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Effect of Agitation Work on Heat Transfer during Cooling in Oil ISORAPID 277HM

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The article is focused on the issue of heat treatment. The cooling curves were obtained for Isorapid 277HM with an experimental way of temperature measuring and their statistical processing. Experimental method was consistent with the test normative ISO standard 9950th (Wolfson's test). The cooling oil Isorapid 277HM was agitated with different agitation work and had a constant temperature of 50 °C. In the next part of this article were calculated the surface temperature depended combined heat transfers. The methodology was based on inverse heat transfer. The interpretation code were software ANSYS and ORIGIN.

Keywords: quenching, cooling curve, agitated oil, heat transfer, Wolfson's probe, ANSYS

0 INTRODUCTION

Heat treatment is a multiparameters process. The selection of appropriate parameters predicts required behaviours of treated components. The kind of quenching medium, the selection of quenching medium temperature and the selection of the medium state (unagitated, agitated) are determining factors. Quenching oil Isorapid 277HM belongs to cooling oils common in use. Prediction of treated components behaviour during a cooling process is possible only in the case if the boundary conditions of the process are defined. Before the application of a cooling process numerical simulation, the heat transfer coefficient on the component surface should be defined quantitatively. The experiment, applying simulation model and numerical solution, is able to test the influence of heat treatment parameters on an immediate and final state of a component. Cooling curve is the basis for determining the combined heat transfer coefficient (*HTC*) as a function of temperature. The current situation presents two ways to get the *HTC* cooling curve: direct and inverse approach. Direct access is represented in the publication [1]. *HTC* is obtained by calculating based on the classical theory of heat conduction in infinite long cylinder with small Biot's number ($Bi < 0.1$) in few simple recursive computations using the "Heat Transfer Coefficient Wizard". The comparison between measured cooling curves (derived cooling rate curve) with calculated curves is only visual.

Heat transfer coefficient inverse method is based on iterative approach loading simulation model in the form of *HTC* and the effect of temperature at thermocouple (TC-temperature) [2] to [4]. The inverse numerical method is implemented in the software SQintegra also. This program is used as the evaluation tool of the IvfSmartQuench instrument [2].

Inverse-numerical-correlation method (INC) defines *HTC* over inverse heat transfer problem which was proposed by the authors of this article. The INC method is applied to solution of direct well-posed inverse problems. Through the controlled iterative process can find a result which is very likely and useful for computer prediction of thermal treatment processes. The main active part of this procedure is researcher with theoretical knowledge and experiences with numerical analyses. Typical for the inverse methods is that there exist an infinite set of solutions in general. Only the right setting of statistical criteria get the result with the high degree of reality. Fig. 1 shows the cooling process of ISO probe in optically transparent quenching oil Isomax166. Photographs in Fig. 1 show that the cooling process in the three forms of heat transfers (radiation, boiling and convection) are a continuous process without step change (photo

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from article authors). Then the determinate *HTC* must be continuous also.

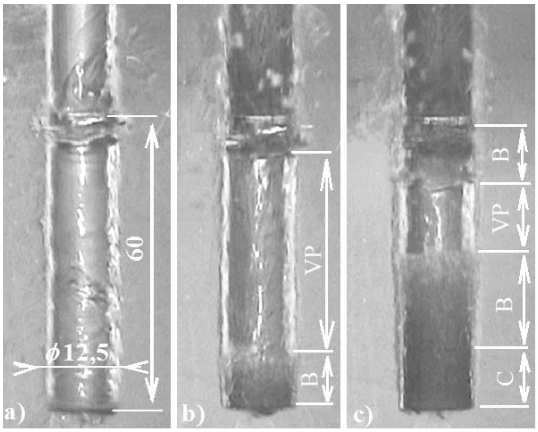

Fig. 1. *ISO probe cooling process in Isomax 166, a) vapour blanket (VP) in time 1 s, b) begin of boiling (B) in time 2.8 s, c) boiling (B) and convection (C) in time 6.3 s*

The methodology and results of cooling effect quantification of oil Isorapid 277 HM with chosen agitation work at temperature 50 °C are presented in the article.

