Proceedings of the 3rd IASME/WSEAS Int. Conf. on HEAT TRANSFER, THERMAL ENGINEERING AND ENVIRONMENT, Corfu, Greece, August 20-22, 2005 (pp277-282)

CFD -Analysis of a Part Under Quenching As a Heat Transfer Conjugate Problem

PAVLO KRUKOVSKYI[1], NIKOLAI KOBASKO[2], ANATOLY POLUBINSKIY[1]
1. Engineering Thermal Physics Institute
Zhelyabova 2a, 03113, Kyiv
UKRAINE
kruk@i.kiev.ua

2. Intensive Technologies Ltd.,
Blwr Wernadskoho 63, off.71, 03142, Kyiv
UKRAINE
nikobasko@yahoo.com, www.itl.kiev.ua

Abstract: - The traditional approach for the parts thermal state analysis under quenching is based on the Newton's sort boundary condition between the solid wall of the parts and fluid surrounding it. This approach often does not produce good results because of the lack of data on heat transfer coefficient for the heat transfer between the part and fluid flow, and the situation becomes worth due to the essential non-stationarity of the convection and boiling processes around the part, and the complexity of hydrodynamic flow of real parts of various shapes. The problem statement and heat transfer analysis results for half-axle cooling under quenching in moving water flows are considered. The problem solves as a conjugate heat transfer problems (Navie-Stocks equations full set solving) with CFD (Computation Fluid Dynamics) computer technology, when it is do not need to know the heat transfer coefficients at the surface of the part. This paper is of great value for the calculation analysis and paprameter optimization of intensive steel quenching method.

Key-Words: heat transfer, quenching, modeling, conjugate problem, critical heat flux

1 Introduction

The process of the boundary boiling layer formation can be divided into three periods:

1. Heating up the boundary cool liquid layer up to the boiling temperature with the simultaneous cooling of the metal surface.
2. Overheating the boundary layer and the bubble germs formation at the metal surface under heat flux reduction condition.
3. a) Vapor bubbles merging and continuous vapor film formation, if the heat flux is above the critical value, that is, $q > q_{cr1}$, b) No vapor film, if the initial heat flux is below the critical value.

It is well-known that there can be no nucleate boiling when the fluid flow rate is high. In this case the boundary layer does not heat up to boiling temperature due to the high rate of fluid flow. There are experimental data that confirm this viewpoint. Thus, the temperature of truck half-axles of 42 mm diameter, during quenching from 860 ^{o}C in water flow of 8 m/s velocity reduces from 860^{o}C to 100^{o}C in 0.1 s, while the temperature of the core reduces in the same range in 50 s. In intensive water flow the one-phase convection heat transfer is established almost instantly.

The simulation of cooling process and stress-strain state is conventionally connected with the use of Newton boundary conditions for heat transfer between the solid surface and fluid flowing around it. This approach often does not bring good results due to the lack of data on heat transfer coefficient for the heat transfer between the part and stream of cooling quenchant, and the situation becomes worth due to the essential non-stationarity of the convection and boiling processes in the boundary layer and complexity of hydrodynamic flow of real parts having various shapes. Because of this, the important task is to set and solve problems of part's cooling, and analysis of heat transfer in the boundary layer on the basis of conjugate heat transfer problems solving (the full Navier-Stokes equations set solving) and application of CFD (Computation Fluid Dynamics) computer technologies, where it is not necessary to know heat transfer coefficients at the surface of the parts. The results of such problems solving for intensive steel quenching methods can significantly improve the knowledge and precision of optimal parameters selecting during parts cooling.

2 Analysis of experimental data

The issue of the existing of different kinds of heat transfer during steel quenching is very important. If, when immersing into the quenchant and formation of a boundary boiling layer, the heat flux is above the critical value, the film boiling is always observed. If below, there is no film boiling. If the rate of fluid flow is very high, there may be no nucleate boiling since the boundary water layer does not boil up. To confirm the arguments above, let us analyze the experimental data of various authors.

