TFAWS06-1036

Conjugate Heat Transfer Analyses on the Manifold for Ramjet Fuel Injectors

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Abstract

Three-dimensional conjugate heat transfer analyses on the manifold located upstream of the ramjet fuel injector are performed using CFdesign [1], a finite-element computational fluid dynamics (CFD) software. The flow field of the hot fuel(JP-7) flowing through the manifold is simulated and the wall temperature of the manifold is computed. The 3D numerical results of the fuel temperature are compared with those obtained using a 1D analysis based on empirical equations, and they showed a good agreement. The numerical results revealed that it takes around 30-40 seconds to reach the equilibrium where the fuel temperature has dropped about 3° F from the inlet to the exit of the manifold.

1. Introduction

As part of a NASA flight demonstration project to advance the state of the art in rocket based combined cycle (RBCC) propulsion development through risk reduction efforts involving ground-based experiments, a full-scale direct connect combustor rig (DCCR) study was initiated. This experiment essentially duplicates the conditions of a regeneratively fuel cooled hypersonic ramjet/scramjet engine flow path of heat sink construction to simulate the actual conditions the engine would be operated at by using a facility fuel heater. The operation of the engine at the lower ramjet speeds was of key interest to the operation of the vehicle. In order to correctly match these conditions a detailed thermal analysis on the upstream fuel delivery components(manifold) was required. A preliminary design of the manifold located upstream of the fuel injector in the ramjet engine is sketched in Fig. 1. The manifold consists of one cylindrical horizontal tube with an outer diameter of 1.0 in and four vertical cylindrical tubes with outer diameters of 0.5 in. The manifold is made of Inconel 625, whose properties at 800° F are

$$c_{p,m} = 0.127 \text{ Btu/lbm-R}, \quad k_m = 0.00336 \text{ Btu/ft-s-R}, \quad \rho_m = 0.305 \text{ lbm/in}^3 \qquad (1)$$

where $c_{p,m}, k_m$, and ρ_m are the specific heat, thermal conductivity, and density, respectively. The fuel enters at the open end of the horizontal tube and flows through the four vertical tubes before reaching the injector. In the current analysis, the equilibrium temperature of the fuel at the exit of the manifold, the equilibrium wall temperature, and the time to reach the equilibrium state are the main interests. For future reference, the vertical tube that is closest to the open end of the horizontal tube is referred to as the first tube while the farthest one is referred to as the fourth tube.

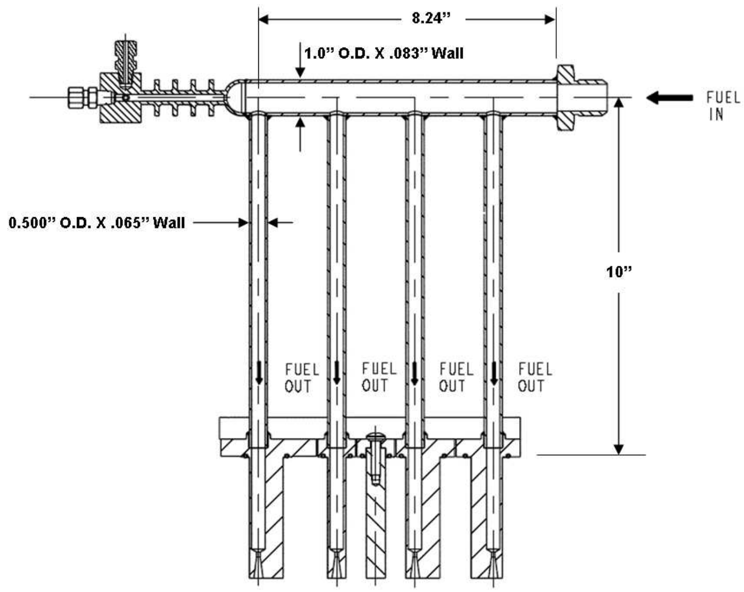

Figure 1: Sketch of the manifold located upstream of the ramjet fuel injector.

In the following, the 1D analysis is presented first, which is followed by the 3D analysis. In the 1D analysis, the horizontal tube and the fourth vertical tube(that represents the worst case for the fuel temperature drop) are considered. It should be pointed out that the effect of the closed end of the horizontal tube is not considered in the 1D analysis.

