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DEVELOPMENT OF A HEAT TRANSFER MODEL FOR QUENCHING BY SUBMERGING

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Abstract. In quenching by submerging the piece is cooled due to vaporization, convective flow and interaction of both mechanisms. The dynamic of these phenomena is very complex and the corresponding heat fluxes that appear are strongly dependent on variables such as velocity of fluid and vapor fraction. This local dependence may produce very different cooling rates along the piece, responsible for inappropriate metallurgical transformations, variability of material properties and residual stresses.

In order to obtain an accurate description of cooling during quenching, a mathematical model of heat transfer was developed. The model is based on the mixture-model for multiphase flows, including an equation of conservation of energy for the liquid phase and specific boundary conditions that account for evaporation and presence of vapor phase on the surface.

The model was implemented on *Comsol Multiphysics* software. Generation of appropriate initial and boundary conditions, as well as numerical resolution details, is briefly discussed.

To test the model, simple flow conditions were analyzed. The effect of vapor fraction on heat transfer is assessed. The presence of the typical vapor blanket and its collapse can be recovered by the model, and their effect on the cooling rates of different parts of the piece is analyzed. Comparisons between numerical results and data from literature are made.

1 INTRODUCTION

Quenching is a technological process that involves the cooling of a heated piece in order to modify its properties. Depending on the material the piece, the cooling needs to be very fast or can be mild. In particular, for low to medium alloy steels the cooling rates should be as fast as possible.

Focusing on steels, quenching produces metallurgical transformations that are responsible for modifications in mechanical properties (hardness, yield and ultimate stresses, toughness) This feature allows us to tailor the steel properties in a broad range that is not easy to replicate in common engineering materials.

In addition to metallurgical transformations that lead to mechanical modifications, geometrical distortions and generation of residual stresses can be developed during the process. In order to get a successful quenching, the final metallurgical phases and mechanical properties should be the desired ones and distortions and residual stresses should be at minimum.

As any other process of interest, several efforts were made in order to describe it through mathematical models. In this area it is important to remark that quenching of steels can be divided in at least three sub-problems. One mayor problem is the modeling of metallurgical transformations. This part it is well known and the available models are robust and reliable (Porter and Easterling, 1992). On another side it is the mechanical description of generation of residual stresses and geometrical distortions. This complex area is also well covered, although new refined models can be found in specialized literature. Finally, these to previously mentioned models strongly rely on an accurate description of the temperature evolution inside the piece. Several attempts to put together a thorough description on quenching process can be found in literature, i.e. (Denis et al., 1992; Song et al., 2004; Kang and Im, 2007; Simsir and Gür, 2008; Sugianto et al., 2009). These, and others, works are based on one approach similar to the one here described and each sub-problem is solved using the most adequate model. But, all the complexity and accurateness of each model is lost if the thermal problem is over simplified. In particular, the boundary conditions imposed to the thermal problem usually are so basic that only very simple problems (rods, disks, etc.) were accurately described. In this work this problem is tackled.

In quenching by immersion the piece transfers heat to the quenching media through vaporization of the fluid, convective flow and interaction of both mechanisms. Generalities about subcooled boiling stages can be found in (Tensi et al., 1994; Dhir, 1998; Incropera et al., 2007). The description of this phenomenon has to take into account the dynamic of a multiphase vapor-liquid flow and specific heat transfer contributions due to vaporization. The problem of multiphase flows with heat exchange is described in general terms in works such as (Clift et al., 1978; Crowe et al., 1998; Ishii and Hibiki, 2006). Based on these models and including the heat partition model for boiling, a heat transfer model for quenching by submerging here is developed. The model includes the presence of vapor phase and how it affects the heat transfer from the piece to the quenching media.

2 MODEL

The analysis of multiphase flows it was based on the methodology presented in (Clift et al., 1978; Crowe et al., 1998; Ishii and Hibiki, 2006), where before the definition of the particular multiphase model it is necessary to analyze coupling parameters between the phases, characteristic times and finally characteristic non-dimensional numbers of the specific problem.

