24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-2579
QUENCHING HEAT TRANSFER PROCESS DURING NUCLEATE BOILING PHASE BY CFD MODELING

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Abstract. *Vapor film, nucleate boiling and convective phase are the cooling stages during quenching heat treatment process. This is a work based on simulation of first cooling stage of a carbon steel quenched in water. Knowing heat transfer behavior during hardening steel process is fundamental to understand metallurgical transformation. Computer fluid dynamics (CFD) is a tool based on applied mathematics and fluid mechanics that permits to simulate complex thermal fluid phenomena. The heat transfer of the quenchant during transition and nucleation cooling phases was simulated using StarCCM+, a CFD software. Using a transition model, this paper presents the simulation of temperature, volume of vapor phase and heat transfer coefficients around the steel sample during the first quenching stage.*

Keywords: *quenching, CFD, nucleate boiling*

1. INTRODUCTION

Quenching is a heat treatment that consists in fast cooling steel after austenitization. The cooling rate must be high enough to avoid metallurgical diffusion process and obtain the metastable microstructure called martensite. Martensite will provide the resistance required to steel be employed in most of engineering services.

The most widely industrial quenching process consists in immerse the steel part in a liquid medium, such as water or oil (Škerget, 2014). Once the austenitization temperature is over 850°C in the instant of hot metal immersion on liquid, so it always overcomes the saturation temperature of the quenchant. This is the first cooling stage, also called vapor blanket. The vapor acts as an insulator around the part. If this stage is long, material can suffer perlitic transformation, which is very undesirable. Mechanical agitation of the fluid could reduce vapor lifetime. The highest cooling rates happens during nucleate boiling, and it must be fast enough to prevent perlitic transformation. During the third stage (convective) is when martensitic transformation occurs. Understand the cooling profile that occurs during quenching is a hard task; once it is a complex process and it depends on part geometry, type of agitation and quenchant (Banka, et al., 2008). Tank fluid-dynamics conditions cause uneven cooling and it results in different microstructures in the same part and distortion (Banka, 2005).

Kobayashi, *el al.*, 2016, reports that the minimum heat flux occurs between film boiling and transient boiling, and critical heat flux happens between transient and nucleate boiling. The last one is when highest cooling rates occurs, what allows controlling the final microstructure.

Boiling process is influenced by surface part and quenchant temperature, as well by thermo-physical properties of steel, surface finishing, fluid temperature and the presence and quality of mechanical flow agitation (Kobayashi, *el al.*, 2016). As fluid and steel properties changes during whole process, controlling immersion quenching becomes a hard task.

This work uses a multiphysics model to simulate the formation and detachment of bubbles on metallic part during quenching. Multiphysics models provides better results when analyzing the effect of vaporization is necessary. Metallic part is a medium carbon steel, quenchant is water and the tank has industrial scale.

2. COMPUTATIONAL PROCEDURE

Cooling stages that occurs during liquid immersion quenching are transition, complete nucleation, nucleation, partial nucleation and natural convention (Kobasko, 2010). In this work, a transition model was used because it can solve both transition and nucleation equations. Nucleation transition model occurs when the wall temperature presents a value between the minimum attainable by vapor blanket stage and the maximum attainable by nucleation stage (Ellion, 1954). Figure 1 illustrates heat exchange process during boiling.

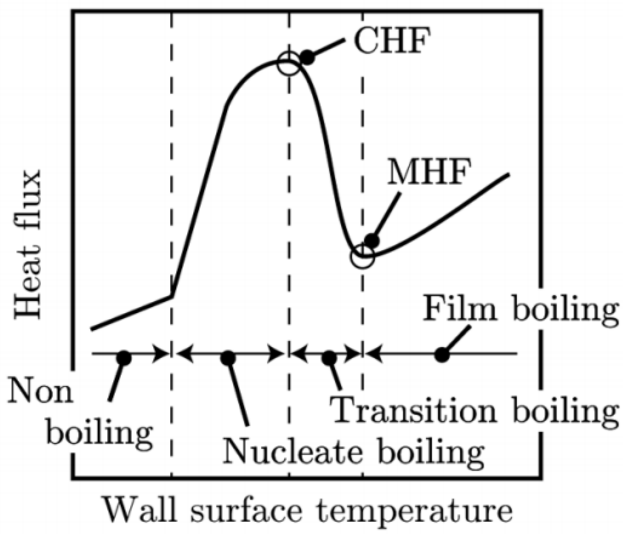

Figure 1. Boiling phenomenon (Kobayashi, *el al.*, 2016)

