Conjugate Heat Transfer

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Abstract: Quenching of material from high temperatures using forced fluid flow has been analyzed and the results compared with experimental data. Heat transfer arising from forced gas flow involves transfer of energy via conduction, convection and radiation. Heat transfer due to quenching into liquid media incorporates the effects of the liquid to gas phase transformation.

Keywords: Conjugate heat transfer, Fluid flow, Conduction, Convection, Radiation.

1. Introduction

The controlled transfer of heat from a component to its surroundings is critical for the operation of many industrial processes. For example, cooling of electronics components is needed to maintain safe operation and extend operating lifetime, while quenching of materials from elevated temperatures is often required to develop specific microstructural features that provide prescribed properties. Heat transfer can occur by mechanisms such as: natural or forced convection, conduction into adjacent material or supports and, if the temperature is high enough, by radiation to the surrounding environment. In some cases, heat transfer may be accomplished while maintaining the fluid as a single phase; in others, heat transfer may be sufficiently high to cause a phase transition from liquid to gas.

The conjugate heat transfer problem has been analyzed using COMSOL Multiphysics and applied to conditions with and without phase transformation. For the simple case when no phase transformation occurs in the coolant media, the rate of heat dissipation is a function of conduction and convection to the flowing fluid. The flow conditions and component geometry may give rise to turbulent flow that affects the heat dissipation over the surface. For this case, the existence of stagnated flow regions is observed and produces limited heat transfer compared to the corners, where high flow rates produce maximum cooling. Using analyses of this type, a more even distribution of heat transfer can be produced by providing a uniform flow of air over the surface and focusing concentrated flow on areas in which higher heat transfer is required.

Analysis of heat transfer under conditions where phase transformation occurs in the cooling fluid is more complex and must consider the range of near-wall effects arising from film boiling, transition boiling, nucleate boiling and pure convection. The near-wall boiling processes that strongly influence heat transfer from the part to the quenching medium operate on a scale that is many orders of magnitude smaller than the component size. To accommodate these different scales, the complex three-dimensional physics near the wall are analyzed using sets of equations that are solved only on the walls of the component. Under these conditions, accurate analysis of the heat transfer can be obtained for the differential heat transfer rates into the gas or liquid phase and the effect of gas formation on the flow behavior

2. Theory and Governing Equations

2.1 Gas Quench

In gas quenching, the part is cooled by means of a combination of radiation to the surroundings and conduction from the surface of the part into the gas. The gas carries the thermal energy away from the part by conduction and convection.

Heat transfer within the solid part is described by the well-known heat equation:

$$\rho\, c_p \frac{\partial T}{\partial t} = \nabla \cdot \left(\lambda \nabla T\right) \qquad (1)$$

where, ρ is the density of the solid material, c_p is the specific heat capacity, T is the temperature, and λ is the thermal conductivity. The density, specific heat capacity, and thermal conductivity are functions of temperature. The heat flux at the surface of the part due to radiation is modeled as

$$q_r = \varepsilon_{emis}\left(G_m + F_{amb}\sigma\, T_{amb}^4 - \sigma\, T^4\right) \qquad (2)$$

where ε_{emis} is the emissivity of the surface, G_m is the mutual irradiation from other surfaces, F_{amb} is the ambient view factor, σ is the Stefan-Boltzmann constant, T_{amb} is the far-away ambient temperature, and T is the temperature at the surface. G_m is a function of the radiosity.

In the presence of mutually irradiating surfaces, COMSOL Multiphysics automatically computes the ambient view factor and mutual irradiation.

High gas flow rates used for quenching typically produce turbulence, and an appropriate turbulence model must be used in conjunction with the standard fluid equations. The optimal model calculates the energy transport in the gas with sufficient accuracy while minimizing memory requirements and computation time. Subject to these constraints, a variant of the k-ε model was implemented in which the physics of the gas are described by the standard equations for continuity, momentum and energy.

2.2 Liquid Quench

Quenching into liquid media represents an extremely complex process, involving a variety of physics operating on vastly different scales. The near-wall boiling processes that strongly influence heat transfer from the part to the quenching medium operate on a scale that is many orders of magnitude smaller than the component size.

