Validation of the Thermal Radiation Heat Transfer of CFX-5.7 code Using Analytical Solutions

Hyoung Tae Kim, Bo Wook Rhee, Byung-Joo Min
Korea Atomic Energy Research Institute
150 Dukjin-Don, Yusong-Gu, Daejon 305-353, Korea
kht@kaeri.re.kr

1. Introduction

During the post-blowdown phase of a postulated Loss of Coolant Accident (LOCA) with impaired Emergency Core Cooling (ECC) in CANDU reactors, either saturated or superheated steam is considered to be the only coolant available in the fuel channel. In this absence of significant convective heat transfer due to coolant, radiation heat transfer from the fuel elements to the pressure tube and eventually to the calandira tube can be the dominant heat transfer mode [1].

Recently the Computational Fluid Dynamics (CFD) code has been used to understand the three-dimensional phenomena in the CANDU fuel. If the CFD code is to be used to analyze postulated accident scenarios such as post-blowdown of LOCA without ECC, the radiation heat transfer model needs to be properly validated using analytical solution and/or experimental data.

This paper presents a validation study to assess the ability of the CFD code (CFX-5.7) to simulate the radiation heat transfer from fuel bundle to pressure tube. Analytical solutions to numerical thermal radiation-only problems were used to validate radiation heat transfer in CFD code.

2. Selection of Radiation Models in CFX-5.7

Calculations are performed with the commercial CFX-5.7 code [2]. It has a direct coupling of mass- and momentum equations leading to a high robustness and efficiency for complex flow. CFX-5.7 includes several radiation modeling options: Rosseland model, the P-1 model, the discrete transfer model and the Monte Carlo model.

In problems where thermal radiation is significant, the choice of the thermal radiation will affect not only the quality of the solution, but also the computational time it requires. Therefore, proper selection must be made from physical considerations.

The radiation model used for this study is the Monte Carlo model, which is based on ray-tracing concepts and a method of statistical simulation. It is selected as it is known to be the most effective when complex geometries and variable properties are involved [3].

3. Radiation-only Problem Considered

The idealized radiation problem to be considered in this study is that every radiant surface is diffuse, gray, and opaque with uniform temperature and uniform radiative properties. A medium in the enclosure surfaces is assumed to be nonparticipating in radiation; that is, it has negligible emission and absorption.

For the two-dimensional problem where more than two solid objects are involved, the analytical solution model needs to employs a two-dimensional view factor matrix. This implies that the cross-sectional geometries specified for thermal radiation are assumed to be axially infinite. Radiation view factors can be analytically derived for simple geometries and are tabulated in several references on heat transfer [3].

4. Validation Using Analytical Solution

4.1 Two-Surface Enclosure Radiation

This validation case involves the problem of the radiation heat transfer from a heated inner pin to a surrounding coaxial thin tube as shown in Fig. 1.

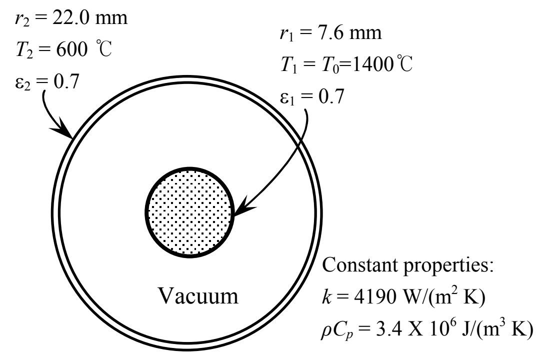


Figure 1. Two infinitely long concentric cylinders for two-surface enclosure problem.

The radii of a solid radiating pin and a surrounding tube are r_1 and r_2, respectively. The geometry and property data are given in Fig. 1. The hot pin has a uniform initial temperature of T_0 and the outside surface of the tube is kept at a constant temperature T_2. Both the pin and the tube are assumed to have a high thermal conductivity (k) so that temperature gradients across wall are negligible. Emissivities of the pin outer surface and the tube inner surface are assumed to be constant at ε_1 and ε_2, respectively. Heat transfer from the pin (surface 1) to the tube inner surface (surface 2) is assumed to be by thermal radiation only.

The steady-state initial condition is obtained by maintaining the steady input power in the hot pin. And then the input power is turned off at the start of the transient calculation.

