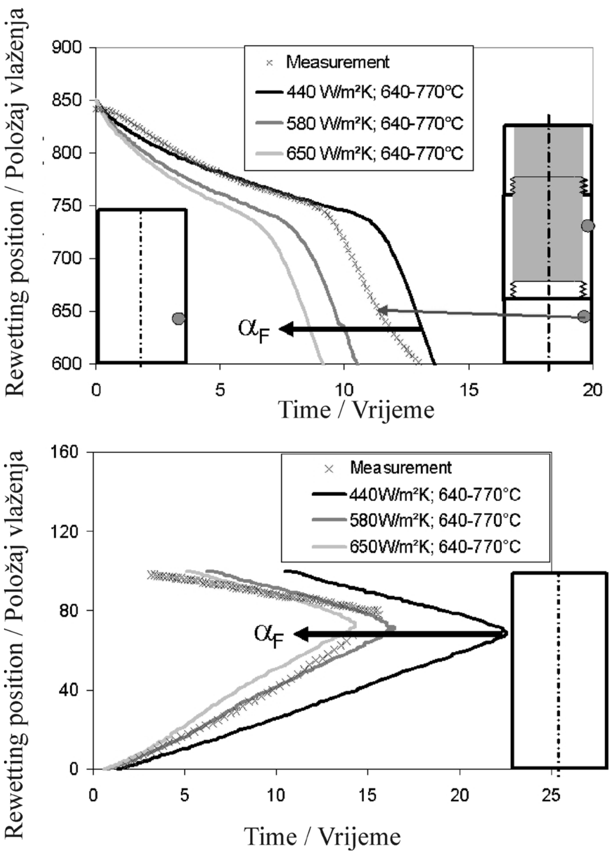


Figure 12. Comparison of measurement and calculations with $\alpha_1=\alpha_1(T, z)$ and different values of α_F, "type a": left: cooling, right: rewetting

Slika 12. Usporedba mjerenja i izračuna s $\alpha_1=\alpha_1(T, z)$ i različitim vrijednostima α_F, 'tip a': lijevo: hlađenje, desno: vlaženje

The results for "type b" show better agreement (Figure 13). But the increase of rewetting rate in the solid part of the sample cannot be achieved with a constant value of HTC during film boiling.

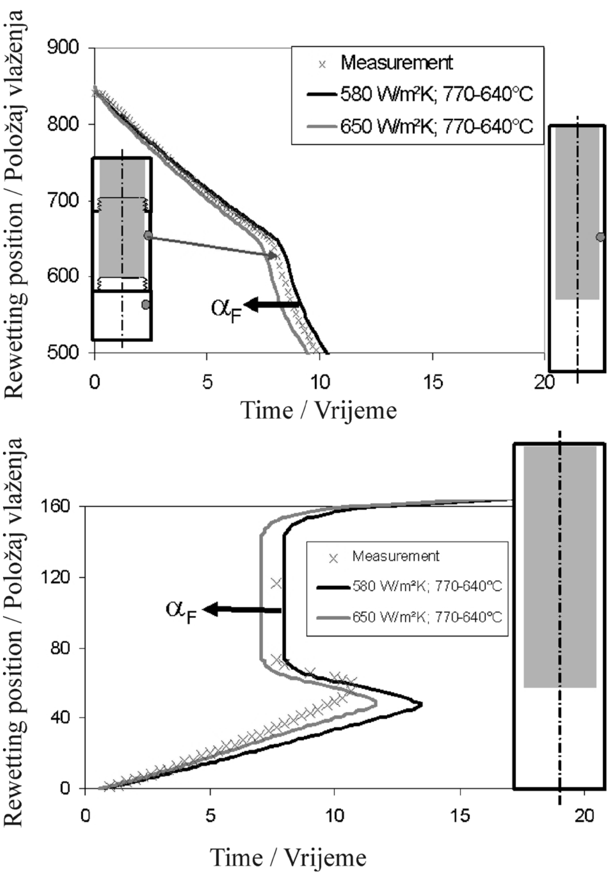


Figure 13. Comparison of measurement and calculations with $\alpha_1=\alpha_1(T, z)$ and different values of α_F, "type b": left: cooling right: rewetting

