

Enhanced Heat Transfer Coefficient (HTC) Method to Model Air Quench Process: HTC Patching for More Accurate FEA Temperature Calculation

James Jan, Eben Prabhu, Xingfu Chen, and Ulrich Weiss
Ford Motor Company

ABSTRACT

Air quenching is a common manufacturing process in automotive industry to produce high strength metal component by cooling heated parts rapidly in a short period of time. With the advancement of finite element analysis (FEA) methods, it has been possible to predict thermal residual stress by computer simulation. Previous research has shown that heat transfer coefficient (HTC) for steady air quenching process is time and temperature independent but strongly flow and geometry dependent. These findings lead to the development of enhanced HTC method by performing CFD simulation and extracting HTC information from flow field. The HTC obtained in this fashion is a continuous function over the entire surface. In current part of the research, two patching algorithms are developed to divide entire surface into patches according to HTC profile and each patch is assigned a discrete HTC value. Also included in this research is the performance comparison of the two patching algorithms by analyzing the errors.

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INTRODUCTION

In metallurgy, quenching is a common manufacturing process to harden materials such as aluminum or steel to enhance mechanical properties. In the case of AL 356, which is a material widely used for cylinder head in automotive industry, air quenching is part of heat treat process to produce high strength components[1]. When aluminum alloy is heated to near solutionizing temperature, some alloying elements are dissolved to produce solute-rich solid solution. The concentration of these hardening elements is preserved when aluminum alloy is rapidly cooled to low temperature to prevent diffusion process from taking place[2]. Because the temperature inside the metal drops rapidly in a very short period of time, uneven cooling rate at different locations could result in high temperature gradients at some locations in the part. When the stress resulted from high temperature gradients surpasses the yield points at high temperature, residual stress is created when the temperature is dropped to room temperature and the part is unloaded with plastic deformation. The high residual stress after quenching usually is the leading cause for distortion or sometimes even causing cracks[3].

With the advancement of computation simulations such as finite element analysis (FEA) method, it is now possible to predict residual stress using numerical methods and more researches are conducted in this fashion because of the efficiency and accuracy[4]. In general, numerical methods require two models in order to predict the thermal residual stress from quenching process. The first model is a heat transfer model, by which the temperature profile and history are calculated. The temperature profile and history then are input to a structural model that calculates residual stress due to thermal

expansion and plastic deformation. For the structural analysis, there are extensive research and publications about applying finite element analysis (FEA)[5][6], with high degree of success, to predict residual stress. Since the residual stress is computed based on temperature input, the accuracy of the temperature data, output from the heat transfer model, will directly affect the accuracy of FEA results.

There are many approaches to construct heat transfer models. Among them, heat transfer coefficient (HTC) method is a widely adapted one since it is simple and computation efficient[7][8][9][10]. Heat transfer coefficient, defined as a parameter in Newton's law of cooling, characterizes the relationship of heat flux through solid/fluid interface to the temperature difference between solid surface and free stream[11]. Since heat transfer coefficient is a characterization of relationship rather than a property of solid and/or fluid, it could not be measured directly and has to rely on some methods, either experimental or numerical or both, to derive it.

The challenge to derive heat transfer coefficient could be explained by the physics of conduction heat transfer. The heat transfer inside the solid during quenching process could be described by heat equation and corresponding boundary conditions[12], assuming no heat generation during quenching process:

$$\frac{\partial(\rho C_p T)}{\partial t} = \nabla \cdot \nabla(kT)$$

(1)



$$\nabla(kT) \cdot \hat{n} = \dot{q} = -h(T_s - T_\infty) \quad (2)$$

Since heat transfer coefficient is a boundary condition and an unknown variable in Equation (2), determining HTC from temperature data, which is the solution to the heat equation, requires a methodology to solve an inverse problem. If thermal material properties are constant, then methodologies based on integral method could be directly applied[13]. If the thermal material properties are temperature dependent, then the problem become nonlinear and different approaches may be required[14].

There have been many researches on solving the inverse heat conduction problem. Some assume uniform temperature in solid and use lumped mass method to determine heat transfer coefficient[15]. Some use finite difference method[16] and others use finite element method[17]. Some researches investigate the stability of inverse heat conduction problem and use the result to develop a method for best positioning of the thermocouples[18].

There is an obvious drawback in HTC method in which the value of HTC are calibrated by experimental temperature data. Because of the complexity to solve inverse heat conduction problem, the formulation usually is greatly simplified to a one-dimensional or two-dimensional problem. But most critical part of the methodology is the hidden assumption of HTC itself. For a general convection heat transfer problem, HTC is a function of temperature, geometry, flow and time. Because number of temperature measurements is limited, it is virtually impossible to include the full effect of geometry and flow field in HTC formulation. Furthermore, quenching parameters such as quench chamber geometry, quench orientation, flow pattern, and etc. have great impact on HTC. The experiments to calibrate HTC also have to be repeated whenever there is a change to quenching parameters.