Boiling transition model is highly empirical and requires some adjustments to achieve accurate results. Such adjustments should be in accordance with actual data of the proposed problem, considering the geometry, properties of the material, temperature of quenchant and agitation level. Equation 1 gives an empirical correlation (Rohsenow, 1951) that calculates the heat flux due nucleation:

$$q_{bw} = \mu_l h_{lat} \sqrt{\frac{g(\rho_l - \rho_v)}{\sigma}} \left(\frac{C_{p1}(T_w - T_{sat})}{C_{qw} h_{lat} Pr_l^{n_p}} \right)^{3.03} \tag{1}$$

where μ_1, C_{p1}, ρ_1 and Pr are dynamic viscosity, specific heat, density and Prandtl number of liquid phase. Prandtl exponent, n_p, is equal 1.7. In addition, g is gravity acceleration, ρ_v is vapor density, σ is surface stress on vapor-liquid interface, T_w, wall temperature and C_{qw} is an empirical coefficient that is function of surface and liquid. In this work, C_{qw}=0,013 (Saiz-Jabardo, et al, 2004). If T_1 is the temperature that fluid changes from boiling to boiling transition and T_2 is the temperature when transition model ends, constants K_1 and K_2 are attained by Eq. 2-4:

$$q_{boiling}(\Delta T) = q_{\max} S \phi \left(\frac{\Delta T}{\Delta T_1} \right)^{K_1} \qquad 0 \le \Delta T \le \Delta T_1 \tag{2}$$

$$q_{boiling}(\Delta T) = q_{\max} S \left[1 - 4(1-\phi) \left(\frac{\Delta T - \Delta T_{\max}}{\Delta T_2 - \Delta T_1} \right)^2 \right] \qquad \Delta T_1 \le \Delta T \le \Delta T_2 \tag{3}$$

$$q_{boiling}(\Delta T) = q_{\max} S \phi \left(\frac{\Delta T - \Delta T_1}{\Delta T_2 - \Delta T_1} \right)^{-K_2} \qquad \Delta T_2 \le \Delta T \tag{4}$$

Transition is a model of phase interaction of Star CCM+. It transfers the mass of liquid phase for the vapor phase. Mass transference promotes energy transference from metal to fluid that can became vapor or remain liquid depending on temperature difference. The model relates heat flux during nucleate stage with the excess of temperature. The excess of temperature (ΔT) is the difference of the solid wall temperature (T) and the fluid saturation temperature (TS). If a heat quantity of heat goes from the solid to fluid, it can change its phase from liquid to vapor or contrariwise (Dhir, 1991). The energy ceded for the fluid by conduction or for the vapor depends of the process. (Ricci, et al., 2011)

Modeling requires the definition of the some parameters (Sanchez-Espinoza, et al., 2000): temperature when the model change to nucleation to transition boiling; maximum heat quantity; constants for nucleation boiling and transition; Schimdt number and the fraction of heat quantity in the wall to create the bubbles.

The problem that is object of study in this work consist in quenching a block of a medium carbon steel, with dimension of 2,5 x 1,0 x 0,8 m, in a tank full of water at 40 °C. Improving heat transfer is necessary; injector nozzles was included near the block and at the both lateral sides of the tank. Heat transfer coefficient and temperature of fluid and part are required to evaluate the process.

Tank's walls and bottom were defined as 40 °C, and surface was defined as no slip. Both are considered adiabatic. Fluid velocity was of 5 m/s in each injector nozzle, and temperature was set at 40 °C also. At outlet, pressure was zero Pa, because outlet velocity is unknown. Implemented model was K-ε turbulence. Second Davis, *et al.*, 2012, K-ε turbulence model is based on turbulent core flows, capable to capture near-wall turbulence effects. This model is a semi-empiric; based on equation of turbulent kinetic energy (K) and dissipation rate (ε).

Water physical properties was set as constant at 40 °C, and physical properties of steel as set as function of temperature. Steel part initial temperature was 900 °C. Vapor and water temperature varies according a polynomial function of software.

Polyhedral mesh was generated by Star CCM+ software. Mesh base size was set as 0.12 m with minimum relative size of 25 %. Prismatic cells improves the accuracy of turbulent problems. At outlet, an extrusion mesh with prismatic elements prevents reverse flow. As the principal interest is at interface of fluid/solid, mesh was refined at these regions in 50 % for the block and 95 % for agitation system. Perpendicular vectors between the centroids of two neighbors faces did not exceed 85 °, this was the quality criterion adopted. Final mesh had the following configuration: tank 2923026 cells, extrusion at outlet 1965 cells and solid domain 960 cells.

Convergence criteria was normalized root mean square error (RMS) of 10^{-3}.

3. RESULTS ANS DISCUSSION

Figure 1 shows the evolution of temperature on part surface. Fluid temperature at part surface variation is very low during transition and boiling stages. At each instant during the duration the first stage cooling process, maximum temperature variation is about 25%. Temperature variation during transition and nucleation is very low. Li, *et al.*, 2015, emphasizes that thermal properties and consequently metallurgical phase transformation are affect by temperature during quenching.

