Numerical Analysis of Conjugate Heat Transfer in a Combustion Chamber and Firetubes

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Introduction

COMSOL was used to verify handbook prediction from Heat Transfer Research Inc. (HTRI) of heat transfer coefficient for a combustion chamber and is firetubes. The COMSOL Conjugate Heat Transfer modules were used to simulate conduction, convection, and surface radiation simultaneously in the combustion chamber, firetubes, collector assembly. The combustion chamber modeled is shown in Figure 1. The combustion chamber shown in Figure 1 is used for cryogenic vaporization.

Figure 1. Combustion chamber modeled in COMSOL.

Figure 2 shows the geometry modeled in COMSOL.

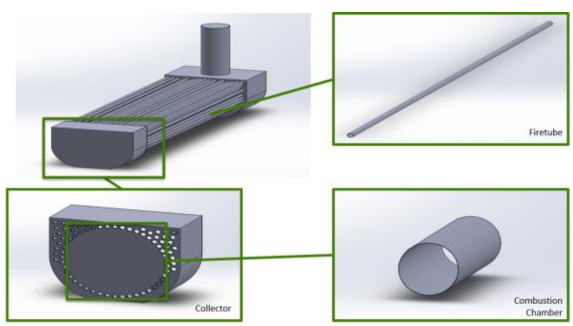

Figure 2. Geometry modeled in COMSOL.

The physical flow consists of flue gas on the tube side and hot water on the shell side of the U-tube bundle heat exchanger. The water volume is 20,000 gallons (75,708 L), the burner size is rate at 20 MBTU/hr (5.86×10^{6} W), with a 40 hp (29,828 W) blower and a water circulation pump of 10 hp (7,457 W). The model of the combustion chamber assumes carbon steel shell with flue gas on the internal side. The model of the collector assumes flue gas flowing in the passages. The firetubes are modeled as carbon steel with flue gas on the internal and water on the external side.

Governing Equations

COMSOL's CFD module using Compressible Navier-Stokes equations was coupled to the Heat Transfer modules for surface radiation and conduction. Equation (1) show the form of Conservation of Energy being solved for generic heat transfer

$$\rho C_p \vec{u}\cdot\nabla T + \nabla\cdot\vec{q} = Q \qquad (1)$$

Fourier's Law of heat conduction is used to model conduction via

$$\vec{q} = -k\nabla T \qquad (2)$$

Equation (3) shows the Conservation of Energy Equation for Heat Transfer in Fluids

$$\rho C_p \vec{u}\cdot\nabla T + \nabla\cdot\vec{q} = Q + Q_{\mathrm{P}} + Q_{\mathrm{vd}} \qquad (3)$$

The collection of radiation heat transfer equations listed as Equation (4) are the surface-to-surface radiation heat transfer equations solved by COMSOL for the radiosity network [2]

$$\begin{aligned}
-\hat{n}\cdot\vec{q} &= \varepsilon\left(G - e_b(T)\right)\\
(1-\varepsilon)G &= J - \varepsilon e_b(T)\\
G &= G_m(J) + G_{amb} + G_{exit} \qquad (4)\\
G_{amb} &= F_{amb} e_b(T_{amb})\\
e_b(T) &= n^2\sigma T^4
\end{aligned}$$

No attempt to model gas-radiation interactions was made in this study, as this was considered beyond the scope of the present work. Turbulent flow was modeled using the k-ε turbulence model. Initial conditions and no-slip boundary conditions for the problem included the specification of the flowrate, pressure, and temperature of the working flue-gas occupying the combustion chamber and flowing through the tubes. Heat transfer coefficients with values based upon experience were prescribed as shown in Figure 3 through Figure 5 for the various components of the model.