If the heat equation in solid, Equation (1), is solved in conjunction with the heat equation in fluid, Equation (3), then heat transfer coefficient in boundary condition, expressed in Equation (2), becomes part of internal solution, expressed in Equation (4):

$$\frac{\partial(\rho C_p T)}{\partial t} + \vec{V} \cdot \nabla(\rho C_p T) = \nabla \cdot \nabla(kT) \quad (3)$$

$$T_f = T_s$$

$$\nabla(k_f T_f) \cdot \hat{n} = \dot{q}_f = \dot{q}_s = \nabla(k_s T_s) \cdot \hat{n} \quad (4)$$

The temperature and heat flux cross the solid-fluid boundary have to satisfy continuity requirement and they are solved simultaneously in the solution process. Once the heat flux cross the boundary is solved, the corresponding HTC could be calculated by Newton's law of cooling with respect to a reference temperature, T_∞ .

$$\frac{\partial(\rho \vec{V})}{\partial t} + \vec{V} \cdot \nabla(\rho \vec{V}) = -\nabla p + \mu \nabla^2 \vec{V} - \rho \beta (T - T_\infty) \vec{g} \quad (5)$$

The heat equation in fluid, Equation (3) is coupled with flow equation, Equation (5), and the coupled two equations could be solved together by computational fluid dynamics (CFD) methods. There have been research works employing 3D CFD methods to model water quenching process for cylinder head and cylinder block and the results have been well validated with experimental measurements[19][20].

This paper detailed the development of an enhanced HTC method for a specific quenching process. When quenching media is a gas-phased fluid and quenching flow is steady, the flow and temperature fields exhibit certain characteristics that could be described by a time and temperature independent HTC. The end results of this part of research are two patching algorithms that could be used to divide the continuous HTC profile on solid surface into a finite number of patches and each patch has a uniform, discrete HTC value. Not only can this method reduce the computation time for 3D CFD conjugate heat transfer calculations, it also produced a more robust method for temperature calculation in FEA model.

HTC FOR STEADY AIR QUENCHING PROCESS

Calculation of HTC by 3D CFD Model

In Newton's law of cooling, the physics of complex convection heat transfer is characterized by a single heat transfer coefficient parameter, expressed in Equation (2). Therefore, heat transfer coefficient (HTC) is a function of all factors that affect the convection heat transfer. In general, HTC is function of thermal material properties of the solid, time, temperature, geometry and flow pattern.

It has been established in the previous research that HTC for steady air quenching process is time and temperature independent but strongly flow and geometry dependent. For air flowing over a flat plate, HTC could be expressed in a generic formula; the constants in the formula will be different for different flow regime:

$$Nu = \frac{hL}{k} = C Re_L^m Pr^n \quad (6)$$

For automotive applications such as air quenching processes for cylinder head and cylinder block, 3D CFD method is an effective way to obtain complete HTC data. In this paper, a CFD model, shown in Figure 1, is constructed to study the characteristics of HTC.

Two cases are selected in our study. One represents quenching at lower cooling rate in which only nozzle #1 is turned on. The other one represents quenching at higher cooling rate in which nozzle #1 & #2 are turned on. The boundary conditions for both cases are shown in Table 1.

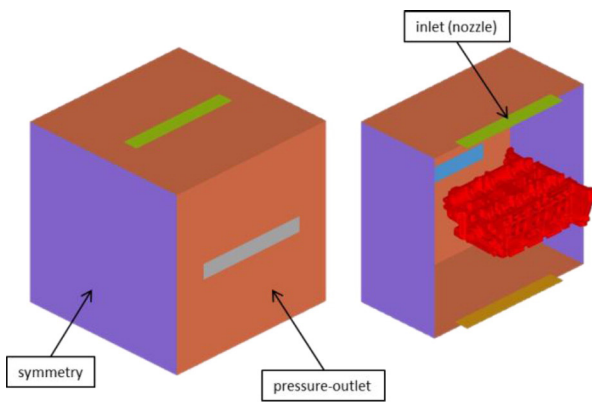


Figure 1. Computational model to simulate the process of air quenching a cylinder head in open environment.

Table 1. Boundary conditions for low cooling rate quenching (1 jet) and high cooling rate (2 jets) quenching.

Case	1 jet	2 jets
inlet-1	40 m/sec	40 m/sec
inlet-2	off	40 m/sec
inlet-3	off	off
inlet-4	off	off

HTC Profile and Flow Field

In the 3D CFD model, transient calculations are performed for flow and temperature field for the entire quenching process. The HTC data respected to time are extracted from CFD solution and plotted against time, shown in Figure 2. Although the temperature is dropping in the quenching process, HTC remains relatively constant over the entire process.