For our particular problem (described below) the main conclusions that were drawn are:

- Both phases (liquid and vapor) are in mechanical equilibrium, therefore the velocities of each phase are strongly correlated
- The heat delivered from vapor to liquid corresponds mainly to latent heat of condensation, because of this reason the vapor temperature can be assumed constant at saturation value
- Both phases are strongly coupled through exchanges of mass and energy due to phase change

Based on these conclusions, the most convenient multiphase model is the mixture-model. Due to the constant vapor temperature assumption, only the conservation of energy of the liquid phase has to be described. The system of partial differential equations (PDE's) that describe this problem is presented in Eqs. (1 - 4). Subindexes m, v and l correspond to mixture flow, vapor and liquid respectively. The fraction of each phase is represented by α and the $=$ and $\widehat{}$ symbols correspond to phase average and density weighted average respectively.

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\boldsymbol{v}_m \rho_m) = 0 \tag{1}$$

$$\frac{\partial \alpha_v \overline{\overline{\rho_v}}}{\partial t} + \nabla \cdot \left(\alpha_v \overline{\overline{\rho_v}} \boldsymbol{v}_m\right) = \Gamma_v - \nabla \cdot \left(\alpha_v \frac{\overline{\overline{\rho_l}}\,\overline{\overline{\rho_v}}}{\rho_m} \boldsymbol{V}_{vj}\right) \tag{2}$$

$$\begin{aligned} \frac{\partial \rho_m \boldsymbol{v}_m}{\partial t} + \nabla \cdot (\rho_m \boldsymbol{v}_m \boldsymbol{v}_m) = -\nabla p_m + \nabla \cdot \left(\overline{\mathbb{T}} + \mathbb{T}^T\right) + \rho_m \boldsymbol{g} \\ -\nabla \cdot \left(\frac{\alpha_v}{1-\alpha_v} \frac{\overline{\overline{\rho_l}}\,\overline{\overline{\rho_v}}}{\rho_m} \boldsymbol{V}_{vj} \boldsymbol{V}_{vj}\right) \end{aligned} \tag{3}$$

$$\frac{\partial \alpha_l \overline{\overline{\rho_l}}\,\widehat{h}_l}{\partial t} + \nabla \cdot (\alpha_l \overline{\overline{\rho_l}}\,\widehat{h}_l \widehat{\boldsymbol{v}}_l) = -\nabla \cdot \alpha_l \left(\overline{\overline{\boldsymbol{q}}}_l + \boldsymbol{q}_l^T\right) - \Gamma_v \left(h_{sat} - \widehat{h}_l\right) \tag{4}$$

This model needs the description of the drift velocity (V_{vj}) and the mass transfer (Γ_v) between the phases. The selected expression for V_{vj} is presented in Eq. (5)

$$V_{vj} = \sqrt{2}\left(\frac{\sigma g \Delta\rho}{\rho_l^2}\right)^{1/4} (1-\alpha_v)^{1.75} \tag{5}$$

The rest of the closure relationships in order to get a well posed problem were taken from (Kocamustafaogullari and Ishii, 1995; Tu and Yeoh, 2002; Yeoh and Tu, 2004; Koncar et al., 2004; Ishii and Hibiki, 2006; Krepper et al., 2007; Koncar and Mavko, 2008; Kocar and Sökmen, 2009; Li et al., 2009; Koncar and Tiselj, 2010). In addition, the $k - \epsilon$ turbulence model (taking into account the presence of disperse vapor) was used to describe the Reynolds stress tensor.

The heat transfer extracted during boiling was described according the heat partition model (Tu and Yeoh, 2002; Yeoh and Tu, 2004; Koncar et al., 2004; Koncar and Mavko, 2008; Kocar and Sökmen, 2009; Koncar and Tiselj, 2010), where the total heat flux on the solid wall is the addition of three different mechanisms, as it is presented in Eq. (6), q_{1f} corresponds to the heat flux devoted to heat the fluid, while the others represent boiling.

$$q_w = q_{1f} + q_e + q_q \tag{6}$$

3 CASE STUDIED

The case of a sphere in an upward fluid flow was used to test the model here developed. The upward flow intends to represent the immersion condition. The flow velocity was set at 1 m/s, based on characteristic flow velocities obtained during the specific analysis of the model.