The transient pin temperature T_1 and the net pin-to-tube radiative heat flux q''_{12} can be determined analytically:

$$\tau = \frac{\rho V C_p (1/\varepsilon_1 + (r_1/r_2)(1/\varepsilon_2 - 1))}{A_1 \sigma} \times \left[\frac{1}{4T_2^3} \ln \left| \frac{(T_1+T_2)/(T_1-T_2)}{(T_0+T_2)/(T_0-T_2)} \right| + \frac{1}{2T_2^3} \left(\tan^{-1}\frac{T_1}{T_2} - \tan^{-1}\frac{T_0}{T_2} \right) \right] \quad \text{(sec)}, \quad (1)$$

where $\sigma = 5.67 \times 10^{-8}\ \mathrm{W/(m^2 \cdot K^4)}$,
T_0 = initial temperature of the hot pin (K),
τ = cooling time from T_0 to T_1 (sec).

Figure 2 shows the mesh configuration and initial temperature distribution for two-surface enclosure problem.

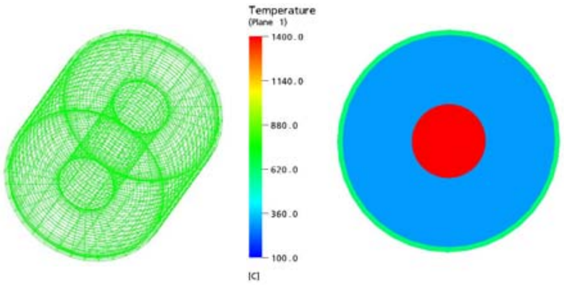


Figure 2. (a) Mesh configuration and (b) initial temperature distribution on the cross sectional view for two-surface enclosure problem.

Because the radiation heat transfer is transparent to the medium between the pin and the tube, the temperature of the medium (300℃) can be lower than that on the tube inner surface (600℃) as shown in Fig. 2 (b).

Figure 3 compares the CFX-5.7 calculation results (see the "• " symbol) for T_1 and q''_{12} with the analytical solutions (solid lines). This comparison shows an excellent agreement.

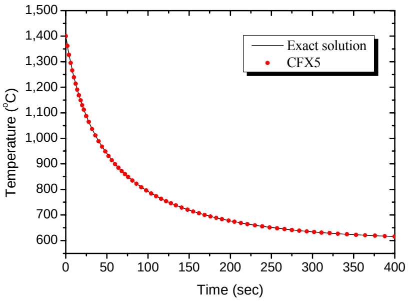
To compute radiative heat transfer among the surfaces in an enclosure, we only need to know either the surface temperature or the heat transfer rate.

In Fig. 4 CFX-5.7 calculated the pin temperature (T_1) with the specified heat transfer rate from which analytical solution of T_1 also can be obtained. This CFX-5.7 result also well agrees with the analytical solution.

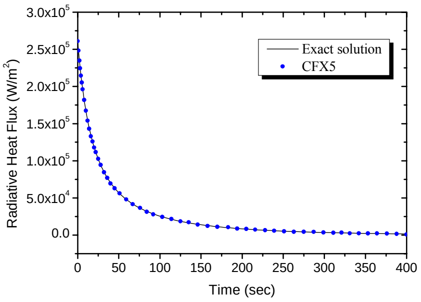
5. Conclusion

The prediction of the thermal radiation heat transfer of CFX-5.7 code was assessed using analytical solutions for the enclosure of two diffuse-gray surfaces. The results show that CFX-5.7 accurately calculates this benchmark problem.

Further validation works are required to reduce uncertainties and thus increase confidence, in the code prediction when the CFX-5.7 code is used to predict the fuel channel behavior under a postulated LOCA scenario.



(a) Pin temperature (T_1)



(b) Radiative heat flux (Q''_{12})

Figure 3. Comparison of CFX-5.7 results with analytical solutions for two-surface enclosure problem

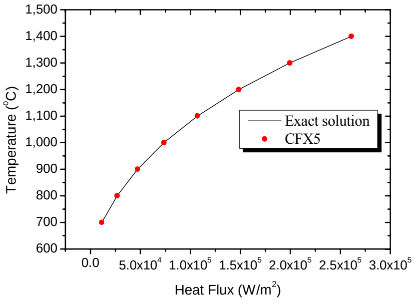


Figure 4. Comparison of CFX-5.7 temperature predictions with analytical solutions when the heat transfer rate is given.

REFERENCES

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[3] R. Siegel and J.R. Howell, "Thermal Radiation Heat Transfer," Third Edition, Hemisphere Publishing Co., Washington, 1992.