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Numerical simulation of immersion quenching process for cast aluminium part at different pool temperatures

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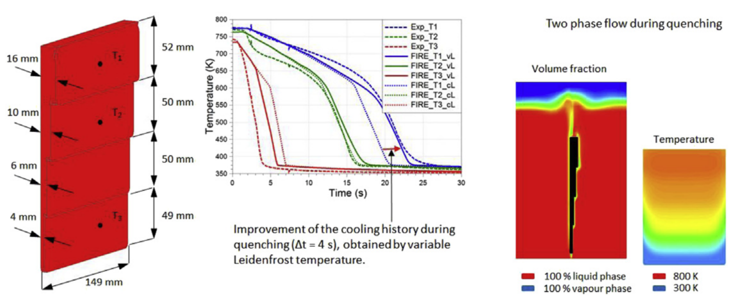
HIGHLIGHTS

- Euler-Eulerian multi-fluid modelling approach for immersion quenching was used.
- Quenching of aluminium alloy with various cooling media temperatures is presented.
- CFD model upgrade by considering interfacial forces and Leidenfrost temperature.
- Detailed comparison between numerical results and available measurement data.

GRAPHICAL ABSTRACT



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ABSTRACT

The present paper outlines the recently improved Computational Fluid Dynamics (CFD) model to simulate the immersion quench cooling process. The main application area of the presented method is heat treatment of cast aluminium parts, mostly cylinder heads in automotive internal combustion engines, where an accurate heat treatment prediction plays an important role in conceptual and thermal analysis. In order to achieve low residual stress levels resulting from even temperature distribution during the cooling process, and thereby to prevent component failure during operation, the numerical model of the quenching process, as developed within the commercial CFD code AVL FIRE®, was improved by allowing for variable Leidenfrost temperature. Preliminary results of variable Leidenfrost temperature model together with the implementation of additional interfacial forces, such as lift and wall lubrication forces are presented. Only the enthalpy equation is solved in the solid domain to predict the thermal field, whereas the Euler-Eulerian multi-fluid modelling approach is used to handle the boiling two-phase flow and the heat transfer between the heated structure and the subcooled liquid. The results of the improved quenching model are compared with available measurement data for various water temperatures ranging from 303 K to 353 K. Using the step plate with variable thickness sections along its height as the model test case, different solid part orientations were investigated and obtained temperature profiles were analysed. The temperature histories predicted by the presented model correlate very well with the provided measurement data at different

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monitoring positions. The temperature distribution within the solid part, obtained from the CFD simulation, can therefore serve as a realistic input for subsequent Finite Element Analysis (FEA) of thermal stresses within the quenched solid part.

1. Introduction

Optimization of heat transfer characteristics of automotive engines is one of the important factors leading to reduction of fuel consumption and emissions values. Improved heat treatment techniques have to be introduced when replacing heavier metals with lower weight alloys for engine components, which results in vehicle weight reduction and consequently improved fuel consumption [1]. Hence, an efficient heat treatment technique is essential to prevent component failure and to provide a homogenous temperature distribution during cooling. This leads to reduction of thermal stresses, higher durability and has consequently an important influence on power requirements [2]. Immersion quenching is one of the most important heat treatment techniques, where the solid part is first heated to a very high temperature and then immediately submerged into a sub-cooled liquid. In order to achieve the desirable microstructure and mechanical properties of the metal piece, liquids such as water, oils or polymers are used [3]. The liquid, which should typically be kept close to its boiling point, starts to evaporate after receiving the heat from the quenched part, and this process has a strong influence on the residual stresses. More than 50% higher stress levels can result from strongly sub-cooled liquid bath during the quenching process compared to the case with liquid (typically water) at temperature closer to saturation temperature, as reported by Koç et al. [4].