1 EXPERIMENTAL

Quenching oils ISORAPID are accelerated quenching oils with very good evaporation stability and fast quenching properties. These oils have been specially designed for application in sealed quench furnaces. They ensure rapid and homogeneous cooling of all parts during batch quenching and also rapid decay of the vapour blanket within the batch. Their application in open quench baths reduces smoke and flame formation significantly [5].

The experimental set-up in Fig. 2 was consisted of electrical resistance furnace of LM 212.10 type, cylinder-shaped experimental probe (Table 1, Fig. 3), oil Isorapid 277HM with mass of 28 kg, portable USB-based DAQ for thermocouples NI USB 9211 for digital record of measured temperatures, frequency converter MICROMASTER 440 (MM440), personal computer and pneumatically manipulator for probe moving. Material of probe was austenitic stainless steel DIN 1.4841 with high temperature resistant. Thermophysical material properties were obtained from experimental measuring by NETZSCH apparatus: LFA 427, DSC 404 C Pegasus and Dilatometer 402 C.

Table 1. Thermophysical material properties of austenitic stainless steel DIN 1.4841

T [°C]	λ [W.m^{-1}·K^{-1}]	ρ [kg·m^{-3}]	c [J.kg^{-1}·K^{-1}]
0	13.5	7880	474
100	15.0	7854	490
200	16.8	7814	512
300	18.6	7773	525
400	20.0	7731	535
500	21.3	7689	544
600	23.2	7645	569
700	24.8	7601	581
800	25.6	7556	589
900	27.1	7511	600

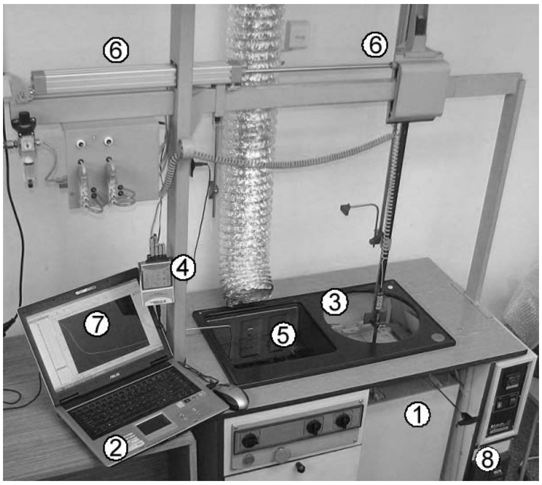

Fig. 2. *Experimental setup: 1- electrical resistance furnace, 2- personal computer, 3 - probe with a thermocouple, 4 - NI USB 9211 converter, 5 - cooling medium and its heater, 6 - pneumatic manipulator, 7- record of cooling curve, 8- frequency inverter,*

Geometrical and initial conditions of the experiment were based on the quenching test ISO 9950 [6]. Before cooling, the probe was heated up to the initial temperature of 850 °C. The temperatures were measured by the standard 304SS thermocouple of K type with diameter of 1.53 mm located in the centre of the probe. Temperatures were recorded 5 times per second. Set of measurement was repeated six times for each state of oil. Each set of measured cooling curves was averaged into core cooling curve. There were realized seven oil states, one for unagitated and six for agitated. Temperature measurement started from the moment when the centre of gravity of probe reached the oil level.

Power parameters (torque moment and input rpm) of the swirl devices were obtained from the data of frequency converter MM440.