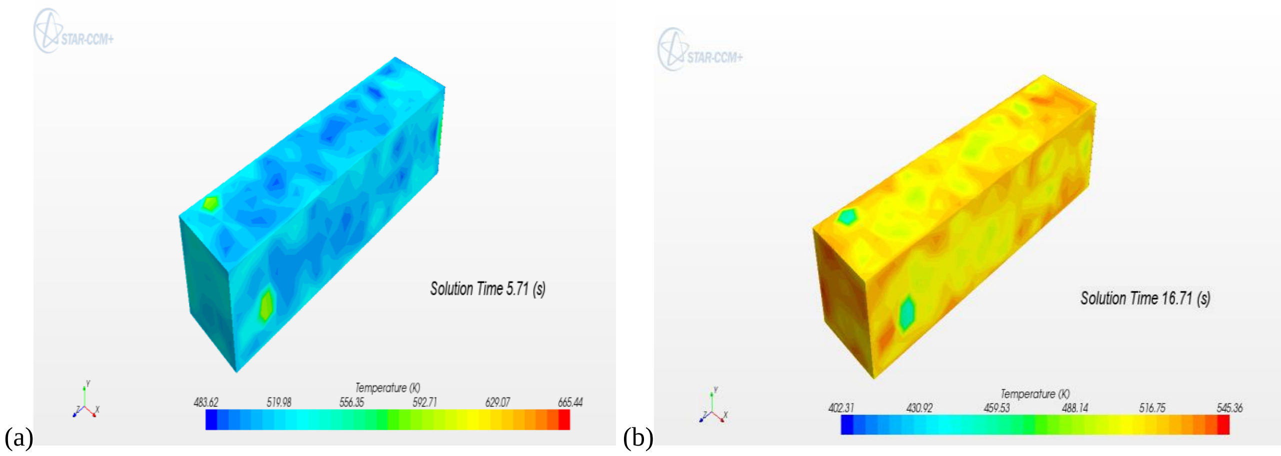

Figure 1. Surface temperature at (a) 5.71 s and (b) 16.71 s.

Figure 2 shows the vapor dispersion near the part at 5 s. It remains constant during first cooling stage. The agitation system certainly contributes to control the film blanket magnitude.

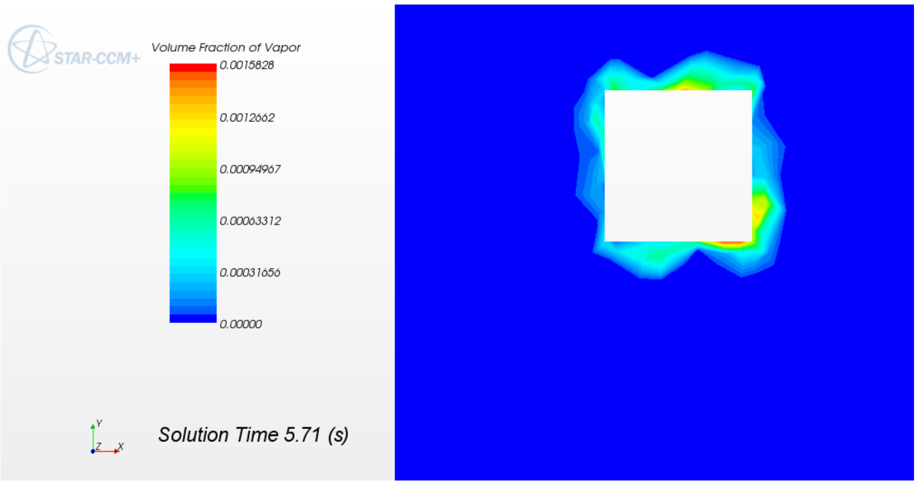

Figure 2: Vapor film near the part at 5 s.

Figure 3 shows the magnitude of heat transfer coefficients on interface of fluid and solid. These data are certainly the most important for modeling any steel quenching process. The magnitude of heat transfer coefficients increases as time goes by, and cooling process goes to boiling mechanism. Stablishing a process to reduce thermal gradients is the great deal of heat treaters. Controlling heat transfer coefficients could result in a reduction of distortion and residual stresses.

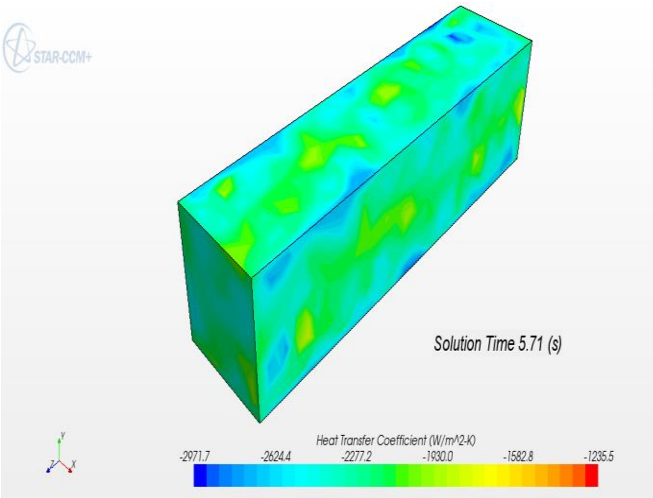

Figure 3: Heat transfer coefficients calculated at 5.71 s.

4. CONCLUSIONS

This work presented a computational study of heat transfer during quenching heat treatment. The volume of vapor produced and heat transfer coefficients were obtained. Although results were not compared with experimental data, they are in accordance with the theory. Results encourage futures works considering solid phase transformation and experimental works

5. ACKNOWLEDGEMENTS

This work was supported by FAPESP process 2010/12797-2. Authors are also grateful by FAPEMIG support.

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