Thus, Fig.1 shows French's experimental data for cooling in water from temperature of 875°C steel and copper balls of 38-mm diameter. As is seen from Fig.1, the ball's surface temperature sharply drops to 100°C and remains at this level. During cooling copper balls, the surface temperature at first sharply drops and when the vapor film is formed, the cooling is slowed down. Let us note that during cooling copper and silver samples, the film boiling is always observed due to high thermal conductivity of the copper and silver.

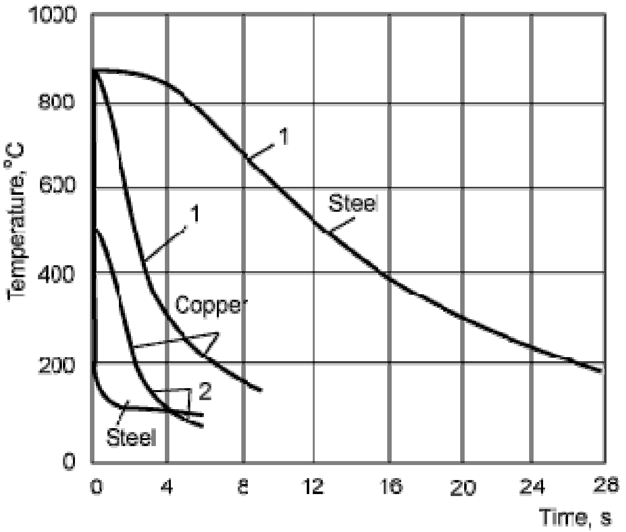

Fig. 1 Temperature at the surface and center versus time for steel and copper balls of 38-mm diameter, quenched from 875°C in water at room temperature (French's experiment [1]): 1 – center; 2 – surface.

The function of cooling rate's change for the core of silver balls of 20-mm diameter quenched in water is presented in Fig. 2. The figure follows that the full film boiling is observed. Some authors tell about the degeneracy of nucleate boiling. However, the analysis of acoustic effects has shown that at the beginning bubble germs are formed, which are obviously merged into a continuous film (see Fig.3).

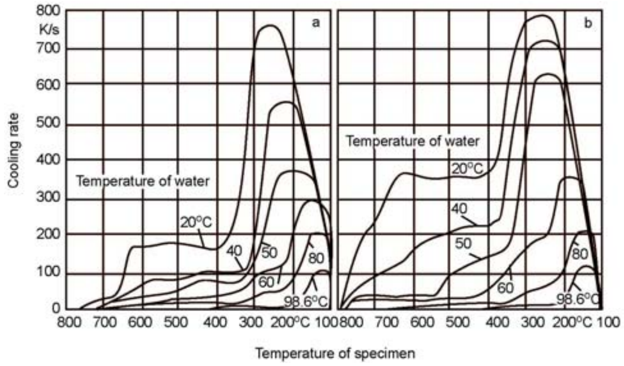

Fig. 2 Cooling rates of a silver ball of 20-mm diameter in still water at different temperatures (a), and circulating water at the rate of 0.25 m/s (b) [2]

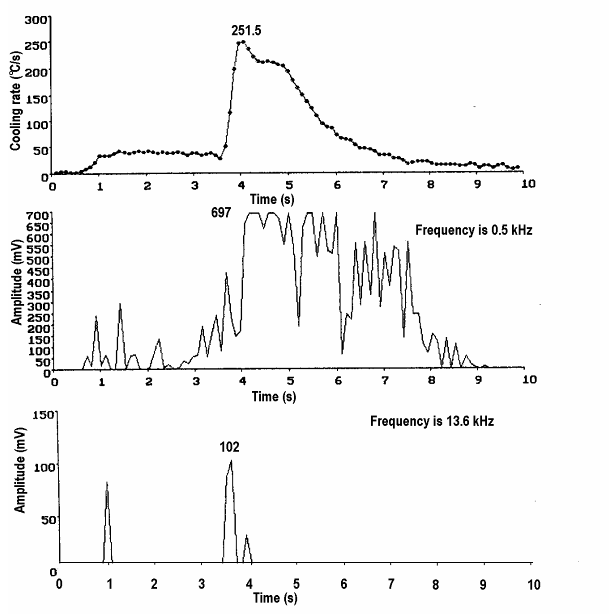

Fig. 3 Temperature – time, broad-band and narrow-band quenching data for plain water:
a) Cooling rate of silver ball of 20-mm diameter;
b) Sound control of the process of quenching at the frequency of 0.5 kHz; c) Sound control of the process of quenching at the frequency of 13.6 kHz [3]

During quenching the half-axles of 42-mm diameter in water flow of 8 m/s velosyti, there is neither film boiling, nor practically nucleate boiling (see Fig.4).