2 THEORETICAL BASE OF THE TASK

Transient temperature field $T = T(r, z, t)$ of cooled probe is described by Fourier-Kirchhoff differential equation (FKDE) of heat conduction for cylindrical coordinate system [8],

$$\frac{\partial T}{\partial t} = \frac{\lambda(T)}{\rho(T)c_{\mathrm{p}}(T)}\left[\frac{\partial^2 T}{\partial r^2} - \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right] \ [\mathrm{K \cdot s^{-1}}], \quad (1)$$

where $\lambda(T)$ is coefficient of heat conductivity $[\mathrm{W \cdot m^{-1} \cdot K^{-1}}]$, $\rho(T)$ density $[\mathrm{kg \cdot m^{-3}}]$, $c_{\mathrm{p}}(T)$ specific heat $[\mathrm{J \cdot kg^{-1} \cdot K^{-1}}]$, r radius [m] and z is height of probe [m].

Combined heat transfer coefficient $HTC(T_{\mathrm{s}})$ $[\mathrm{W \cdot m^{-2} \cdot K^{-1}}]$ was determined as the function of the probe surface temperature T_{s} [°C] for constant oil temperature T_{r} [°C]. The condition of equality of heat flux is valid on the probe surface in time point t_{i} [s] by formula [4]

$$-\lambda(T)\,\mathrm{grad}T\Big|_{t_{\mathrm{i}}} = HTC(T_s)\left[T_{\mathrm{s}}(t_{\mathrm{i}}) - T_{\mathrm{r}}\right] \ [\mathrm{W \cdot m^{-2}}]. \quad (2)$$

Other assumptions of thermal tasks: the probe material is isotropic and its thermophysical properties are temperature dependent, the cooling process is isobaric, the temperature field is not dependent on the angle φ, $T \neq f(\varphi)$, coolant temperature is constant throughout the process, $T_{\mathrm{r}} \neq f(t)$. Heat generation in unit volume per unit time was not take account, because in probe material are not phase transformations in the temperature interval 50 to 850 °C.

Thermal task is solved by the finite element method (FEM). The FEM solution procedure is in the form of equation

$$\mathbf{K}_1.\mathbf{T} + \mathbf{K}_2.\mathbf{T} + \mathbf{K}_3.\dot{\mathbf{T}} - \mathbf{P} = \mathbf{0}\,, \qquad (3)$$

where $\mathbf{K}_1$ is heat conduction matrix, $\mathbf{K}_2$ matrix of boundary conditions, $\mathbf{K}_3$ enthalpy matrix, $\mathbf{T}$ temperature vector, $\dot{\mathbf{T}}$ time derivation of temperature and $\mathbf{P}$ is vector of outer loads.

Absolute value of relative error δ_{T} was obtained by formula

$$\delta_{\mathrm{T}}\Big|_{t_i} = \left|\frac{T_{\mathrm{TC}} - T_{\mathrm{ans}}}{T_{\mathrm{TC}}}\right|.100\% \ , [\%] \qquad (4)$$

where T_{TC} [°C] is measured temperature and T_{ans} [°C] is temperature of numerical solution, both for time t_{i}.

Input power into oil per 1 kg P_{w} was calculated from torque moment and angular velocity values at device for swirling by formula

$$P_{\mathrm{w}} = \frac{2\pi\, M_{\tau}\, n}{m}\,, \qquad [\mathrm{W \cdot kg^{-1}}], \qquad (5)$$

where M_{τ} is torque moment [Nm], n rotational speed $[\mathrm{s^{-1}}]$ and m is mass of oil in device [kg].

3 NUMERICAL SIMULATION

Engineering-scientific program code ANSYS [7] was the interpretation program of numerical simulation. Geometrical model of the probe was the lower half part of the cylinder, Fig. 3.