3.1 Materials and geometry

The fluid was quenching oil, whose properties were obtained from (HoughtonIbérica, 2008), and the material of the sphere was Inconel 600. This alloy was selected in order to make experimental results form (HoughtonIbérica, 2008) and numerical simulations comparable. Summary of oil, its vapor and Inconel properties is presented in Table 1.

The initial temperatures of fluid and piece were 313 and 1050 K respectively.

	Liquid		Vapor	Solid
ρ $[kg/m^3]$	870		2	8470
μ $[kg/(m.s)]$	9.40×10^{-2}	(293 K)	2.3×10^{-5}	–
	2.35×10^{-2}	(313 K)	–	–
	4.35×10^{-3}	(373 K)	–	–
	1.00×10^{-4}	(490 K)	–	–
k $[W/(m.K)]$	0.14		0.014	14.9
c_p $[J/(kg.K)]$	1800	(290 K)	3000	444
	2300	(420 K)	–	–
σ $[N/m]$	3×10^{-2}		–	–
h_{lv} $[J/kg]$	–		10^6	–
D_b $[m]$	10^{-3}		–	–

Table 1: Material properties

The domain was described on the $r-z$ plane taking axial symmetry along the z-axis. A sketch of the domain, showing the spherical piece and the surrounding fluid is presented in Fig. 1. The sphere had 30 mm of diameter and the flow domain was a 200 mm long and 200 mm diameter cylinder. The sphere was situated in the centerline, at 60 mm from the bottom. The fluid domain extends in the back of the piece in order to allow an appropriate development of the wake.

3.2 Resolution using *Comsol*

The PDE system presented in Eqs. (1 - 4) can be assimilated to a regular fluid mechanics problem, with some extra sources, plus two additional conservation equations, one for the dispersed phase and another for the liquid phase energy.

Comsol Multiphysics allows the resolution of multiphase flows, including the mixture-model, and general diffusion-convection heat transfer problems. Based on these features, the corresponding application modes were used to solve the problem here presented. In addition, the cooling of the sphere was solved using an extra heat transfer application mode for the solid temperature. The translation of the model to the Comsol application modes was rather straightforward. For the mixture model, the extra terms due to the drift velocity are already incorporated in the model. The mass transfer and the drift velocity were user-defined according the development of the model. The only mayor modification was made to the internal definition of the

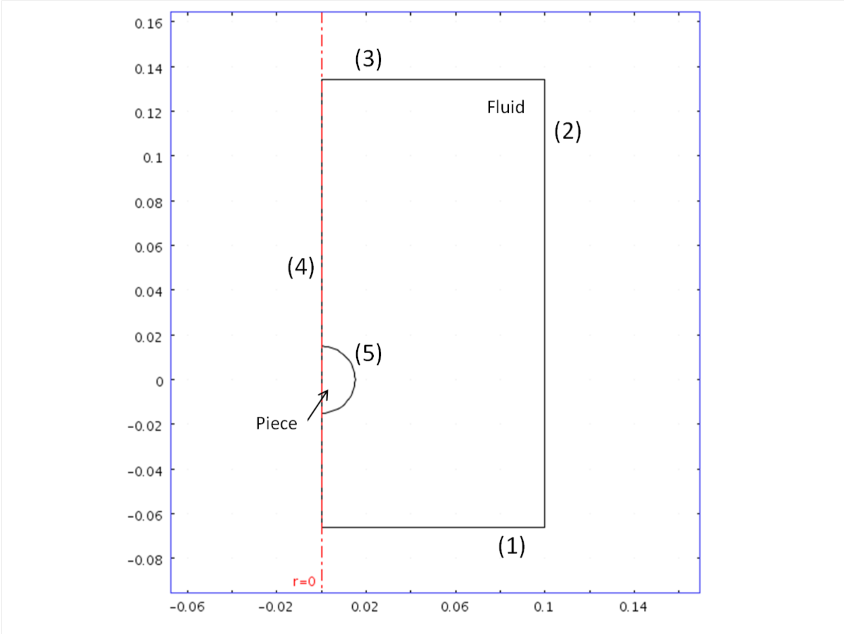

Figure 1: Analyzed domain

turbulent viscosity, where the effect of second phases was included according to (Ishii and Hibiki, 2006). For the conservation of energy on liquid phase, the extra terms due to vapor phase were included as user-defined sources.

