

Transient Modeling of Vehicle Under-hood and Underbody Component Temperatures

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ABSTRACT

In this paper, transient component temperatures for the vehicle under-hood and underbody are estimated. The main focus is on the component temperatures as a result of radiation from exhaust, convection by underbody or under-hood air and heat conduction through the components. The exhaust surface temperature is simulated as function of time and for various vehicle duty cycles such as city traffic, road load and grade driving conditions. At each time step the radiation flux to the surrounding component is estimated, heat addition or removal by convection is evaluated based on air flow, air temperature and component surface area.

Simulation results for under-hood and underbody components are compared against vehicle test data. The comparison shows very good agreement between simulated and measured component temperatures under both steady state and transient conditions.

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INTRODUCTION

Due to the ever increasing requirement for fuel economy improvements, the under-hood and underbody environment are getting hotter than before [1-2]. In addition, the need to reduce vehicle weight has led to a significant increase in the use of lightweight materials which include thermoplastic and thermoset materials which are sensitive to heat. Therefore, it is becoming a very challenging task during vehicle development to meet both the requirement of high fuel economy and component durability. Vehicle components are expected to retain an acceptable level of their initial properties. However, exposure to heat will reduce component life due to negative effect of heat on material properties. Though all materials are expected to experience some level of thermal degradation, the material life and component life can be improved by efficient thermal management of the vehicle environment. This requires understanding of the thermal profile of vehicle components which are exposed to heat. Efficient management of the heat can be addressed by some clearance requirements during the packaging phase, upgrading component materials, using heat shields or managing airflow around these components. In order to understand the thermal environment and its effect on the expected component life, the development engineer has to know the expected component temperature for a duty cycle that represents the customer usage. Estimating component temperature and the time of exposure to these temperatures under these driving and duty cycle conditions, requires a transient thermal analysis of the vehicle under-hood and under-body components. Conducting a full CFD analysis for airflow and thermal analysis

requires very long simulation time [3-4]. Therefore, it is the subject of this paper to present the approach and process of how to efficiently estimate component temperatures in a transient mode. The results are compared to data obtained from vehicle testing under the same driving conditions.

TRANSIENT ANALYSIS

It has been the general practice to simulate the worst case thermal conditions in order to determine the maximum temperatures that the components will be exposed to during a given driving schedule. Evaluation of thermal risk, in this case, is based on the highest temperatures that a component will be exposed to, and does not consider the time duration of exposure to high temperature or customer duty cycles. Driving conditions such as city traffic, extended idle or soak represent highly transient situations where the component temperatures may not quickly reach steady state. Therefore, it is required to estimate transient component temperatures during various driving conditions which represent customer duty cycle for a given vehicle. Due to radiative and convective heat transfer in the under-hood and underbody environment, the temperature of several components in the underbody may exceed their design limits. For an estimate of component life, the temperature of vehicle components and the time duration of exposure to temperature have to be understood.

Therefore, it will be more efficient and more accurate to develop thermal protection plans based on realistic scenarios that the vehicle will experience during its service life. In this paper, the development of the Virtual Time-Temperature Analysis (VTTA) software is described in relation to the vehicle components. The development of exhaust gas temperatures and exhaust surface temperatures are addressed by the authors in a separate study.

DESCRIPTION OF VTTA SOFTWARE

The VTTA software described in this paper addresses the effect of exhaust surface temperature and driving conditions on the transient temperature of vehicle components. Each component has to be described in an input file which includes its dimensions, material type, and component location relative to the exhaust. Exhaust components and dimensions are described in an input file. Exhaust gas temperature and surface temperature along the exhaust are estimated using a transient thermal analysis model.

GEOMETRY PROCESSING

The components geometry is described relative to each other and relative to the exhaust. The view factors between the various components and the exhaust system are calculated. The heat transfer coefficients between the components and surrounding air are estimated based on vehicle speed, component dimensions and geometry. Figure 1 shows the algorithm adopted in this study in order to estimate transient component temperatures for each case. Geometric parameters and view factors are calculated once and saved for later implementation since they are independent of time.

