Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, November 2-3, 2006

Performance Prediction of a Compact High Temperature Heat Exchanger by Using a Periodic CFD analysis

Min-Hwan Kim, Won-Jae Lee
Korea Atomic Energy Research Institute
P.O.Box 105, Yuseong, Daejeon, Korea, 305-350
mhkim@kaeri.re.kr

1. Introduction

Plate-fin type compact heat exchangers are a preferable design candidate for the intermediate heat exchanger (IHX) of a VHTR (Very High Temperature gas-cooled Reactor) due to their operation ability in high pressure and temperature conditions. Among them, offset strip fin and printed circuit types are being considered in the NHDD design of the IHX.

Studies has been made to predict the thermo-fluid performances for these types of the IHX by using a full single channel CFD (Computational Fluid Dynamics) analysis [1][2]. However, a further simulation in detail could not be performed because it requires more computer resources even though the single channel approach is adopted.

As an effort to overcome the above difficulty, we focused on a periodic flow pattern of the plate-fin type heat exchanger core. For this, a concept of a periodically developed flow, as treated by Partankar et al. [3], is adopted for the performance prediction of the IHX.

The purpose of this study is to assess if the concept of the periodic CFD approach could be applicable to the IHX performance analysis. To verify the adopted approach, several benchmark problems are selected and analyzed by using CFX. The results are compared with analytic solutions or CFD results for a full single channel.

2. Periodic Approach

For a fully developed periodic flow for the streamwise direction, the velocity field and the pressure difference repeat themselves with the period length L. The pressure field can be divided into two components.

$$p(x,y,z) = -\beta x + P(x,y,z) \qquad (1)$$

The first term on the right hand side in Eq. (1) represents the pressure variation in the periodic module and the second one is the pressure component repeating itself. The β is a pressure gradient which drives the periodic streamwise flow and is written as follows.

$$\beta = [p(x,y,z) - p(x+L,y,z)]/L \qquad (2)$$

As is the case with the pressure field, we can write the temperature in the following.

$$T(x,y,z) = \gamma x + \widetilde{T}(x,y,z) \qquad (3)$$

$$\gamma = [T(x+L,y,z) - T(x,y,z)]/L = Q/\dot{m}c_p L \qquad (4)$$

By using equations (1) and (3), the streamwise momentum and energy equations for the periodically developed region can be written as

$$\rho u_j(\partial u_i / \partial u_j) = \beta - \partial P/\partial x_i + \mu(\partial^2 u_i / \partial x_j{}^2) \qquad (5)$$

$$\rho c_p u_j \left(\partial \widetilde{T} / \partial u_j\right) = -\rho c_p u_1 \gamma + k\left(\partial^2 \widetilde{T} / \partial x_j{}^2\right) \qquad (6)$$

If the first terms on the right-hand side of both equations are treated as a source term, we can obtain a solution for the periodic developed regime by solving the equations.

3. CFD Analyses for Benchmark Problems

3.1 Fully-Developed 2D Laminar Flow

As one of the benchmark problems for the validation of the periodic approach, we selected a fully-developed two-dimensional laminar flow between parallel flat plates with a distance 2H. The following are the exact solutions of velocity and temperature.

$$u/u_{\max} = 1 - (y/H)^2 \qquad (7)$$

$$(T - T_c)/(T_s - T_c) = 1.2[(y/H)^2 - (y/H)^4/6] \qquad (8)$$

where $u_{\max} = -(dp/dx)(H^2/2\mu)$.

With a uniform wall heat flux assumed, we solved the problem. Comparison of the CFD results with the exact solutions is made in Figure 1. Seeing that the CFD results precisely follow the exact solution, the periodic approach is valid for the fully developed parallel flow.

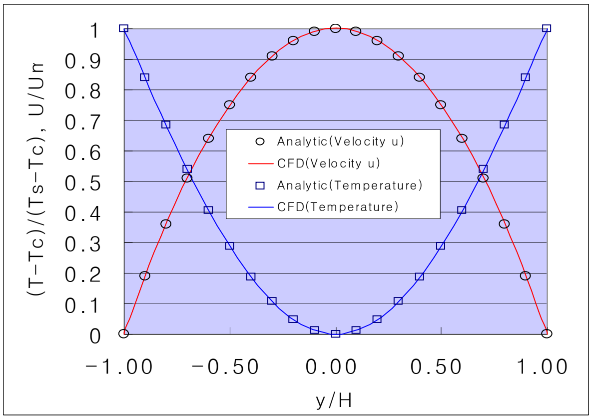

Figure 1. Comparison of velocity and temperature distribution between the CFD results and the exact solution

3.2 Conjugate Heat Transfer in a Fully-Developed 2D Laminar Flow

The second benchmark problem is a two-dimensional conjugate heat transfer problem between two fully developed laminar cross-flows separated by a plate, as shown in Figure 2.