The coupling between the temperature of the solid and the quenching flow equations was made through the heat fluxes extracted to the piece. The heat fluxes related to evaporation are responsible for the vapor generated, which in this case is considered injected through the surface of the solid to the quenching flow. This relationship is represented in Eq. (7).

$$q_e + q_q = \alpha_v \rho_v \mathbf{v}_v \cdot \mathbf{n}\, h_{lv} \tag{7}$$

The rest of the heat flux (q_{1f}) is taken to the thermal wall law.

The relationship presented in Eq. (7) is exact but do not capture the effect of thermal insulation that produces a vapor blanket surrounding the piece. In order to dump the vapor generation in the presence of a considerable vapor fraction on the piece, the following modification is proposed in Eq. (8).

$$\alpha_v \mathbf{v}_v \cdot \mathbf{n} = \frac{(q_e + q_q)}{\rho_v h_{lv}} \alpha_l^m \tag{8}$$

According to this, the vapor injection is stopped if there is no liquid available. Therefore, the heat extraction due to q_q and q_e is also stopped. This physical aspect of the boiling phenomena usually is not accounted for in the current models.

The dumping function presented in Eq. (8) is a very basic first proposal and further analysis of it is needed.

The resolution of the whole problem was made using the direct solver UMFPACK and the time integration was made along 10 seconds using an implicit scheme. The boundaries of the domain marked in Fig. 1 correspond to: (1) inlet of oil liquid at constant temperature, (2) sliding wall, (3) outlet, (4) symmetry axis, (5) dynamic and thermal wall laws and evaporation heat transfer model.

4 RESULTS

4.1 Vapor blanket and temperature fields

The evolution of vapor around the sphere and the temperature field of it is presented through snapshots at three different times. In Fig. 2 the early stages of the cooling are presented. Most of the surface of the piece is densely covered by vapor. In Fig. 3 the partial collapse of the vapor blanket and its thermal insulation effect is observed. In Fig. 4 the last stages of presence of vapor is depicted. Except for the little region in the wake that is still boiling, the temperature looks radially distributed.

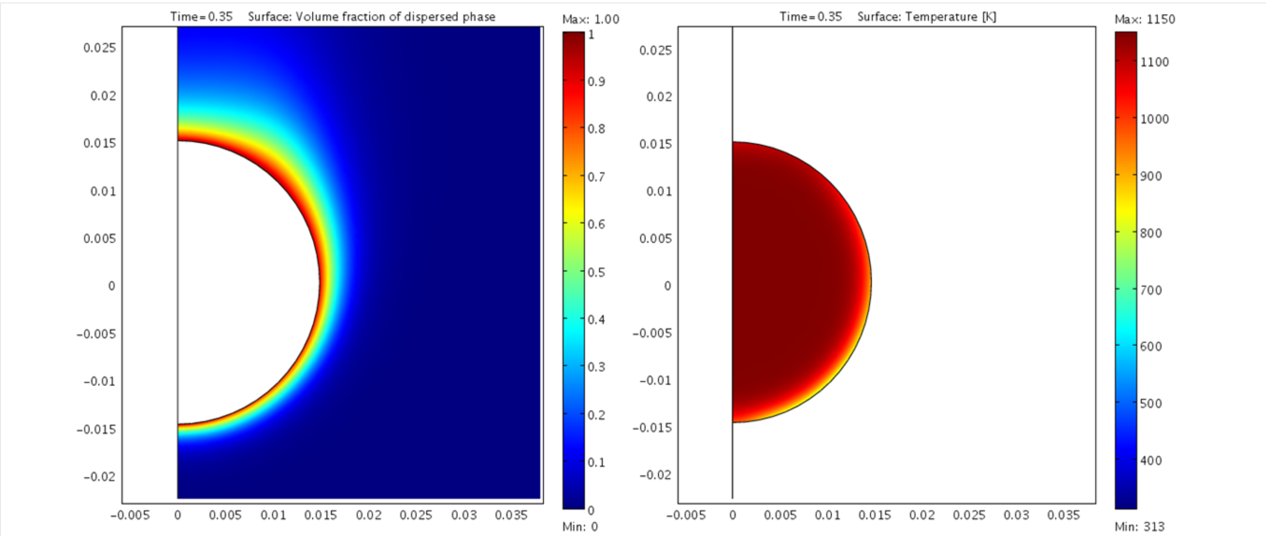

Figure 2: Vapor blanket and piece temperature at t=0.35 seg.