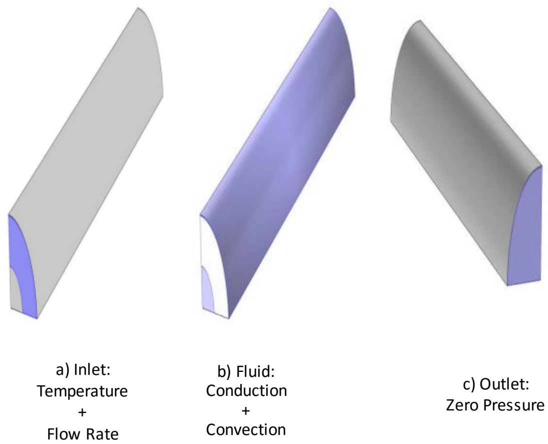

Figure 3. Boundary conditions for combustion chamber.

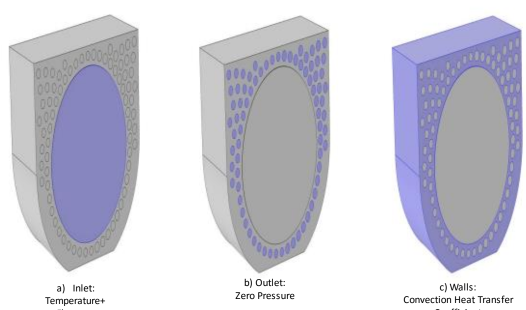

Figure 4. Boundary conditions for collector.

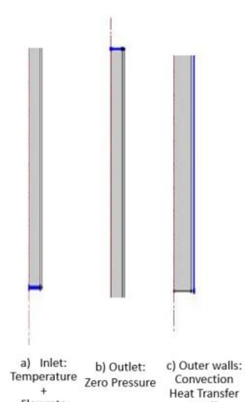

Figure 5. Boundary conditions for firetubes.

Meshing

The COMSOL physics based meshing capabilities were employed. Figure 6 shows the mesh for the various components.

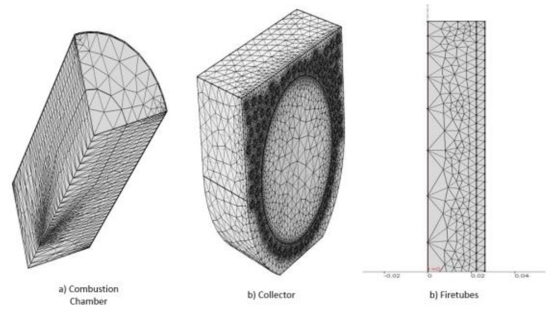

Figure 6. Mesh for combustion chamber, collectors and firetubes.

Simulation Results / Discussion

Figure 7 shows the results for the combustion chamber post-processing for a duty of 5.6 MBTU/hr (1.64×10^6 W).

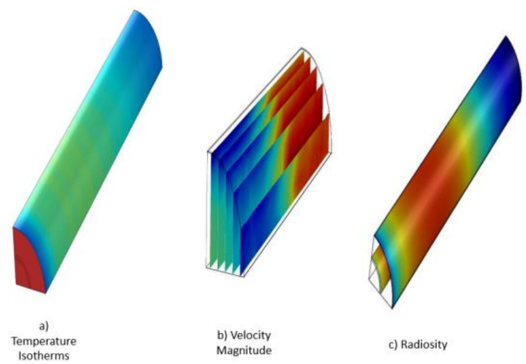

Figure 7. Combustion chamber post-processing results.

Figure 8 shows the post-processing results for the firetubes having a load of 9.6 MBTU/hr (2.8×10^6 W) and a back pressure of 2.3 in w.c. (572.33 Pa).

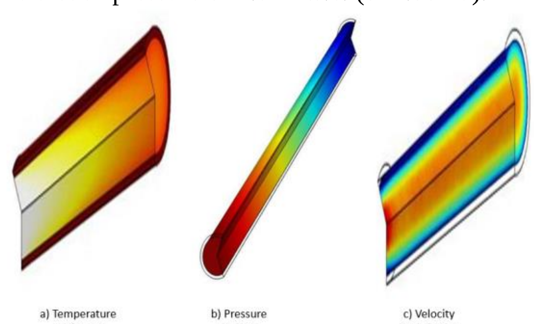

Figure 8. Firetubes post-processing results.

