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Numerical study on crossflow printed circuit heat exchanger for advanced small modular reactors

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ABSTRACT

Various fluids such as water, gases (helium), molten-salts (FLiNaK, FLiBe) and liquid metal (sodium) are used as a coolant of advanced small modular reactors (SMRs). The printed-circuit heat exchanger (PCHE) has been adopted as the intermediate and/or secondary heat exchanger of SMR systems because this heat exchanger is compact and effective. The size and cost of PCHE can be changed by the coolant type of each SMR. In this study, the crossflow PCHE analysis code for advanced small modular reactor has been developed for the thermal design and cost estimation of the heat exchanger. The analytical solution of single-pass, both unmixed fluids crossflow heat exchanger model was employed to calculate a two-dimensional temperature profile of a crossflow PCHE. The analytical solution of crossflow heat exchanger was simply implemented by using built-in function of the MATLAB program. The effect of fluid property uncertainty on the calculation results was evaluated. In addition, the effect of heat transfer correlations on the calculated temperature profile was analyzed by taking into account possible combinations of primary and secondary coolants in the SMR systems. Size and cost of heat exchanger were evaluated for the given temperature requirement of each SMR.

1. Introduction

Small modular reactors (SMR) are being developed to provide heat and electricity to the remote regions where the large nuclear power plants cannot be built. In addition, recently, the SMRs have been considered as good energy sources for the process heat application. Contrary to typical water-cooled SMRs, advanced SMRs use various coolant materials such as gases (helium, supercritical carbon dioxide), molten-salts (FLiNaK, FLiBe and KFZrF4), and liquid metal (sodium). The operating temperature and pressure of an advanced SMR can be varied by the type of reactor coolant. Table 1 describes the typical temperature and pressure conditions of SMRs according to the reactor coolants. Inlet and outlet temperatures of primary and secondary fluids are based on the intermediate heat exchanger (IHX). Thus, the inlet temperature of the primary fluids shown in Table 1 is the outlet temperature of reactor coolant. Fig. 1 shows some of the potential options that the IHX and secondary heat exchanger (SHX) could be configured in the system. It could be linked to production of power system and also could be used for providing the process heat from the reactor for industrial applications. In this case, both IHX and SHX could be either conventional-type heat exchanger or compact heat exchanger, such as PCHE.

The word "small" in SMRs refers not only to the reactor power, but also to the size of the reactor. In this regard, the compact heat exchanger can be a good design option because the compact heat exchanger has a large heat transfer surface area per unit volume, which can result in the reduced size, weight, and cost. Fig. 2 shows the surface compactness that is a criterion for classifying the heat exchanger. Printed circuit heat exchanger (PCHE) is a compact heat exchanger and has been considered one of the candidate heat exchangers in designs of advanced SMRs. Fine grooves in the plate of the PCHE are made by employing the technique used for making printed circuit boards. The PCHE has been commercially manufactured by Heatric™ [1]. Fig. 3 shows the typical PCHE manufactured by Heatric Ltd.

The PCHE can be classified by the flow configurations. The arrangement of flow channels are parallel in the parallel and counter flow PCHEs, whereas it is orthogonal in the crossflow PCHE. Temperature distribution of the crossflow heat exchanger is two-dimensional so that it is more complicated to analyze than parallel or counter flow heat exchangers. Due to this complexity, many previous studies have used computational fluid dynamics (CFD) codes such as CFX or FLUENT. However, CFD simulation is not adequate for the design process of the PCHE since CFD simulation requires vast computational time and cost. In the CFD model of PCHE, since