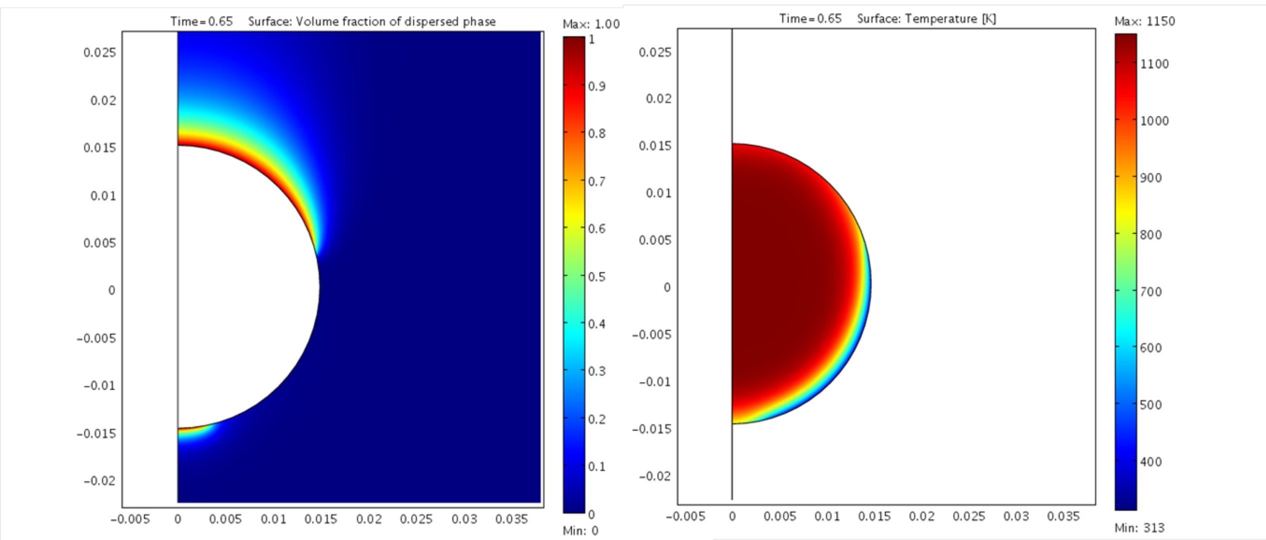

Figure 3: Vapor blanket and piece temperature at t=0.65 seg.