2. 1D Thermal Analysis on the Manifold

When the hot fuel starts flowing inside the manifold, the manifold will be heated up and heat will transfer to the ambient air. Let $T_a (= 70^\circ$ F) and T_w be the ambient air and tube wall temperatures; T_i and T_e be the inlet and exit temperatures of the fuel; and D_i, D_o, and L be the inner diameter, outer diameter, and length of the tube, respectively. The inlet conditions of the fuel are given as follows:

$$p = 600 \text{ psia}, \quad T_i = 800^\circ \text{ F}, \quad \dot{m} = 0.27 \text{ lbm/s} \tag{2}$$

where p and $\dot{m}$ are the pressure and mass flow rate. The properties of the fuel(JP-7) at the inlet are also given as

$$c_p = 0.77475 \text{ Btu/lbm-R}, \quad \mu = 1.44 \times 10^{-5} \text{ lbm/ft-s},$$

$$k = 0.05285 \text{ Btu/ft-hr-R}, \quad \rho = 1.9025 \text{ lbm/ft}^3, \quad \gamma = 1.077 \tag{3}$$

where c_p, μ, k, ρ, and γ are the specific heat, viscosity, thermal conductivity, density, and specific heat ratio, respectively. The Reynolds number, Re, and Mach number, Ma, can be computed by

$$Re = \rho V D_i/\mu, \quad Ma = V/a \tag{4}$$

where V and a are the velocity and sound speed, respectively. Further, $V = \dot{m}/(\rho\pi D_i^2/4)$ and $a = \sqrt{\gamma g_c p/\rho}$ with g_c being a conversion constant. Since $D_i = 0.834$ in for the horizontal tube, we have $V = 37.41$ ft/s and $a = 1254$ ft/s, which gives $Re = 3.435\times 10^5$ and $Ma = 0.03$. We can conclude that the flow is incompressible and turbulent. The heat transfer coefficient, h_1, between the fuel and inner surface of the tube can be computed as

$$h_1 = Nu_d k/D_i \tag{5}$$

where Nu_d is the Nusselt number, and

$$Nu_d = 0.023 Re^{0.8} Pr^{0.3} \tag{6}$$

for turbulent flows [2], where $Pr = c_p\mu/k$ is the Prandtl number. The heat transfer coefficient, h_2, between the ambient air and outer surface of the tube, can be computed using

$$h_2 = 1.42((T_w - T_a)/L)^{0.25} \tag{7}$$

for horizontal cylinders [2] and

$$h_2 = 1.32((T_w - T_a)/D_o)^{0.25} \tag{8}$$

for vertical cylinders [2]. Let q_1 be the heat flux by forced convection inside the manifold, q_2 be that by natural convection to the ambient air, and q_3 be that by radiation outside the manifold. We can define

$$q_1 = h_1 A_1((T_i + T_e)/2 - T_w), \quad q_2 = h_2 A_2(T_w - T_a), \quad q_3 = \epsilon\sigma A_2(T_w^4 - T_a^4) \tag{9}$$

where $A_1 = \pi D_i L$, $A_2 = \pi D_o L$ are the heat transfer surface areas, $\epsilon = 0.22$ is the surface emissivity, and $\sigma = 0.1714 \times 10^{-8}$ Btu/h-ft^2-R^4 is the Stefan-Boltzmann constant. Let m and m_f be the mass of the tube and the fuel, respectively. The heat balance equations for both the solid and the fluid are

$$m c_{p,m} \partial T_w/\partial t = q_1 - q_2 - q_3 \tag{10}$$

and

$$m_f c_p \partial T_e/\partial t = -q_1 + \dot{m} c_p (T_i - T_e) \tag{11}$$

Note that the thermal resistance by conduction through the wall is ignored in Eq. (10) since the wall is relatively thin. Substituting Eq. (9) into Eqs. (10) and (11), we have

$$m c_{p,m} \partial T_w/\partial t = h_1 A_1((T_i + T_e)/2 - T_w) - h_2 A_2(T_w - T_a) - \epsilon\sigma A_2(T_w^4 - T_a^4) \tag{12}$$

and

$$m_f c_p \partial T_e/\partial t = -h_1 A_1((T_i + T_e)/2 - T_w) + \dot{m} c_p (T_i - T_e) \quad (13)$$

that are used to solve T_w and T_e. Assuming $T_w(t = 0) = 70°$ F, we can compute $T_e(t = 0)$ by using