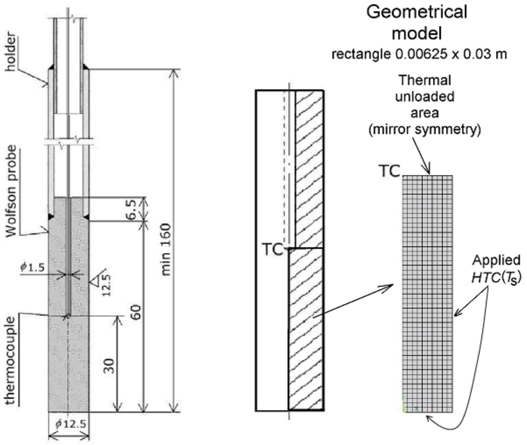

Fig. 3. *Probe geometry and geometrical model with generated mesh*

Applied elements were axisymmetric with linear base function and surface temperature behaviour option. Surface temperature behaviour allows to apply thermal load $HTC(T_{\mathrm{s}})$ as the actual surface temperature function. Generated mesh was mapped with length of element edge

0.25 mm. Calculation procedure was transient and nonlinear. Time step was 0.01 s.

Through the solution of simulation model of thermal nonlinear and transient task in the ANSYS the temperature curve for chosen HTC-loads values was found. Then was followed the comparison with measurement temperature curve and the process was repeated. The curve fitting takes account the temperature and cooling rate curve. Task solution by the INC method must meet the following criteria: absolute value of relative error for measured and calculated temperature in the *i*-time must be less than 1.0 %, absolute value of relative error for cooling rates derived of measured and calculated temperature must be less than 5.0 % and the correlation coefficient between measured and calculated temperatures in the cooling time must be greater than 0.99. Block diagram of iterative solution of the boundary condition - INC method is showed in Fig. 4.

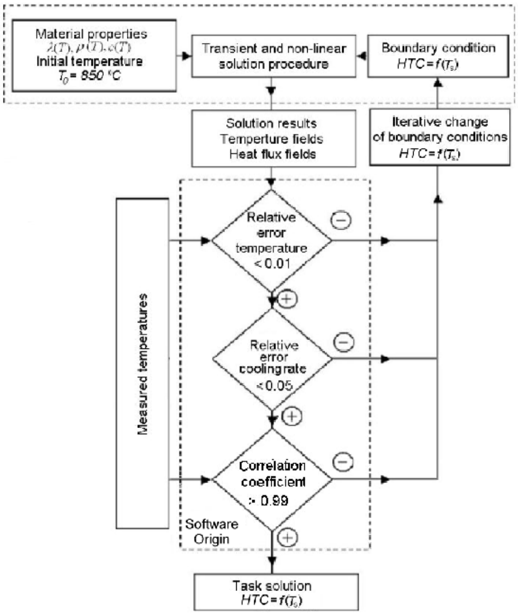

Fig. 4. *Block diagram of iterative solution of the boundary condition - INC method*

4 OBTAINED RESULTS

Time dependences of 7 measured temperatures during probe cooling from 850 °C into unagitated and agitated oil at temperature 50 °C are shown in Fig. 5. These core cooling curves were the basis for INC method applying.

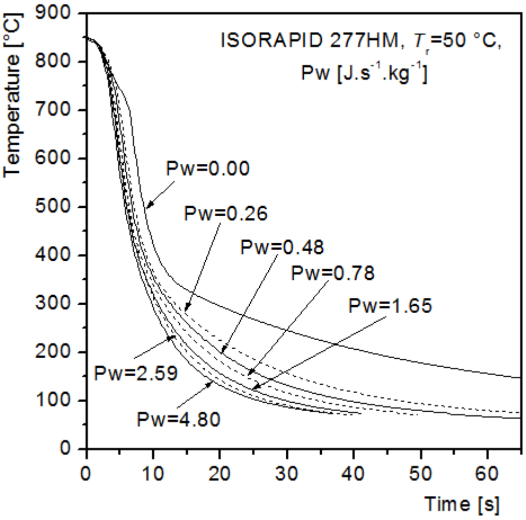

Fig. 5. *Set of measured temperatures, unagitated and agitated oil ISORAPID 277HM*

In Fig. 6 are plotted cooling rates curves (derived from core cooling curves).