During immersion quench cooling the heat transfer develops through three main stages [5]. Immediately after the heated piece enters the sub-cooled liquid domain, the film boiling regime occurs, which results in the formation of a vapour film covering the quenched structure. Heat transfer rate in this regime is relatively low and stable as the vapour layer acts as an insulator. As soon as the wall temperature of the heated piece drops below the minimum film collapse temperature, also known as the Leidenfrost temperature, the second cooling stage starts [6]. The vapour film in the nucleate boiling regime becomes unstable and starts to disintegrate. The sub-cooled liquid starts to evaporate immediately after coming in contact with the heated surface. This results in higher heat transfer rate between the metal and the fluid, and leads to a more rapid cooling of the solid part. After the surface temperature of the heated part drops below the boiling temperature of the liquid, convective cooling regime is established and the cooling rate becomes stable at lower level [7].

Based on the complexity and phenomena of the multi-phase flow in quenching applications, the heat transfer model within the engineering use of CFD typically builds on a variety of empirically obtained correlations [8]. The flow boiling coefficient for nucleate and convective boiling was first provided by Rohsenow and afterwards extended by Chen, who proposed the first cohesive boiling method [9]. In recent years, many researchers reported on successfully implemented numerical predictions of the immersion quenching process with commercial CFD codes [5]. Krause et al. [3] employed the Eulerian multiphase model to simulate boiling flow, heat and mass transfer during the quenching process. The derived boiling model was based on a mixture model assumption and bubble crowding model approach for the two phase flow. Similar model for mass transfer prediction was proposed by Srinivasan et al. [10], who made an assumption that the mass transfer parameters are proportional to the heat transfer rate from the liquid system [11]. The latter model has already been implemented within the commercial CFD code AVL FIRE® [15] and applied for numerical simulations of quenching process, where according to Wang et al. [12], a significant improvement in accuracy of simulations has been achieved. In their simulations, separate momentum and mass conservation equations were solved for liquid and gas phases, where the energy mixture model was applied together with the heat conduction equation in the solid part. Further improvement of the model was made by Srinivasan et al. [13] in order to simulate the immersion quenching cooling process. The boiling heat transfer was accounted for by using an Euler-Eulerian multi-fluid method. The model was validated by simulating a quenching process of a test specimen, which was of different shape than the one presented in present paper. The specimen was cooled in water at temperatures ranging from 20 °C to 80 °C. The model was also applied for simulation of the quenching process of a real engine cylinder head and an assessment was made by comparing the predicted cooling curves with experimental data, reported by Greif et al. [14].

In the present work, the boiling phase change process, occurring between the heated part and the sub-cooled liquid phase, is handled by using the Euler-Eulerian multi-fluid modelling approach. Within the fluid domain mass, momentum and energy equations are solved in the framework of the multi-fluid modelling approach, and only the energy equation is solved to predict the thermal field in the solid part of the domain. In the following section, description of the mass transfer model is provided. Aforementioned models, presented by Srinivasan et al. [10], Wang et al. [12] and Greif et al. [14], used a constant Leidenfrost temperature approximation and considered only a drag force in the context of momentum interfacial exchange terms. Present paper describes further improvements of the quenching model, where additional forces, such as the lift and the wall lubrication force, are taken into account. Based on the complexity of determination of the boiling regimes, the variable Leidenfrost temperature approximation is introduced and first results are presented. The paper provides further quenching model details, simulation setup details and discuses theoretical limitations of the proposed model. Finally, simulation results of a real-time quenching process are compared and discussed based on comparison with the available measurement data. The paper closes with concluding remarks and upcoming future work.

2. Numerical modelling

The Euler-Eulerian multi-fluid model considers each phase as interpenetrating continua coexisting in the flow domain, with inter-phase transfer terms accounting for phase interactions. The main system of conservation equations consists of the averaged continuity and momentum equations, see Drew et al. [16], as presented in the following sections.

2.1. Continuity equation

The continuity equation describes mass conservation of each phase,

$$\frac{\partial \alpha_k \rho_k}{\partial t} + \nabla \cdot (\alpha_k \rho_k v_k) = \sum_{l=1, l \neq k}^{N} \Gamma_{kl} \quad k = 1, \ldots, N \tag{1}$$