$$h_1 A_1((T_i + T_e)/2 - T_w) = \dot{m} c_p (T_i - T_e) \quad (14)$$

which yields $T_e(t = 0) = 737.4°$ F for the horizontal tube and 620° F for the vertical tube. Equations (12) and (13) are solved using the program Mathematica 5.0 for both horizontal and vertical tubes. The calculated time history of tube wall temperature is plotted in Fig. 2, while the fuel temperature drop across the manifold at the steady-state is plotted in Fig. 3. The results showed that the horizontal tube wall temperature reaches 791.5° F and the vertical tube wall reaches 794° F within about 30 s. The horizontal tube wall temperature is 2.5° F lower than the vertical tube wall due to the larger heat transfer surface area. The fuel temperature drops approximately 3° F from the inlet to the exit of the manifold.

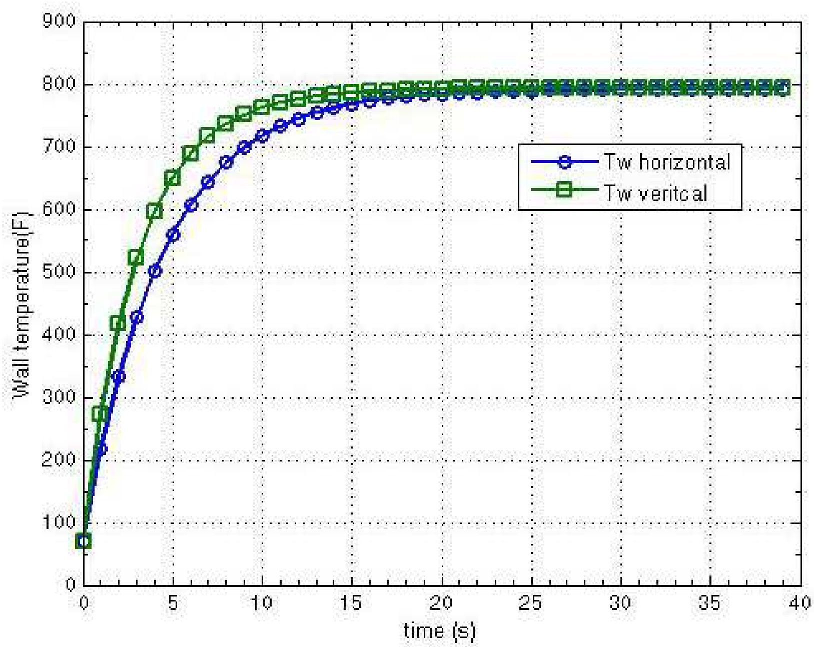

Figure 2: Time history of the tube wall temperature.

3. 3D Thermal Analysis on the Manifold

A finite-element CFD software, CFdesign, is used here for the 3D analysis. The numerical formulation in CFdesign is derived from the SIMPLER scheme introduced by Patanker[1]. In the current analysis, a finite-element model that has approximately 42,000 nodes in the fluid and 14,000 nodes in the solid is used. The flow field is simulated first assuming a

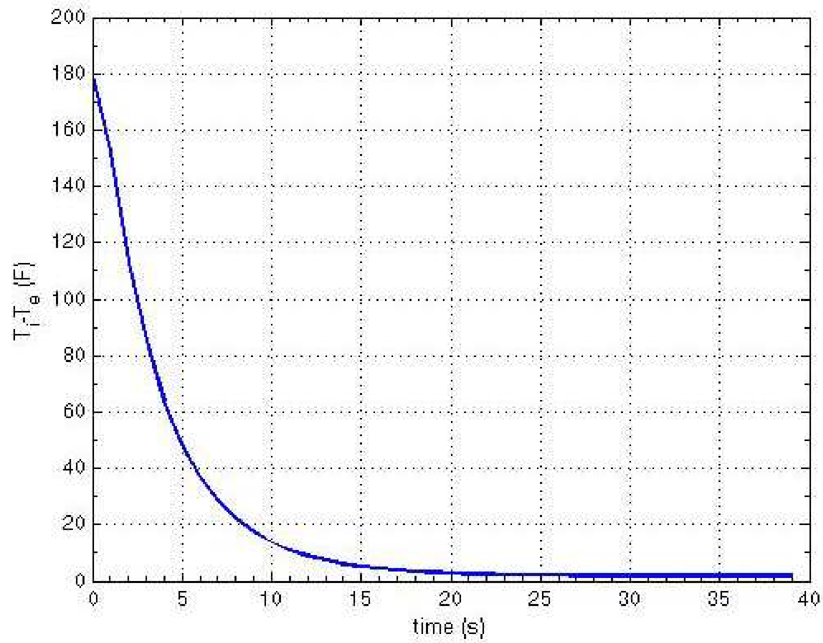

Figure 3: Time history of the temperature drop of the fuel.