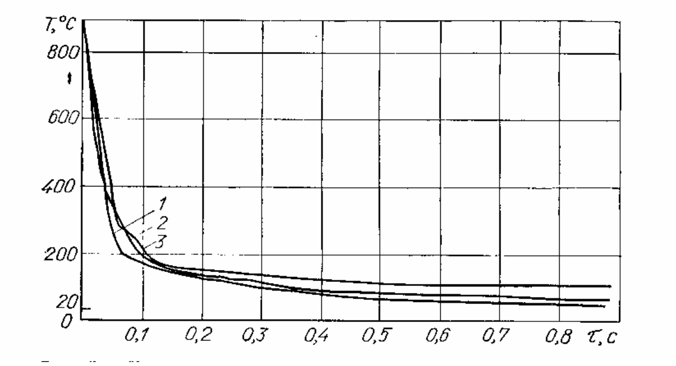

Fig. 4 Surface temperature vs. time for a half-axle of 42-mm diameter with slots, quenched in cool water flow of 8 m/s: 1 is slot hollow, 2 is the side surface of the slot, 3 is the slot head [4,5]

3 Conjugate Problem Setting

All heat transfer processes at the boundary between the solid wall and fluid in the nature are of conjugate character, that is, natural conjugation conditions for heat flux and temperature are met. Such kind problems modelling always meets certain difficulties, first of all due to simultaneously solving the equations for hydrodynamic and heat transfer proseses for fluid and a solid body necessity. For simplified unidimensional conjugate problems various analytical solutions were obtained some time ago. For more complex conjugate problems (many-dimensional, flowing around parts of comlicated shape, presence of complex hydrodynamic flows, non-linear character of models) various numerical methods have been developed for their solving, which in turn were applied in computer programs and formed the solving technologies, called later CFD (Computation Fluid Dynamic) technologies, aimed at a large number of users. Thus, it became possibility to get numerical solutions of conjugate heat transfer problems for various engineering and scientific applications.

Below we consider the application of CFD analysis for the deep study of cooling a half axle and heat transfer in the wall layer on the basis of conjugate problem solving, which allows to obtain heat fluxs and heat transfer coefficients in the boundary layer.

For the study we took a steel cylinder (half axle) of 42-mm diameter, 600-mm height, which was cooled from 860°C in water flow of 8 m/s. The temperature of the water stream was 20°C. The initial temperature distribution was assumed to be uniform and equal to 860°C. The half axle was cooled along the axis by water flow from left to the right. The thermal conductivity and diffusivity versus temperature are presented in Tables 1 and 2.

Table 1. Thermal conductivity of material versus temperature

T, ºC	100	200	300	400	500	600	700	800	900
$\lambda, \frac{W}{mK}$	17.5	18	19.6	21	23	24.8	26.3	27.8	29.3

Table 2. Thermal diffusivity a of material versus temperature

T, ºC	100	200	300	400	500	600	700	800	900
$a \cdot 10^6, \frac{m^2}{S}$	4.55	4.63	4.70	4.95	5.34	5.65	5.83	6.19	6.55

Fig.5 shows the distribution of the heat flux along the surface of the half-axle cylinder at various times. The maximum value of heat flux reached 11.7 MW/m^2. Here there were no film boiling, since the maximum value of the heat flux was less than the critical value calculated by the formula:

$$q_{cr1}^{uh} = 2.8\left(0.75W^{0.5} - 1\right) + 0.1(W^{0.35} - 1)\vartheta_{uh}$$

where W is water speed rate = 8 m/s,

$\vartheta_{uh} = T_S - T_M$ is underheating temperature.