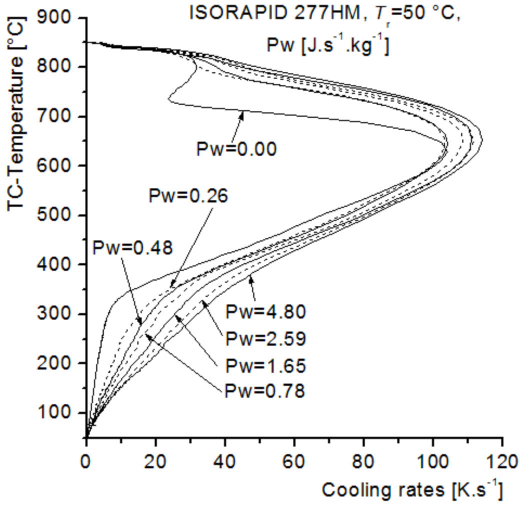

Fig. 6. *Cooling rates for unagitated and agitated oil ISORAPID 277HM*

There is a distinct difference between cooling in unagitated and in agitated oil. The lowest value of cooling rate is for unagitated oil and with energy supplied into oil increases the cooling rate and temperature at the centre at which the maximum cooling rate. The cooling rate interval is of 103 K·s^{-1} to 114 K·s^{-1}.

Combined heat transfer coefficient dependences of probe surface temperatures for unagitated and agitated oil are the main results of INC method and are shown in Fig. 7.

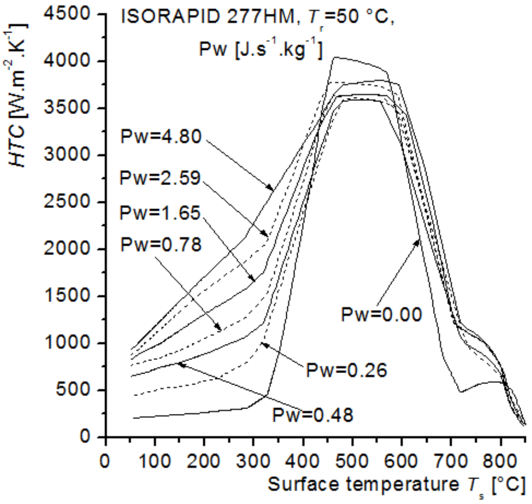

Fig. 7. *HTC curves for unagitated and agitated oil ISORAPID 277HM*

Forced movement of Isorapid 277HM oil alters the cooling process of probe in the vapour phase. The existence of vapour phase is shorter at higher surface temperatures and *HTC* reaches higher values than in the case of unagitated oil also. An important feature is the knowing that the effect of agitation of oil will be reflected most in the convection heat transfer surface temperature below 317 °C. *HTC* varies with the size of the energy supplied into oil. *HTC* values are readable from Fig. 7.

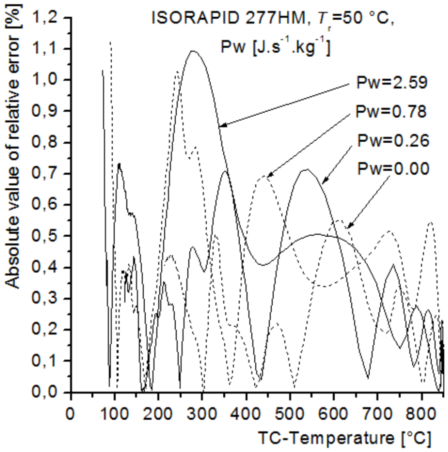

Fig. 8. *Absolute values of relative errors for core cooling curve fitting for chosen energy input*

Combination of experimental cooling curves and numerical simulation using INC method gives the values of absolute value of relative errors that are showed in Fig. 8.

For clarity the Fig. 8 has been selected four values of energy supplied into oil. Evaluated was the absolute relative error between measured and calculated values of cooling curve. The maximum value was 1.09% and the average error for all cases was less than 0.45%.

The temperature curve fitting was then very close and it was not possible to represent graphically both curves. The correlation coefficient between calculated and measured temperatures was obtained 0.9998 for all solved cases.