constant temperature. After the steady-state is reached, the temperature field is computed under both steady-state and transient runs. At the inlet, pressure, temperature and mass flow rate are specified as the boundary conditions. On the outer surface, natural convection and radiation boundary conditions are specified in the same way as those in the 1D analysis. The steady-state velocity and pressure contours on an x-y cut plane are shown in Figs. 4 and 5 respectively. The velocity contour shows high velocity near the turning point of the flow from the horizontal tube to the vertical tubes. The pressure contour shows the effect of the closed end of the horizontal tube with an increase in static pressure as the velocity decreases near the closed end. The steady-state temperature contour predicted by the steady-state run is plotted in Fig. 6. It is observed that the fuel exit temperature at the fourth vertical tube is very close to the fuel inlet temperature. However, the steady-state temperature obtained by the transient run plotted in Fig. 7 shows around 20° F drop from the inlet of the manifold to the exit of the fourth tube. Further, the steady-state temperature distribution along the centerline of the horizontal tube and the first and fourth vertical tubes is plotted in Figs. 8 and 9, respectively. It can be seen that the temperature drops within both the horizontal and vertical tubes are higher than the results obtained by the steady-state run. The fuel temperature near the closed end of the horizontal tube is about 13° F lower than that shown in the steady-run results. Based on the steady-state run results, the temperature drop from the inlet of the manifold to the exit of the fourth vertical tube is 2.4° F, which agrees well with the 1D prediction (3° F). Since different solvers are used for steady-state and transient runs in CFdesign, the discrepancy between the steady-state temperature results obtained by steady-state and transient runs is attributed to the accuracy of the solver based on the conclusion provided by the technical support group at Blue Ridge Numerics Incorporation. For completeness, the time history of the fuel temperature at the exit of the first and fourth tubes is plotted in Fig. 11, showing that it takes about 40 s to reach the equilibrium for the first tube, while it takes about 70 s to reach the similar equilibrium state for the fourth tube. Since the 1D results agree well with the 3D steady-state run results, the 1D results are considered to be valid and will be based on to draw conclusions.

4. Conclusions

Both 1D and 3D conjugate heat transfer analyses on the manifold for the ramjet fuel injector have been performed. The numerical results are presented and compared, showing a good agreement between the 1D and 3D results obtained by the steady-state analysis. The equilibrium temperature of the fuel at the exit of the manifold drops about 3° F from the inlet to the exit of the manifold, and it takes approximately 30-40 seconds to reach equilibrium conditions.

Acknowledgments

The NASA integrated systems test of an air-breathing rocket (SITAR) project has supported this work. The author greatly appreciates the support received from Derrick Cheston and helpful guidance from Ananda Himansu. Furthermore, the author is grateful to Robert Buehrle, Thomas Cressman, Thomas Krivanek and James Yuko for reviewing this paper.

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[2.]Holman, J.P. , **Heat Transfer**, McGraw-Hill Book Company, 1981.