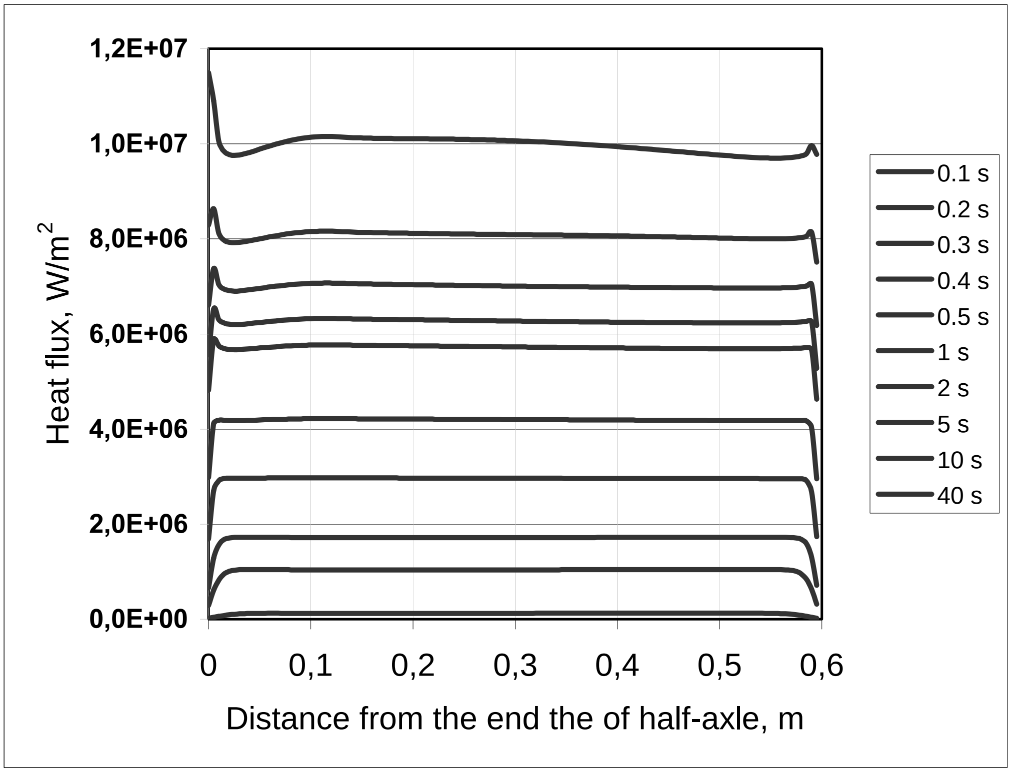

Fig. 5. Heat flux of the half-axle at various times

The calculation has shown that the critical heat flux is 13.7 MW/m^2, which is greater than the maximum heat flux, therefore, there is no film boiling. There is neither film boiling, nor nucleate one. The criterion of the absence of nucleate boiling is presented in Ref. [4] and as follows:

$$Bi \ge \frac{2(\vartheta_0 - \vartheta_I)}{\vartheta_I + \vartheta_{uh}}$$

where $\vartheta_I = \frac{1}{\beta}\left[\frac{2\lambda(\vartheta_0 - \vartheta_I)}{R}\right]^{0.3}$, $\vartheta_0 = T_0 - T_S$,

$\beta = 7.36$, R is radius.

In this case, to avoid nucleate boiling, Bi must be not less than 16.7. Number Bi=16.7 is reached at the flow rate of about 5 m/s [1]. Thus, at the flow rate of 8 m/s there is neither film boiling nor nucleate boiling, and the prevailing process is the one-phase convection.

The convection heat transfer coefficient versus the distance from the end is presented in Fig. 6. The results of calculation of surface temperature agree well with the experiment (see Fig. 7).