The quenching process can be divided into at least five stages:

1) Cooling during transfer
2) Film boiling
3) Transition boiling
4) Nucleate boiling
5) Pure convection

Radiation from the solid to the liquid across a gap of vapor dominates the first stage of the quenching process. Thus, the solution in this stage focuses on the surface temperatures of the quenched part and the liquid. Stages 2-4 involve complex interaction of vapor and liquid on the microscale at the walls of the part as the fluid boils. Each stage of boiling consists of distinct phenomena occurring at the solid surface, and the wall equations adjust during the analysis to describe the physics for each stage. Equation 3 shows the general form of the heat source across Stages 2-4

$$q = \frac{\lambda_g}{\delta}\left(T - T_{sat}\right) \qquad (3)$$

where λ_g is the thermal conductivity of the gas, δ is the film thickness, and T_{sat} is the boiling temperature of the liquid.

During Stage 5 (purely convective heat transfer), the boiling has stopped, and the physics may be characterized as a typical conjugate heat transfer problem with the wall equations enforcing temperature continuity between the solid and liquid. Thus, the two-phase fluid flow reduces to standard fluid equations (continuity, momentum and energy)

$$\nabla\cdot\left(\rho\,\mathbf{u}\right) = 0 \qquad (4)$$

$$\rho\,\mathbf{u}\cdot\nabla\mathbf{u} = -\nabla p + \nabla\cdot\left(\eta\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right) - \frac{2}{3}\eta(\nabla\cdot\mathbf{u})\mathbf{I}\right) + \rho\,\mathbf{g} \qquad (5)$$

$$\rho\, c_p\mathbf{u} = \nabla\cdot\left(k\nabla T\right) \qquad (6)$$

3. Results

An example of the air flow behavior over the surface of a heated component appears in Figure 1 for the simple case of forced flow from a single point below the component. For this case, the existence of stagnated flow regions is observed and produces limited heat transfer compared to the corners, where high flow rates produce maximum cooling.

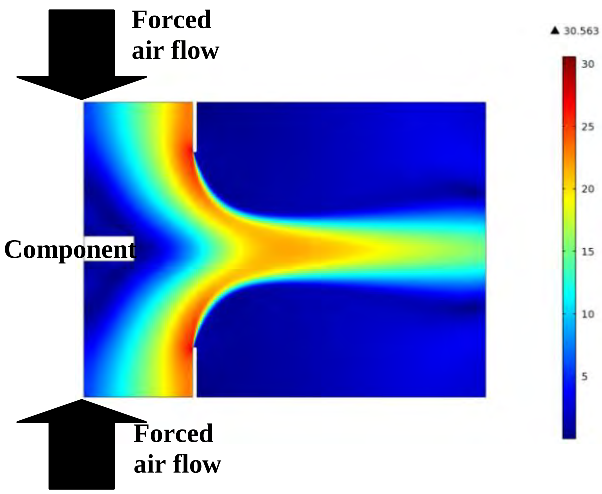

Figure 1: Results of axisymmetric analysis of flow from above and below the hot component showing the velocity of fluid flow over a hot component. Flow stagnation is seen directly above and below the component surface resulting in minimal heat transfer. Highest flow is seen at the corners resulting in maximum heat transfer.

A comparison of the results obtained from temperature measurements during forced air quenching and analysis using COMSOL Multiphysics is provided in Figure 2.

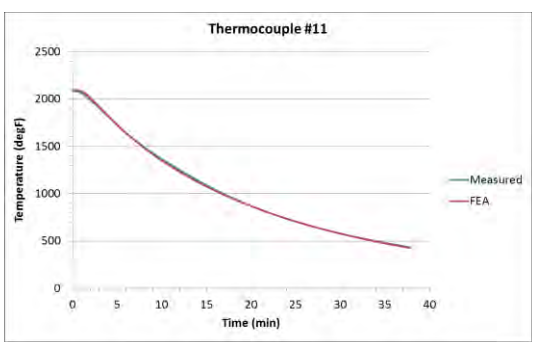

Figure 2: Comparison of Temperature vs Time during quench for thermocouple measurements and analytical predictions

The results show excellent agreement between the predicted and measured values of the temperature as a function of time for a variety of thermocouple locations, especially over the critical temperature range of interest. Small variations between the predicted and experimental results are believed to be associated with the perturbations in local air flow at the edge caused by the presence of the supporting structure.