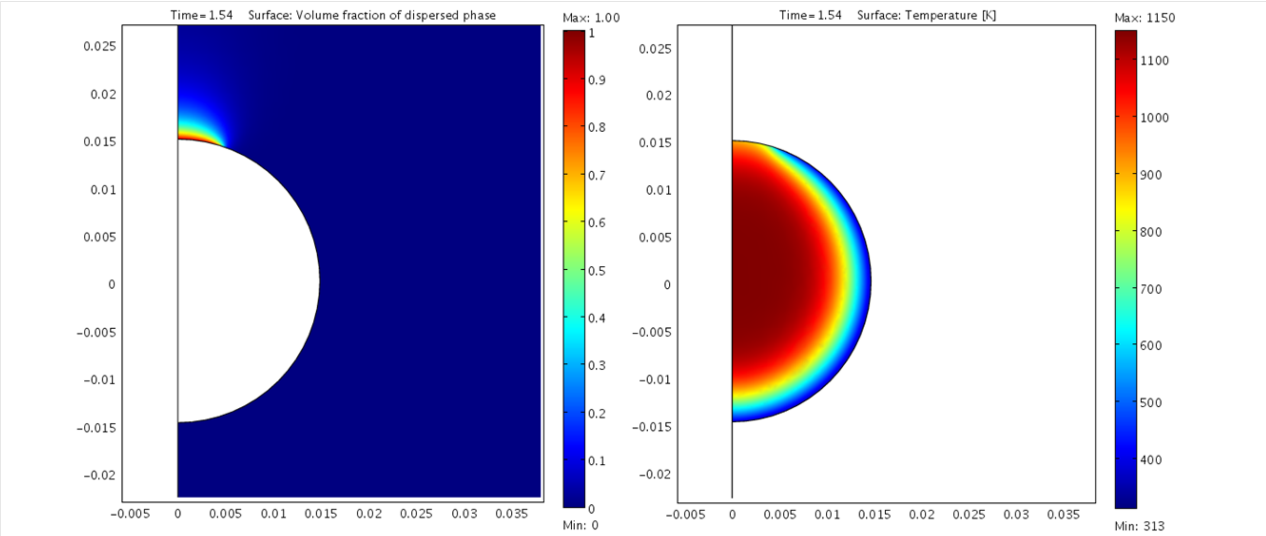

Figure 4: Vapor blanket and piece temperature at t=1.54 seg.

4.2 Cooling curves and heat transfer coefficient

In order to assess the local effect of the heat transfer model four different points of the sphere were analyzed. They are located: one at the center of the sphere (*center*); and three at 1 mm below the surface, two along the symmetry axis (*upper* and *lower*), and one in the center plane (*lateral*).

The evolution of the temperature at each point is presented in Fig. 5. There it is observed that lower and lateral zones had similar evolutions, while the upper point is clearly delayed. This difference is even more evident when the cooling velocities curves (T vs. dT/dt) are considered, as it is presented in Fig. 6. These results highlight the effect of vapor as thermal insulator and how locally affect the heat transfer along the surface of the piece. The temporal and spatial variation of the heat transfer coefficient (h) is depicted in Fig. 7, where the lower part of the circumference is the left side of the axis. This behavior is unlikely that can be captured by the typical correlations of h depending on mean parameters of the problem.

Finally, results for the center point are compared to data extracted from (HoughtonIbérica, 2008). Both geometries are different in shape but with similar volumes and oil and alloy properties are fairly the same. This allowed us just to compare the order of magnitude of the numerical results. In Figs. 8 and 9 the evolution of temperatures and cooling velocities curves are presented. The shapes of the curves are not exactly the same, but the matching of the order of magnitude obtained for both curves is highly satisfactory.

5 CONCLUSIONS

Heat transfer during quenching should be described including boiling phenomena; this should be done through an appropriate multiphase flow model and adequate heat fluxes that are exchanged with the treated piece. The reduction of the specific model from a general frame depends on characteristic values of the problem.

A model that couples vapor dynamics, energy conservation of the liquid phase and heat transferred from the quenched piece was presented. Our model is based on the mixture model for multiphase flows and the heat partition model for heat transfer. Vapor fraction evolution and heat fluxes are obtained as main results.

The effect of thermal insulation of the vapor phase is clearly pointed out. Local analysis