Figure 9 shows velocity streamlines within the collector.

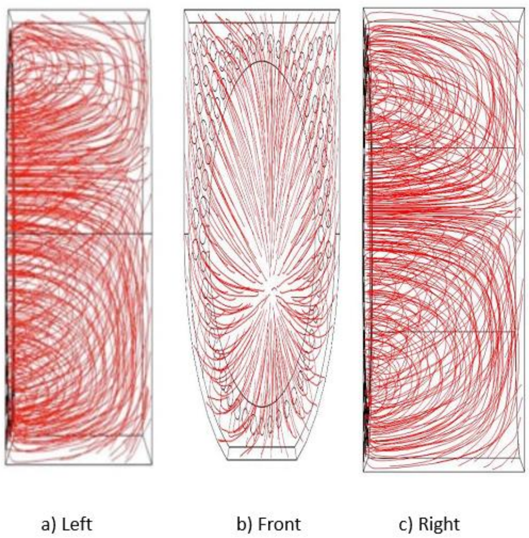

Figure 9. Velocity streamlines within the collector.

Figure 10 shows backpressure isobars within the fire tube locations in the collector with a back pressure of 3 in w.c. (746.52 Pa).

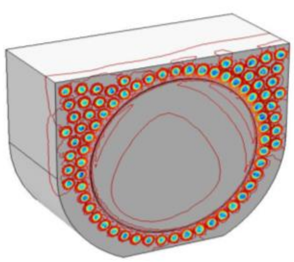

Figure 10. Pressure isobars in collector.

Figure 11 shows the flue gas temperature versus fire tube length as a function of flowrate.

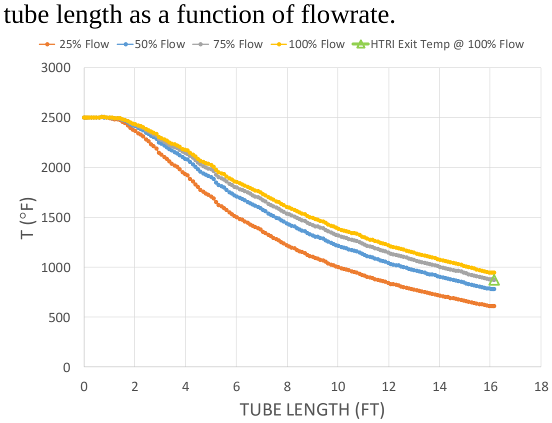

Figure 11. Flue gas temperature vs. fire tube length as function of flow rate.

The trends of Figure 11 are seen to match the predictions of HTRI closely, as indicated by the HTRI exit temperature at 100% flow. The heat transfer coefficients for the components of the system determined from COMSOL as compared to those of HTRI are summarized in Table 1.

Component	COMSOL h (W/m2-K)	HTRI h (W/m^2-K)
Chamber	44.80	45.19
Firetubes	62.46	62.06

Table 1. Heat transfer coefficient comparison

The heat transfer coefficients predicted by COMSOL is within 2% agreement of those given by HTRI handbook formulae. The back pressure predicted by COMSOL is within 6% of the values predicted by HRTI based analysis. Thus, the COMSOL heat transfer model is deemed reliable.

Conclusions

This paper has presented the study of conjugate heat transfer in a combustion chamber / firetubes eat exchanger assembly. The motivation for the study was to compare the COMSOL findings to those obtained using Heat Transfer Research Institute's correlations. The COMSOL model has been found to be within acceptable agreement with the handbook based calculations.

References

1. HTRI, https://www.htri.net/
2. COMSOL Users Guide