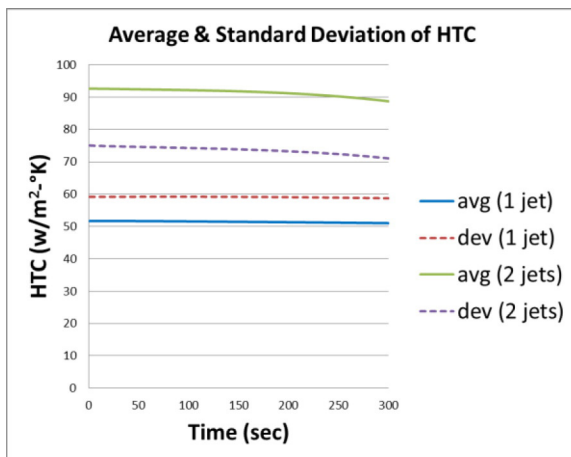


Figure 2. Average and standard deviation of HTC for low cooling rate (1 jet) and high cooling rate (2 jets) quenching.

The velocity field near the cylinder head and HTC profile on the surface is shown in Figure 3 at 60 seconds into quenching. It could be seen in the figure that the highly irregular geometry of the cylinder head has great impact on the velocity field. Few low velocity zones are observed near flow impingement point above and below the

cylinder head, forming low heat transfer zones. Also can be seen is a large portion of flow at the side of cylinder head that is near stagnant, forming other low heat transfer zones.

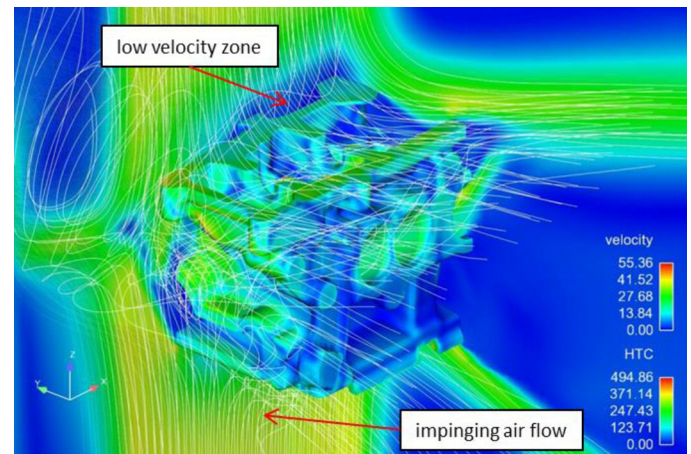


Figure 3. Velocity field near cylinder head and HTC profile on the cylinder head.

The majority of heat transfer takes place on surface facing the impinging flow, shown in Figure 4. What is interesting to see in the figure is the HTC on the interior surface of intake/exhaust port. Because part of impinging flow enters the internal channel through valve port, HTC on those surfaces are higher than a large portion of exterior surfaces where the flow is almost stagnant.

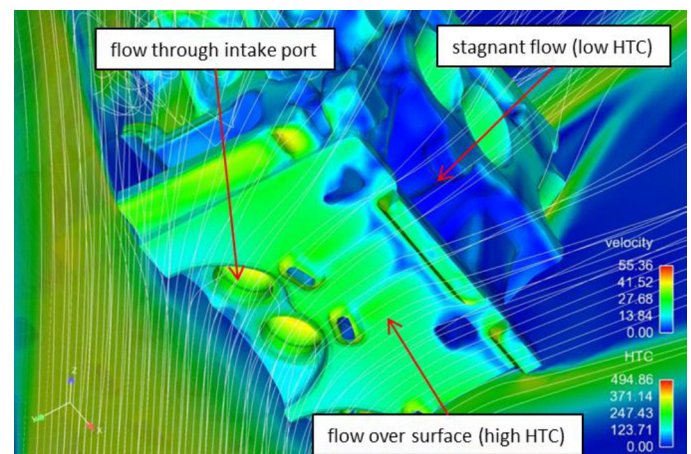


Figure 4. Heat transfer coefficient on the cylinder head surface.

TRANSFORMING CONTINUOUS HTC PROFILE TO DISCRETE HTC PATCHES

Continuous HTC Profile

For steady air quenching processes, HTC profile is a continuous function over entire surface that remains relatively the same for whole quenching period. Figure 5 shows HTC profile for low cooling rate quenching process. In this section, two patching algorithms are developed and studied. The function of a patching algorithm is to divide surface into finite number of patches and each patch is assigned a uniform, discrete HTC value. In theory, when number of patches increases, it will approach to a continuous function.