Slika 13. Usporedba mjerenja i izračuna s $\alpha_1=\alpha_1(T, z)$ i različitim vrijednostima α_F, 'tip b': lijevo: hlađenje, desno: vlaženje

5. Conclusions

The simulations have shown that a HTC model with a constant Leidenfrost temperature can predict instantaneous rewetting phenomena quite well when the value of the Leidenfrost temperature equals the critical temperature. This was shown for hollow regions of cylinders and should be true for spheres too. But the movement of rewetting fronts and cooling curves cannot be described with such a simple model. Here a position dependent Leidenfrost temperature has to be used. But a simple linear model together with the simplification of a constant HTC during vapour boiling (α_F) does not predict the measured rewetting velocities correctly. A more complicated model with non-linear dependencies of Leidenfrost temperature and HTC in the boiling phase is necessary, but will need more positions for temperature measurements at samples without screw threads for determination of the model parameters.

6. Summary and outlook

The determination of rewetting kinetics of massive and hollow cylinders together with corresponding cooling curve measurements and quenching simulations have shown that a simple HTC model with position independent Leidenfrost temperature can principally predict instantaneous rewetting phenomena. But rewetting kinetics with finite velocities cannot be calculated correctly. For this purpose a position dependent model is necessary. Further work will study the influence of the shape of the corner at the end of the workpiece and a forced convection by measurement of rewetting kinetics and cooling at different positions especially for quenching oils. For temperature measurements samples without screw threads will be used, so that the uncertainties coming from the additional rewetting front which arise from the screw thread will disappear.

Up to now pure phenomenological models were used and their parameters have to be determined for each set of conditions such as geometry, dimensions, kind of fluid, velocity, temperature, etc. Within the frame of the Collaborative Research Centre SFB 570 "Distortion Engineering" at the University of Bremen (www.sfb570.uni-bremen.de) a working group is dealing with Computational Fluid Dynamics (CFD). They are developing a simplified - but physically motivated – model for boiling to overcome the above mentioned problem. Their first results are promising [9].

Acknowledgement

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REFERENCES

[1] FRERICHS, F.; LÜBBEN, T.; HOFFMANN, F.; MAYR, P.; ZOCH, H.-W.: *The influence of asymmetrical manufacturing conditions on distortion of cylinders*. HTM Z. Werkst. Wärmebeh. Fertigung 60 (2005) 6, pp. 323 – 330 (in German).

[2] LÜBBEN, T., BOMAS, H.; HOUGARDY, H.P.; MAYR, P.: *Description of the cooling characteristics of fluid quenchants at the example of two quenching oils (Part 1)*. Härterei-Techn. Mitt. 46 (1991) 1, pp. 24 – 34 (in German).

[3] MAJOREK, A, MUELLER H. AND MACHERAUCH, E.: *Computer simulation of immersion cooling of steel cylinders in vaporizing liquids*. Härterei-Techn. Mitt. 51 (1996) 1, pp. 11-17 (in German).

[4] LISCIC, B., TENSI, H.M. AND LUTY, W.: *Theory and Technology of Quenching.* Springer-Verlag, Berlin, Heidelberg, New York, ISBN 3-540-52040-6.

[5] JESCHAR, R. AND MAASS, R.: *Heat transfer in water-quenching spherical bodies.* Gaswaerme International, Vol 35, (1986) 7, pp. 370 – 375.

[6] MAASS, R. AND JESCHAR, R.: *Factors determining heat transfer in quenching metals in water*. Gaswaerme International, Vol. 38, (1989) 3, pp. 142 – 149.

[7] FRERICHS, F.; LÜBBEN, T.: *The influence of surface temperature on rewetting behaviour during immersion quenching of hollow and solid cylinders*. Journal of ASTM International (JAI), online version, 2009, Vol. 6, Issue 1, DOI: 10.1520/JAI101852.

[8] FRERICHS, F., LÜBBEN, T., FRITSCHING, U., HUNKEL, M., LOHNER, H., HOFFMANN, F. AND MAYR, P.: *Simulation of Gas Quenching*. Journal de Physique IV, Vol 120, 2004, pp. 727-736.

[9] KRAUSE, F.; SCHÜTTENBERG, S.; FRITSCHING, U.: *Modelling and Simulation of Flow Boiling Heat Transfer*. Int. Journal of Numerical Methods for Heat and Fluid Flow (submitted).