The test was made for relative error between the cooling rate obtained from the measured cooling curve and the curve of the INC method also. Fig. 9 shows two selected cooling rate curve for unagitated and agitated oil with energy input 2.59 J·s^{-1}·kg^{-1}. For unagitated oil was average absolute value of relative error 0.23 and for energy input was the error calculated 2.02%.

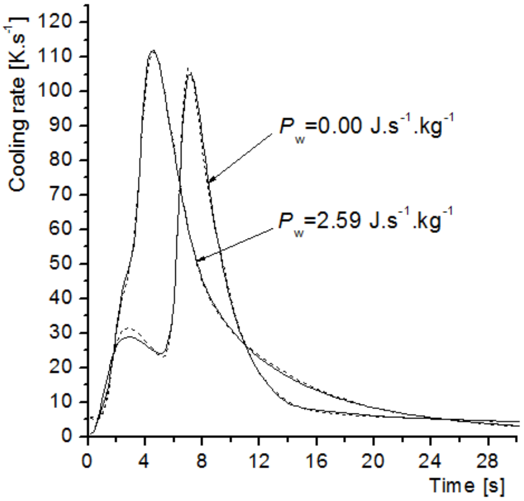

Fig. 9. *The fitting comparison for cooling rate curves for unagitated oil and agitated oil with energy input 2.59 J·s^{-1}.kg^{-1}*

5 CONCLUSION

Definition of heat transfer from the probe into the coolant as the inverse problem of heat conduction using a suitably selected control parameters is an appropriate method to quantify the *HTC* under different conditions. Energy input into agitated oil in the form of work per 1 kg media allows the reproducibility of the experiment. The obtained *HTC* are properties of the tested oil and use as the boundary condition of heat transfer in the heat treatment processes also. The *HTC* obtained for unagitated oil is used only for application to vertical surfaces. *HTC* data for agitated oil may be entered into the simulation models for outer surface regardless of the location of surfaces.

The results showed that the effect of oil agitation on the cooling process was reflected in the vapour phase and the significant influence of agitation in the convective heat transfer. Use of *HTC* for agitated oil is suitable for numerical experiments through software SYSWELD or DEFORM and of course for real experiments in the heat treatment process.

6 REFERENCES

[1] The Heat Treatment Simulation Solution from ESI GROUP (2011). from *http://www.esigmbh.de/downloads/ESI/Dokumente/Welding/old/The_Heat_Treatment_Solution_Overview_180306.pdf,* accessed on 2011-11-18.

[2] Troell, E., Kristoffersen, H., Bodin, J. Segerberg, S., Felde, I. (2007). *Unique software bridges the gap between cooling curves and the result of hardening*. Carl Hanser Verlag, Munchen, p. 110-115.

[3] Bodin, J., Segerberg, S., Lövgren, M. (2005). IVF SmartQuench för att säkerställa tillförlitligheten hos kylmedel (IVF SmartQuench to ensure the reliability of the coolant, from *http://extra.ivf.se/smartquench/articles_and_lit.asp*, accessed on 2011-11-18.

[4] Taraba, B., Španielka, J. (2010). Combined heat transfer coefficient calculation for cooled probe to 850 °C in quenching oil. *The international conference of the Carpathian Euro-region specialists in industrial system*, p. 281-286.

[5] Petrofer Hildesmein (2011). from *http://www.norteks.ru/en/product/petrofer/branded_items/harden_comp/*, accessed on 2011-11-18.

[6] Totten, G.E., Werster, G.M., Tensi, H.M., Liscic, B. (1997). Standards for Cooling Curve Analysis of Quenchants. *Heat Treatment of Metals*, vol. 4, p. 92-94

[7] Ansys Theoretical Manual (2011). from *http://www.pdfqueen.com/pdf/an/ansys-10-users-manual/10/*, accessed on 2011-11-18.

[8] Incropera, F.P., Dewitt, D. (1996). *Fundamentals of heat and mass transfer*. John Wiley & Sons, New York.