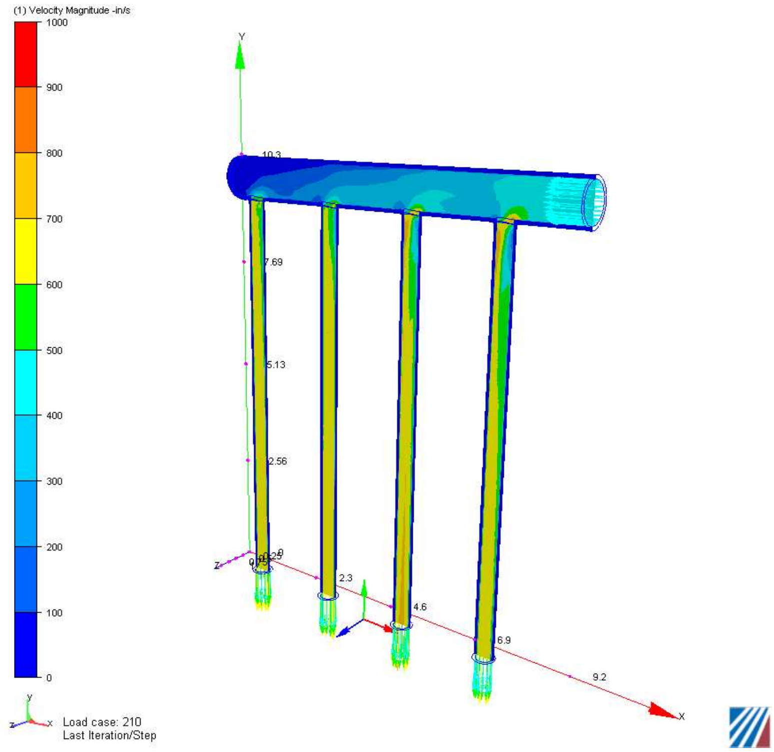


Figure 4: Steady-state velocity contour on an x-y cut plane.

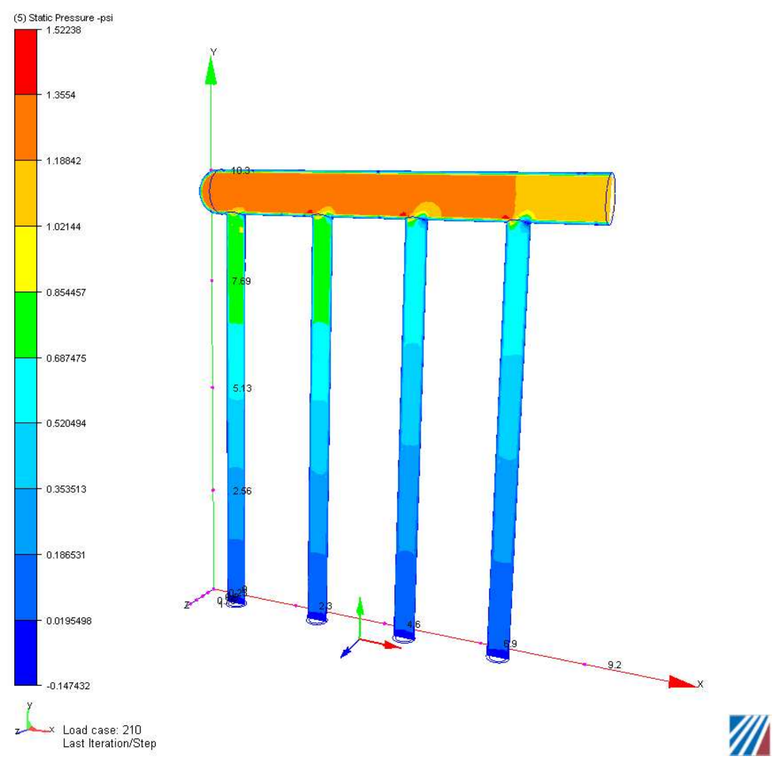


Figure 5: Steady-state relative pressure contour on an x-y cut plane.

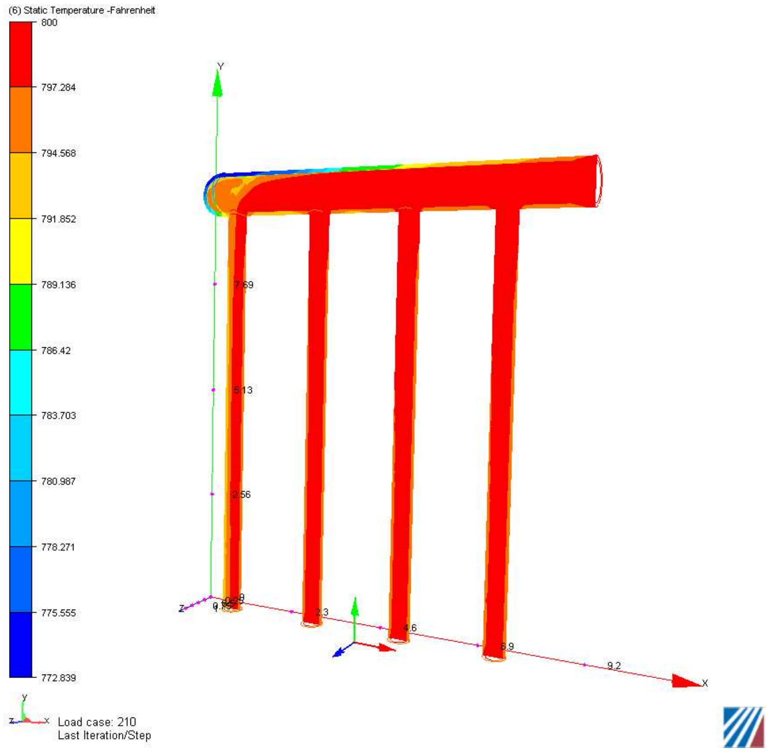


Figure 6: Steady-state temperature contour on an x-y cut plane (steady-state run).