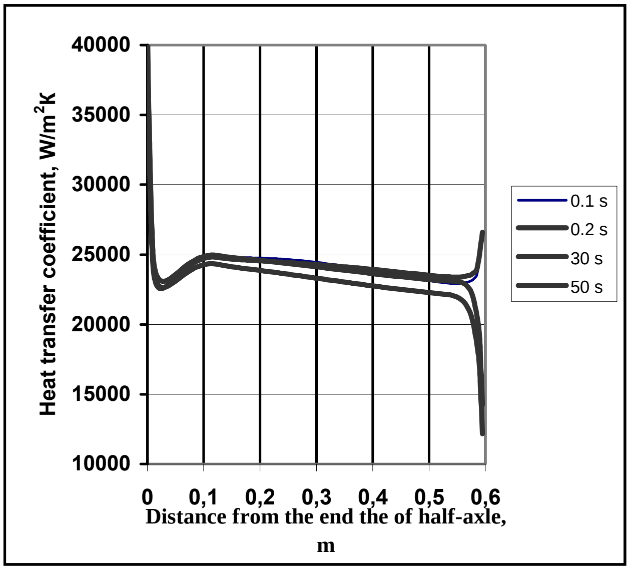

Fig. 6. Heat transfer coefficient vs.distance from the end at various times.

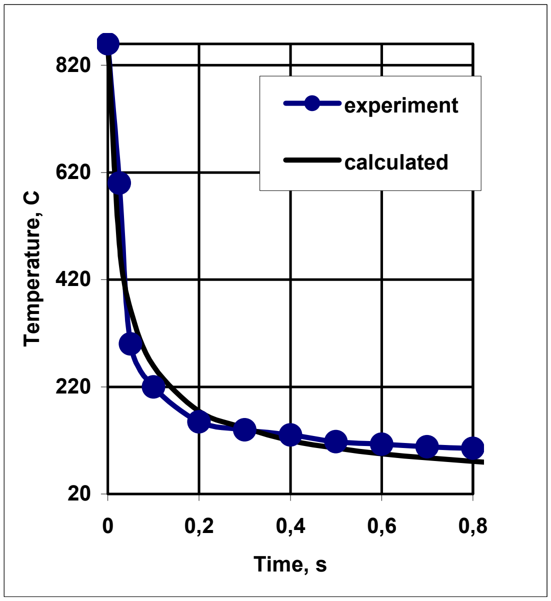

Fig. 7. Cylinder surface temperature as a function of time time

Fig. 8 presents the character of temperature field distribution at the end part of the cylinder at 1 s.

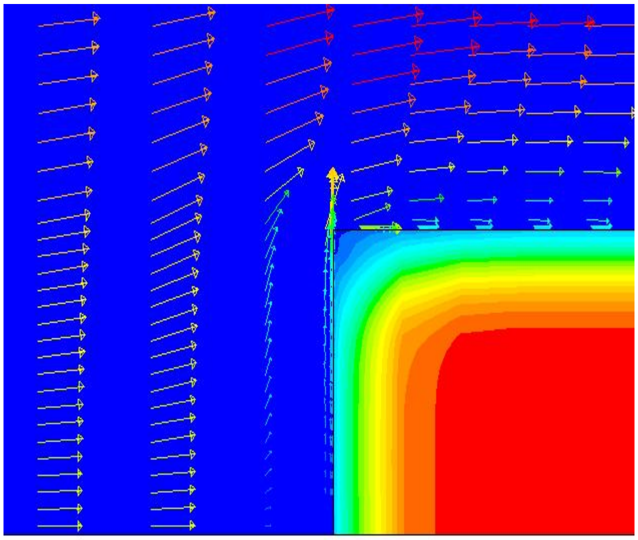

Fig. 8 Temperature field distribution at the end of the cylinder and the fluid at 1 s.

Thus, the calculations have shown that the heat flux can be below the critical value. At high water flow rate the boundary water layer does not boil up.