Analysis of quenching into a fluid is more complex and must consider the range of near-wall effects arising from film boiling, transition boiling, nucleate boiling and pure convection. The near-wall boiling processes strongly influence heat transfer from the part to the quenching medium and operate on a scale that is many orders of magnitude smaller than the component size. To accommodate these different scales, the complex 3D physics near the wall are analyzed here using sets of equations that are solved only on the walls of the component. Under these conditions, accurate analysis of the heat transfer can be obtained for the differential heat transfer rates into the gas or liquid phase and the effect of gas formation on the flow behavior, see Figure 3.

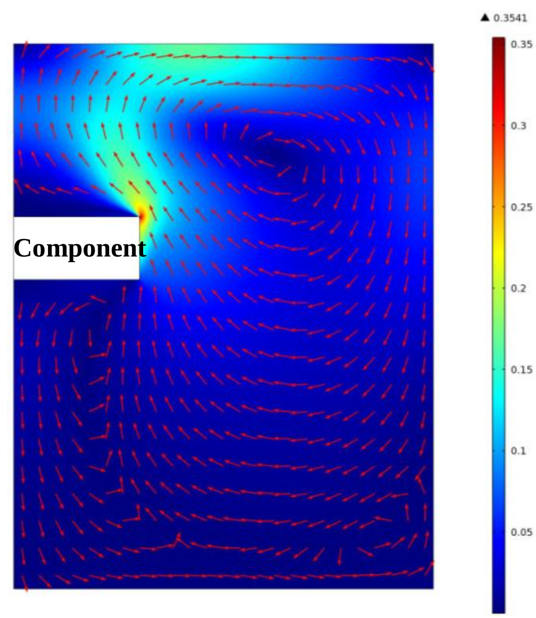

Figure 3: Fluid flow velocity associated with bubble formation at the interface between the hot component and the fluid during quenching where phase transformation occurs from liquid to gas.

Commercial quenching operations generally include forced fluid flow as well as fluid flow introduced by the phase transformation from liquid to gas. To provide a complete analysis of the flow pattern within a commercial quenching tank and the resulting thermal distribution in the specimen, the effect of the two fluid flow components must be integrated. The analyses developed here used a multiphase flow model that included forced convection due to mechanical pumping, agitation caused by gas bubbles and vapor formation in complex geometries. The turbulent flow models were modified to account for the two-phase flow. Figure 4 shows the results of analyses of a commercial quench tank in which fluid is forced through nozzles and impinges on the bottom surface of a hot component lowered into the tank. The results show the variation in the thermal conductivity due to the multiphase flow resulting from forced fluid flow and flow due to the liquid to gas phase transformation caused by fluid boiling at the specimen surface. Using these analytical approaches the fluid flow conditions can be modified to produce a more regular distribution of heat extraction from the hot component. This allows the development of quench conditions in which an even temperature gradient can be maintained leading to more homogeneous microstructural variability within the final component shape and limited development of residual stresses in the component.

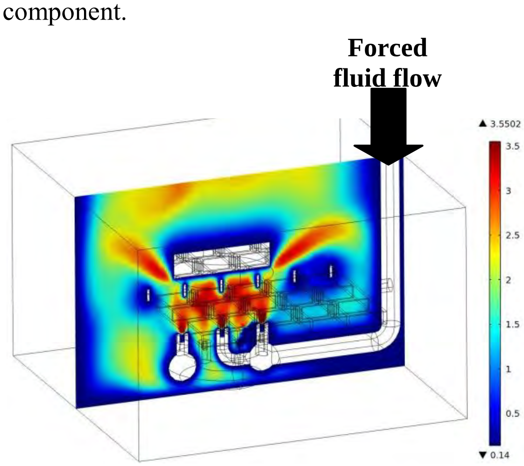

Figure 4: Results of variation of thermal conductivity developed under conditions of turbulent flow that combines multiphase flow due to forced fluid flow and flow due to buoyancy effects associated with bubble formation due to fluid boiling.

4. Summary

This paper has demonstrated the implementation of fluid flow algorithms into COMSOL Multiphysics to predict heat transfer during quenching of hot components. The details of the fluid flow rates over the surface govern the rate of heat transfer to the surrounding environment and therefore the rate at which the temperature of the component passes through critical temperature regimes that may govern the distribution of microstructural features and the development of residual stresses. Quenching into liquid media can be analyzed by considering the effect of any liquid to gas phase transformation and the role that this may play on the local heat transfer characteristics.