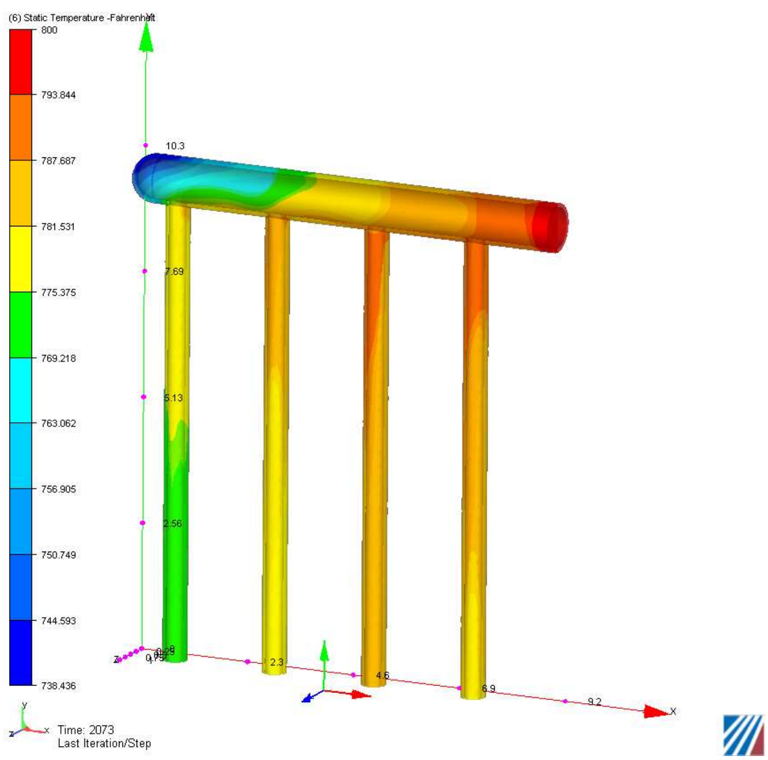
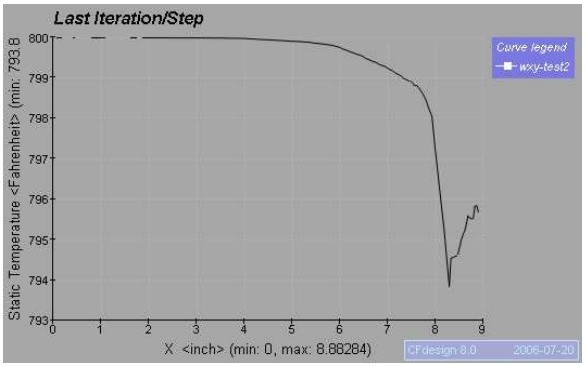
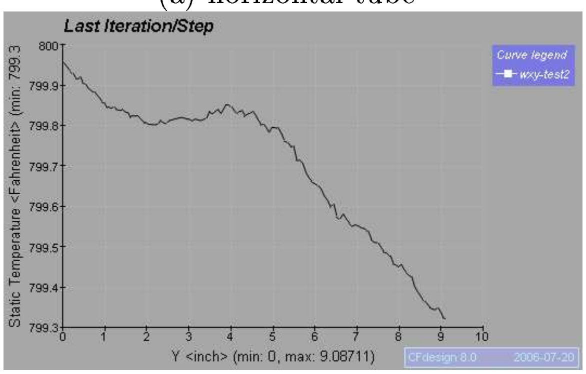


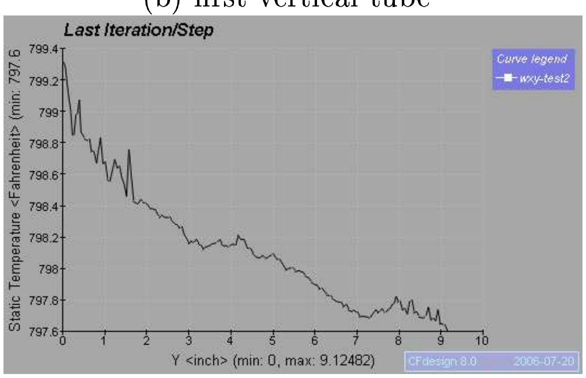
Figure 7: Steady-state temperature contour on an x-y cut plane (transient run).