When convective heat transfer coefficients h_1 and h_2 are given, the transferred heat per unit area is calculated as follows.

$$q_w = Q/A = \Delta T / \left(1/h_1 + L/k_s + 1/h_2\right) \tag{9}$$

From the exact solution for a 2D laminar flow between plates, the convective heat transfer coefficient is

$$h_c = q_w/(T_s - T_b) = 2.058 k_w / H \tag{10}$$

Substituting the heat transfer coefficient into Eq. (9), calculated from given k and H, the wall heat flux is obtained and then exact temperature difference between the surface temperature and the bulk temperature is obtained.

The CFD analysis is performed with the assumptions that k_s and k_w are constants, 60.5 and 0.6069 W/m-K respectively. The resulting wall and bulk temperatures are compared with the exact values in Table 1. The CFD results satisfy the exact values to within an error of 0.1%.

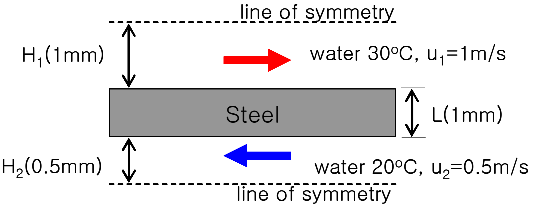

Figure 2. Schematic description of two dimensional conjugate heat transfer problem

Table. 1 Temperatures of the CFD result and the exact solution

	Region 1	Region 2
T_b (K)	304.672	294.672
T_s (K)	298.098	297.963
$\Delta T = \|T_b - T_s\|$ (K)	6.574	3.291
$\Delta T_{analytic}$ (K)	6.576	3.288

3.3 Conjugate Heat Transfer in a Compact High Temperature Heat Exchanger

An offset strip type compact heat exchanger being developed in the UNLV HTHX Project is selected as the last benchmark problem. The heat exchanger is made of a SiC composite. The primary fluid is helium, and the secondary fluid is a Molten-Salt. The 3D geometry of the flow channels and the grid systems are shown in Figure 3. Details about the flow conditions and physical properties are given in reference [1].

The exact solution or experimental data are not available in the HTHX module. For the purpose of the benchmark problem, we compared the present results with a full channel analysis[1] that has 37 periodic modules, the same meshes for each module as the present one, and the same flow conditions. The performance parameters for both results are presented in Table. 1. The present results for the pressure drop through each channel provide a good agreement with the full channel analysis. Comparing the outlet temperatures, LMTD, and overall heat transfer coefficient, there is a little difference between the two results but the difference is not so much as the assumption that the heat transfer rate is constant along the wall.

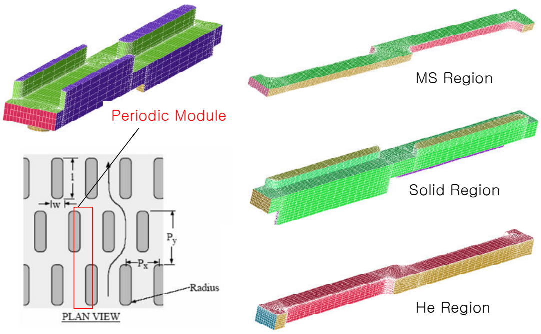

Figure 3. HTHX periodic geometry and grid systems

Table 1. Comparison of performance parameters

Property	Full channel	Present
He side ΔP	15.1 (kPa)	15.0 (kPa)
MS side ΔP	10.9 (kPa)	10.9 (kPa)
He inlet(fixed)/outlet T(K)	1273/930	1273/936
MS inlet/outlet(fixed) T(K)	833/1257	833/1262
LMTD(K)	44.9	41.2

4. Conclusions

A periodic CFD approach being used for a high temperature heat exchanger was introduced and applied to selected benchmark problems, which are a fully developed 2D laminar heat transfer and a conjugate heat transfer between parallel plates which have exact solutions, and a heat transfer in the HTHX module. The results for the first and second problems had a very good agreement with the exact solutions. For the HTHX module, the pressure drops were predicted well but some difference was observed in the temperature parameters when compared to the full channel CFD analysis. Considering its assumptions and simplicities, the results showed that the periodic analysis provides physically reasonable results and can be used as a method to predict the performance of a heat exchanger within an engineering margin.

Acknowledgement

This study has been carried out under the Nuclear R&D Program by MOST.

REFERENCES

[1] M.H. Kim, W.J. Lee, and J.H. Chang, “A CFD Assessment of a Compact High Temperature Heat Exchanger,” Transactions of the KNS Spring Meeting, 2006.

[2] N.I. Tak and W.J. Lee, “Evaluation of Thermo-Fluid Performance of Compact Heat Exchanger with Corrugated Wall Channels,” Transactions of the KNS Spring Meeting, 2006.

[3] S. V. Patankar and C. Prakash, "An Analysis of the Effect of Plate Thickness on Laminar Flow and Heat Transfer in Interrupted-Plate Passages," Int. J. Heat Mass Transfer, Vol. 24, No. 11, pp. 1801-1810, 1981