4 Discussion of results

At the present there is no reliable data on the intensity of heat transfer at the time of immersing a body heated up to high temperature into a fluid. The characteristic of this initial time period is that the fluid is not heated up to the boiling temperature (it is cold), and the metal is heated to temperature of 800-1000°C. When immersing a heated part into a cold quenchant, at first the boundary fluid layer is heated up to the boiling temperature, that is, the boundary boiling layer is formed. At the same time, the metal surface temperature is reduced. When the process of the boundary boiling layer formation is finished, the initial maximum value of heat flux is reached, which gradually reduces. If this maximum heat flux is greater than the first critical heat flux, the film boiling will be observed. If less, there will be no film boiling. If the maximum heat flux is comparable with the first critical heat flux, the transition boiling is observed, that is, the formation of local vapor films. Thus, on the basis of solving heat transfer problems, one can forecast the thermal processes occuring during quenching.

For engineers to easily calculate thermal processes, it is necessary to create databases: on critical heat flux densities and maximum heat flux densities for various shapes and sizes of parts, for various quenchants and quenching conditions.

To check the reliability of this approach, convection heat transfer coefficients and part's surface temperature have been calculated. The comparison has shown that the results of these calculations agree well with the criterion methods and results of experiments.

The advantage of solving conjugate problems is that we have the view of heat transfer distribution at all the surface, which cannot be obtained through the use of criterion methods.

The further development of these methods with regard to phase transformations in both fluids and solids is promising since it will allow to accurately calculate the thermal stress-strain state without setting heat transfer coefficients, which are not always available, for example, in case of bodies of complex configuration or complex conditions of heat transfer.

Even in case of simple setting of a conjugate heat transfer problem, it can be efficiently used for the calculation of thermal stress state for patented IQ-3 quenching method, in which there is no boiling from the very beginning and the prevailing process is one-phase convection.

When implementing intensive steel quenching methods, through solving conjugate problems one can correct boundary conditions by changing heat fluxes so that reach the uniformity of cooling, which will increase the strength and service life of parts quenched.

5 Conclusions

1. On the basis of solving conjugate problems one can determine initial maximum heat flux densities reached at the time of the formation of boundary boiling layer. Comparing calculated heat flux with the critical heat flux for a specific quenching medium, one can forecast the presence or absence of the full film boiling.
2. It is expedient to create a database on the basis of this approach for various shapes and sizes of parts, and also initial temperature of heating, for various kinds of quenchants.
3. Here the criterion of the absence of nucleate boiling is presented for quenching in intensive water streams and it has been shown that in this case the prevailing process is one-phase convection.
4. On the basis of solving conjugate problems, one can calculate convection heat transfer coefficients. The results of the conjugate problem agree well with criterion equations.
5. The solution of a conjugate problem allows to analyze the heat transfer distribution at all the surface of the part being cooled. Thus, in the forepart of the half-axle high heat transfer coefficients are observed, in the back, low ones.
6. The results of surface temperature calculation on the basis of the conjugate problem agree well with the results of experiments.
7. This method of heat transfer analysis is quite promising, it should be further developed with regard to phase transformations in both fluid and solid bodies. Without this approach it is impossible to efficiently use the potentialities of computers ans software.

References:

1. N.I.Kobasko, Steel quenching in liquid media under pressure, Kyiv, Naukova dumka, 1980, 206 p.
2. N.I.Kobasko. Intensive Steel Quenching Methods. In book: Theory and Technology of Quenching, B.Liscic, H.M.Tensi, W.Luty, Springer-Verlag, New York, 1992, 484 p
3. N.I.Kobasko, W.S.Morhuniuk, V.V.Dobrivecher, Control of Residual Stress Formation and Steel Deformation during Rapid Heating and Cooling In a “Handbook of Residual Stresses and Deformation of Steel” (J. Totten, M. Howes, T. Inoue (Eds)), ASM International, 2002, 499 p
4. N.I.Kobasko, US Patent # 6364974B1
5. N.I.Kobasko, Ukraine Patent # 4448
6. N.I.Kobasko, Ukraine Patent #56189
7. Software “TANDEM” for calculation of thermal and stress-strain state.
8. M.A.Aronov, N.I.Kobasko, J.A.Powell, D.V.Lipnicki, Peculiarity of Intensive Quenching Equipment, Proceeding of the 13th International Federation for Heat Treatment and Surface Engineering Congress, Columbus, Ohio, (2002)