(a) horizontal tube

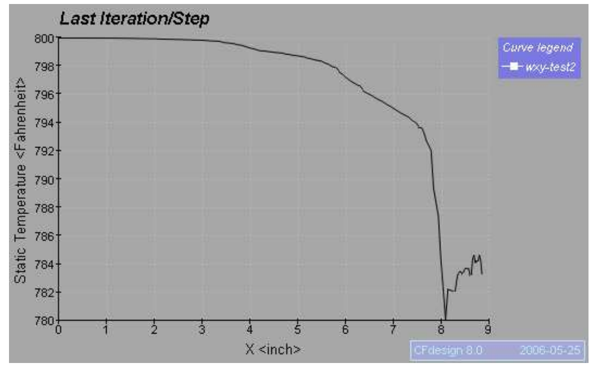


(b) first vertical tube

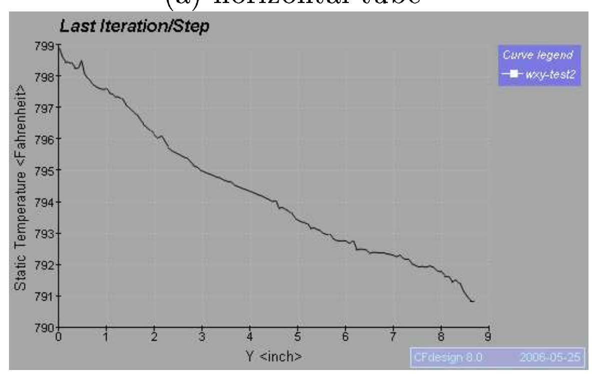


(c) fourth vertical tube

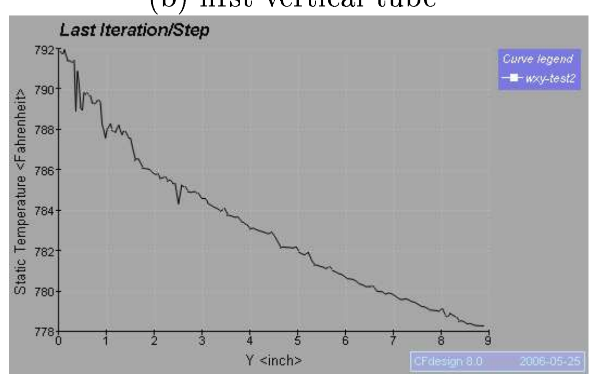
Figure 8: Steady-state temperature distribution along the flow direction (steady-state analysis).



(a) horizontal tube



(b) first vertical tube



(c) fourth vertical tube

Figure 9: Steady-state temperature distribution along the flow direction (transient analysis).

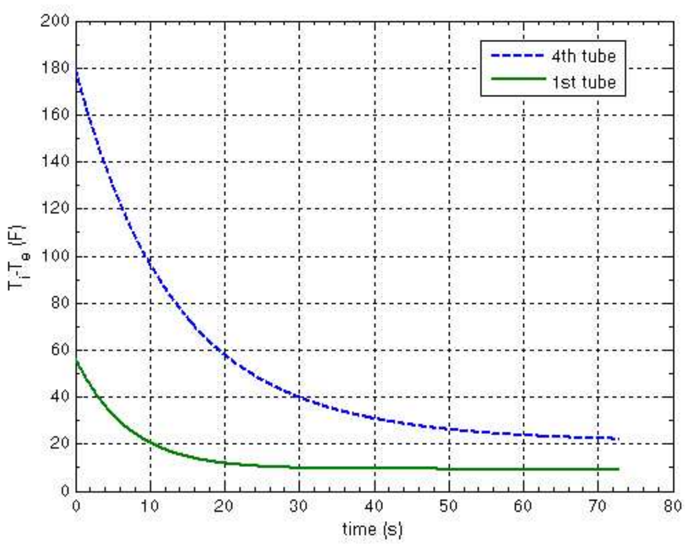


Figure 10: Time history of the fuel temperature at the exit of the vertical tubes (transient analysis).