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Nomenclature

A	area or overall heat transfer surface area (m^2)
C	flow stream heat capacity rate ($= \dot{m}c_{p,j}$)
C_M	material cost factor (USD/kg)
C_{op}	operating cost factor (USD/Wh)
c_p	specific heat capacity (kJ/kg K)
C^*	the ratio of heat capacity rate ($=C_{min}/C_{max}$)
CP	capital cost of PCHE (USD)
D, d	diameter (m)
f	friction factor
h	convective heat transfer coefficient (W/m^2 K)
I_0	modified Bessel function of the first kind and zero order
k	thermal conductivity (W/m K)
L	length (m)
M	total mass of heat exchanger (kg)
$\dot{m}$	mass flow rate (kg/s)
N	number of flow channel
NTU	number of transfer unit
Nu	Nusselt number (=hD/k)
OP	operating cost of PCHE (USD)
P	channel pitch (m) or Pressure (Pa)
p	the order of scheme
Pe	Peclet number ($=Re \times Pr$)
Pr	Prandtl number ($=c_p\mu/k$)
Q	heat duty (W)
R	thermal resistance ($m^2 \cdot K/W$)
Re	Reynolds number ($=\rho VD/\mu$)
T	temperature (K)
t	thickness (m)
U	overall heat transfer coefficient (W/m^2 K)
X	normalized length in x-coordinate ($=x/L_1NTU_1$)
Y	normalized length in y-coordinate ($=y/L_2NTU_2$) or Operation period of heat exchanger (yr)
V	volume (m^3) or Fluid velocity (m/s)

Greek and symbols

Δ	difference
δ	plate thickness
ε	effectiveness of PCHE ($=Q/Q_{max}$)
η_o	surface efficiency
θ	dimensionless temperature ($=(T-T_{2,in}))/(T_{1,in}-T_{2,in})$
μ	dynamic viscosity of fluid (Pa s)
$\mathcal{P}$	pumping power ($= \dot{m}\Delta P/\rho$)
ρ	density (kg/m^3)
Φ	approximated exact solution by Richardson extrapolation method
ϕ	numerical solution

Subscript

f	fin
h	grid width or Hydraulic diameter
HX	heat exchanger
in	inlet
j	index of fluid (1: primary, 2: secondary)
max	maximum
min	minimum
L	Laplace transformation operation
out	outlet
p	plate
tot	total
w	wall
x–s	cross-sectional

the structure of PCHE is complicated and the dimensions of flow channel of PCHE are small, the fine structure of mesh is required to obtain accurate results. In this study, we developed the crossflow PCHE analysis code to perform the thermal design and cost estimation of PCHE.

2. Development of crossflow PCHE analysis code

In order to perform the thermal design and cost estimation of a crossflow PCHE, the analysis code was developed based on the MATLAB program [8]. The analytical solution of single-pass, both unmixed fluids crossflow heat exchanger was employed to solve the temperature profile of crossflow PCHE. Although typical PCHEs manufactured by Heatric™ have zigzag-shaped flow channel, the straight pipe is assumed in this study. The analytical modeling method, analytical solution, and thermal design procedure are described in following sections.

2.1. Analytical modeling and solution of crossflow heat exchanger

For single-pass crossflow design, a solution to the problem of both fluids unmixed in the heat exchanger was obtained by Nusselt [9] in the form of analytical series expansions by assuming the longitudinal conduction can be neglected. Since the flow mixing is not occurred in the PCHE, this model is applicable. The analytical model of crossflow PCHE has been developed by the energy balance between the hot and cold fluid sides shown in Fig. 4.

The energy balance equations in Fig. 3 are as follows:

Fluid 1 (Hot fluid):

$$\underbrace{d\dot{m}_1 c_{p,1} T_1}_{\left(\begin{array}{c}\text{Fluid enthalpy rate}\\ \text{into the C.V.}\end{array}\right)} - \underbrace{d\dot{m}_1 c_{p,1}\left[T_1 + \frac{\partial T_1}{\partial_x}dx\right]}_{\left(\begin{array}{c}\text{Fluid enthalpy rate}\\ \text{out of the C.V.}\end{array}\right)} - \underbrace{dQ}_{\left(\begin{array}{c}\text{Heat transfer rate}\\ \text{from fluid to wall}\end{array}\right)} = 0 \tag{1}$$

Table 1
Typical temperature and pressure conditions of advanced SMRs.

Coolant type	Coolants	Operation conditions		
	Primary/secondary	Inlet/outlet temperature (°C)		Primary/secondary pressure (MPa)
		Primary	Secondary	
Water-cooled [2]	Water/Water	323/295	200/293	15.0/5.0
Gas-cooled [3]	He/He	950/637	351/925	7.0/7.0
Liquid metal-cooled [4]	Na/Na	545/390	320/526	0.1/0.1
Molten salt-cooled [5]	FLiBe/FLiNaK	700/650	600/690	0.1/0.1