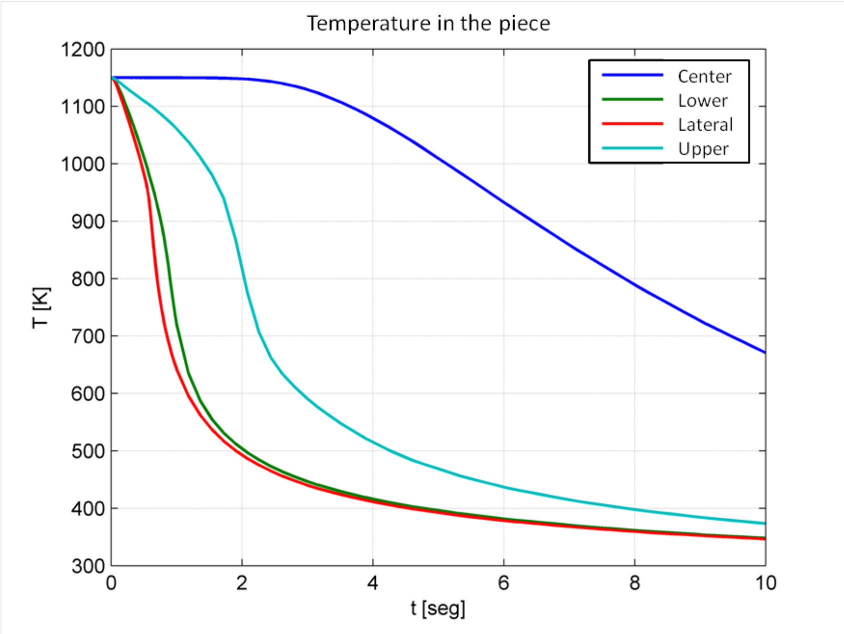

Figure 5: Temperature evolution in different zones of the piece

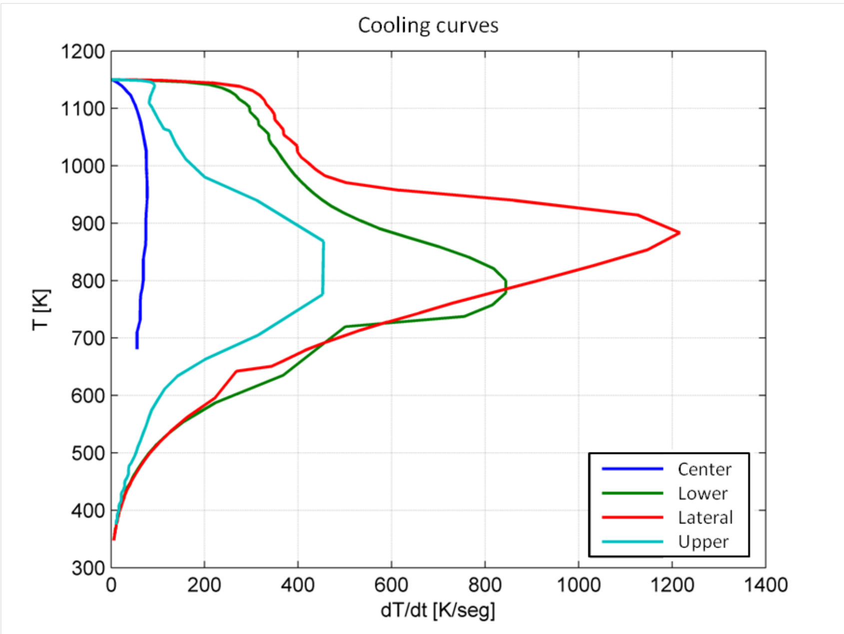

Figure 6: Cooling velocity in different zones of the piece

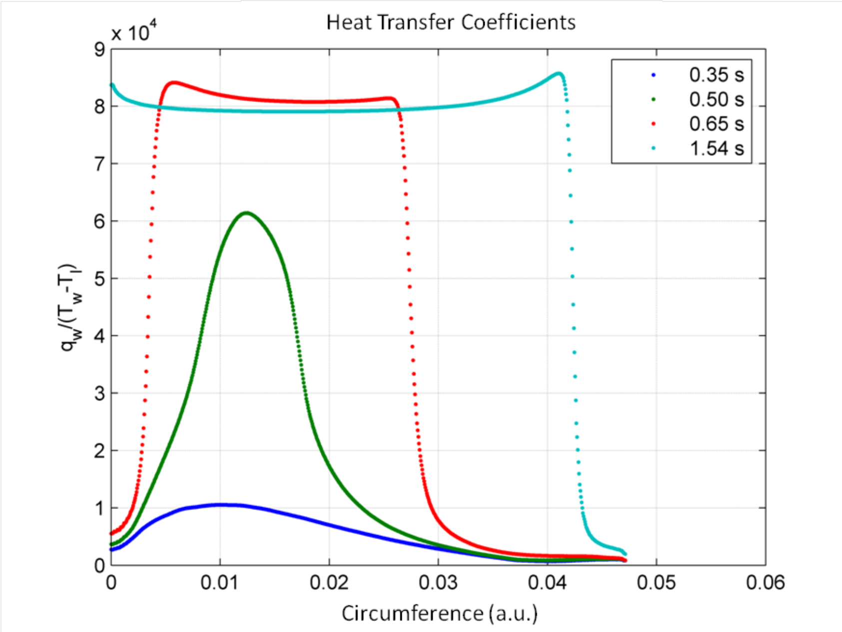

Figure 7: Variation of heat transfer coefficient

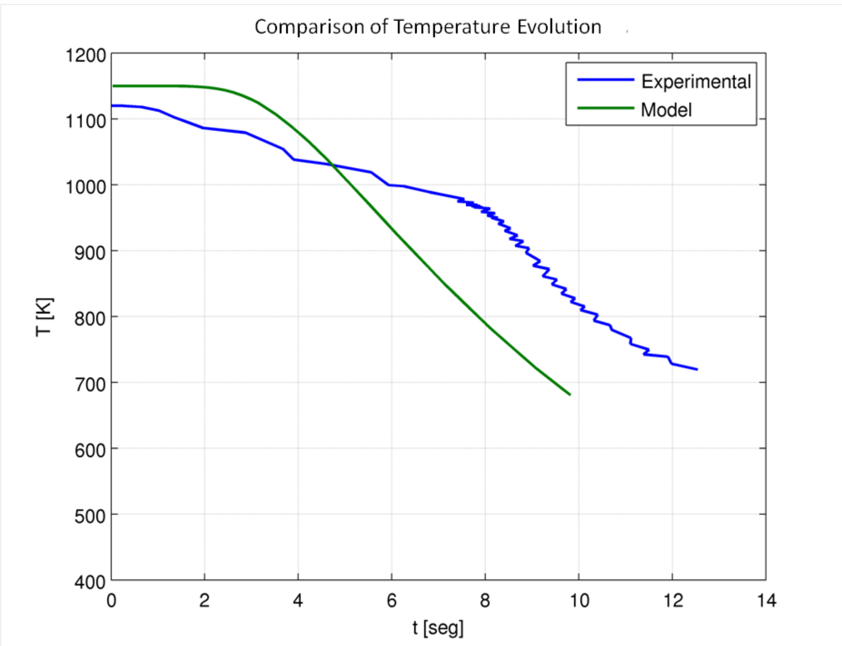

Figure 8: Comparison of temperature evolution

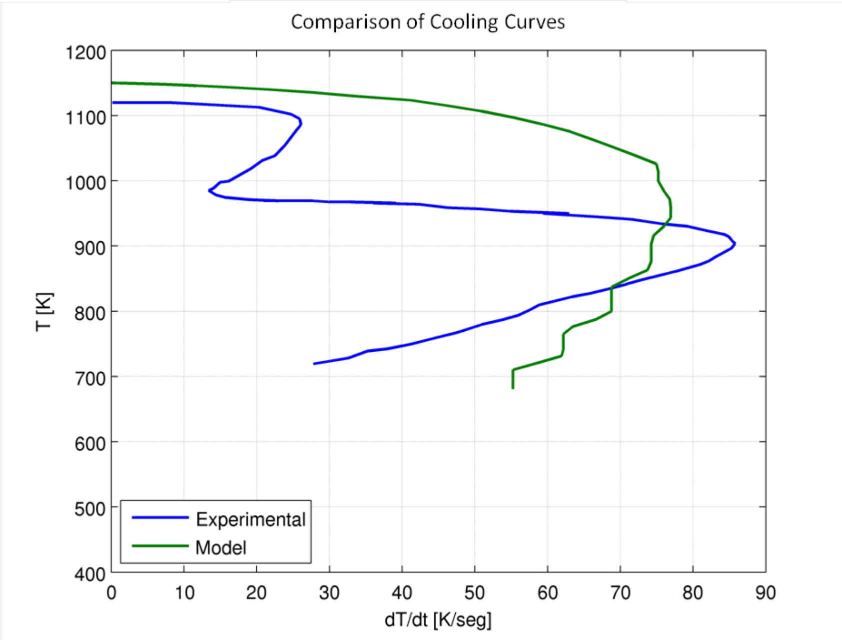

Figure 9: Comparison of cooling curves

shows that cooling velocities are strongly correlated to the presence of vapor, and the resulting heat transfer coefficients are quite complex to be described using regular heat transfer correlations.

The model adequately captures the order of magnitude of the physical problem. Further analyses on different conditions are needed in order to obtain a quantitative calibration of it.

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