VTTA requires a work-flow consisting of geometry data preprocessing, case data preprocessing, solving the problem and post-processing for data analysis. The case data file contains vehicle speed vs. time, engine speed and exhaust gas temperature at the engine outlet. A geometry file will contain data related to component dimensions, location (x, y, z), component properties such as emissivity, thermal conductivity, density and heat capacity. Exhaust system components and dimensions are described in the same geometry file.

Geometrical properties of the components are obtained by fitting them into pre-set shapes (e.g., cylinders, spheres, ellipsoids, etc.). For the heat conduction calculations, the information needed to model the components with the previously described fitting based method (e.g., volume, shape, principle dimensions, etc.) are automatically extracted from the cad files directly.

Radiation view factors are estimated based on component geometry and location relative to the exhaust heat source. Exhaust and component emissivity are assigned based on historical data and prior knowledge about components and exhaust surface finish condition. The vehicle test data file is a time table with the vehicle speed, engine speed, exhaust mass flow rate, exhaust gas temperature, fan speed, grille dimensions, and radiator coolant inlet and outlet temperature. This data file is used to update the boundary conditions of the solution with time.

Vehicle Components Input

The vehicle components are modeled as homogeneous objects with simplified fitting shapes. The four main shapes available are blocks, spheres, cylinders, and hollow cylinders. The user will specify for each component a fitting shape, main dimensions for the selected shape, its center's location, and its orientation relative to the global coordinate system. A multi-layer specification input can be used for components that are not homogenous in material (e.g. fuel tank).

An optional input for a component-to-component surface contact connection can be used to include the conduction between components in contact or to model a complex shape with several simple shapes.

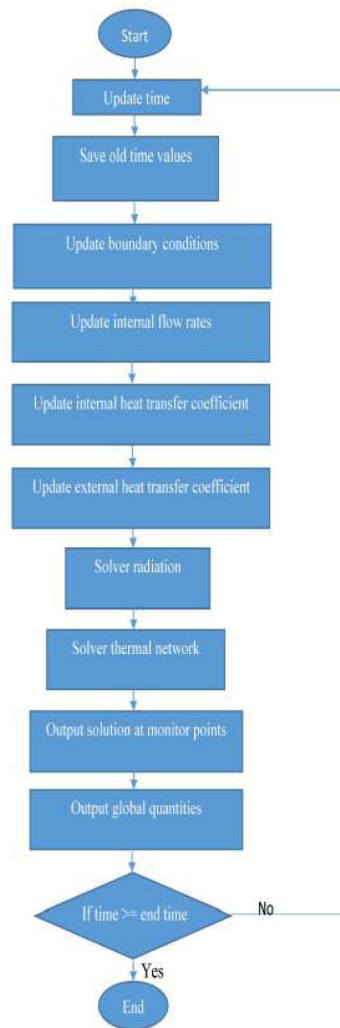


Figure 1. VTTA Solver Subroutine

Figure 2 shows the generated grid for the exhaust system and some of the surrounding components.

Figure 3 describes the way geometry faces are constructed within VTTA's native coordinate system. Block faces are constructed such that faces 1 & 4 are parallel to YZ plane, faces 2 & 5 are parallel to XZ plane, and faces 3 & 6 are parallel to XY plane.

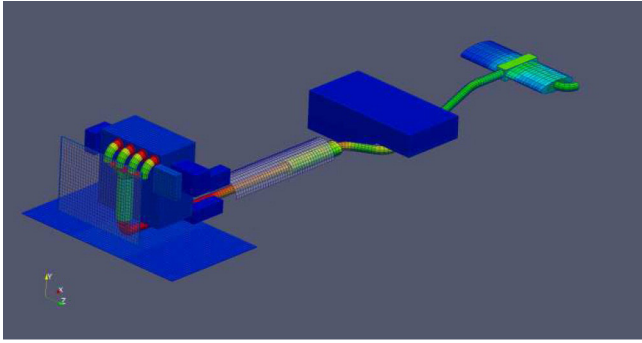


Figure 2. VTTA generated grid and geometry interpretation

For a solid cylinder, faces 1 & 2 are the two end faces (caps), while the other faces on the circumference are numbered starting with 3 in the counter clockwise direction.

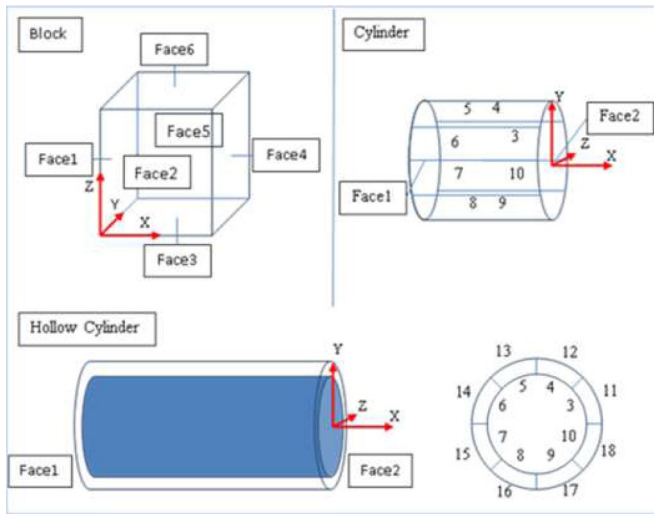


Figure 3. vehicle component shapes and faces

The external surface of each component shape is divided into a set of faces. The set of faces of each shape are ordered relative to its local coordinate system. Figure 4 represents the interface between a cylindrical component and a block component as an example.

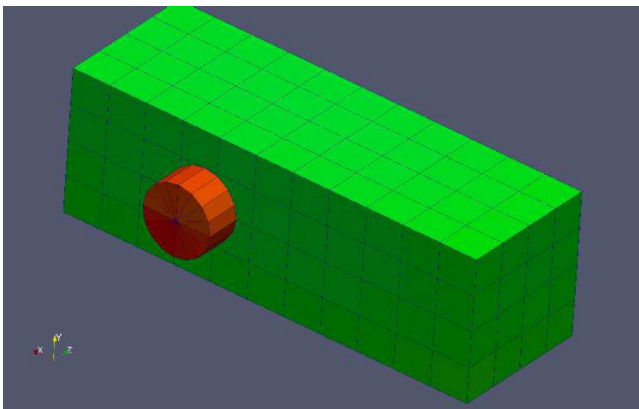


Figure 4. Contact connection between cylindrical component and block component

Energy Equation in Solids

For estimation of transient component temperatures, the energy equation is solved at each time step. The form of the energy equation implemented is given by [5-6]:

$$\frac{\delta \rho E}{\delta t} = \nabla \cdot k \nabla T + S_u \quad (1)$$

The solution domain is discretized into finite volumes. The terms of equation (1) are discretized following the finite volume approach as follows:

$$\frac{[(\rho E_p)V_p]^{n+1} - [(\rho E_N)V_N]^n}{\Delta t} = \sum_{face i} (Ak \nabla T)^{n+1} + S_u \quad (2)$$

$$Ak \nabla T = A_{face} h_{face}^{eff} [T_N - T_P] \quad (3)$$

$$h_{face}^{eff} = \frac{\left(\frac{k}{dl}\right)_p \left(\frac{k}{dl}\right)_N}{\left(\frac{k}{dl}\right)_p + \left(\frac{k}{dl}\right)_N} \quad (4)$$

$$\left(A \frac{k}{c_p} \vec{\nabla} H\right)_j^{n+1} = A_f h_{eff} * \left[\left(\frac{H}{C_p}\right)_p - \left(\frac{H}{C_p}\right)_N\right] \quad (5)$$

In equation (2), the superscripts n, and n+1 refer to the solution variables at the previous and current time steps, respectively. The subscripts P and N refer to this cell, and the neighboring cell, respectively. The above formulation yields the time-implicit solution of the heat conduction equation; which is second-order accurate. The first term on the right-hand-side of equation (2) is the summation of the conductive fluxes on all the faces of the control volume.

View Factor Relation

The view factor between elements 1 & 2, F_{12} , is given by

$$F_{12} = \frac{1}{A_1} \int_{A_1} \int_{A_2} \frac{\cos \theta_1 \cos \theta_2}{\pi r^2} dA_1 dA_2 \quad (6)$$

Where A_1 and A_2 are the areas of radiating elements 1 and 2. θ_1 and θ_2 are the angles between the incident/emitted ray with face normals of elements 1 and 2, respectively

And from reciprocity relation we have

$$A_1 F_{12} = A_2 F_{21} \quad (7)$$

For gray, diffuse surfaces