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Simplified optimum sizing and cost analysis for compact heat exchanger in VHTR

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ABSTRACT

In this study, the optimum size of the compact heat exchanger has been developed based on its weight and pumping power for the reference design of 600 MWt very high temperature gas-cooled reactor (VHTR) system. Alloy 617 was selected as a construction material. The optimum size and a number of configurations for the reference design of the VHTR with an intermediate heat exchanger (IHX) were investigated and our initial calculations indicated that it has an unrealistically too large aspect ratio of the length and height due to its small-sized channels, which might cause manifolding problems and a large number of parallel modules with high thermal stress. The flow area and channel diameter were then adjusted to achieve a smaller aspect ratio in this paper. Achievement of this aspect ratio resulted in higher cost, but the cost increase was less than would have occurred by simply reducing the flow area by itself. The appropriate channel diameter is estimated to be less than 5.00 mm for the reference system. The effect of channel waviness enhanced the compactness and heat transfer performance, but unfavorably increased the aspect ratio. Therefore, the waviness should be carefully determined based on performance and economics. In this study, the waviness of the IHX is recommended to be selected between 1.0 and 2.5. Calculations show that reducing the duty dramatically decreases the aspect ratio, indicating that the compact heat exchanger is easy to be optimally designed for low duty, but many modules are required for high duty operation proportional to the operating power. Finally, the effect of working fluids was investigated, and it reveals that using carbon dioxide instead of helium in the secondary side reduces the size and cost by about 20% due to the lower pumping power in spite of its lower heat transfer capability by a factor of 4.

1. Introduction

The Idaho National Laboratory and the U.S. Department of Energy are developing a Next Generation Nuclear Plant (NGNP) as part of the Generation IV program. A very high temperature reactor (VHTR) with a closed gas turbine cycle is envisioned as one of the most promising nuclear reactor technologies due to its passive safety features and capability to supply high temperature heat to hydrogen production plants and other potential industrial users. The efficiency of the power conversion system (PCS) for the NGNP will be enhanced over those used in the current generation of light water reactors due to the significantly higher outlet temperatures of the VHTR. Besides demonstrating a system design that can be used directly for subsequent commercial deployment, the NGNP will demonstrate key technology elements that can be used in advanced power conversion systems for other Generation IV reactors. In this type of reactor, an intermediate heat exchanger (IHX) transfers heat from the reactor core to an electricity or hydrogen production system. The IHX is a key component because its effectiveness is directly related to the system overall efficiency. In VHTRs, the gaseous coolant (i.e., helium) generally has poor heat transfer capability that requires very large surface area for the given conditions. To meet this large surface area requirement, the compact heat exchanger (CHE), which is widely used in the chemical and petroleum refining industries for gas-to-gas and gas-to-liquid heat exchange, is considered as a potential candidate for an IHX as a replacement for the classical shell and tube type heat exchanger. A compact heat exchanger is arbitrary assumed to be a heat exchanger having a surface area density greater than 700 m^2/m^3. This high compactness is usually achieved by fins and microchannels, and leads to an enormous heat transfer enhancement with an overall size reduction.

For decades, much research has been carried out on the design and performance of compact heat exchangers. Kays and London (1984) have studied and published a book about the various types of the compact heat exchangers. They categorized the configurations

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Nomenclature

A	flow area ($A_h = 0.5A$, $A_c = 0.5A$) (m^2)
A_f	frontal area ($A_f = H^2$, $A_{f,h} = 0.5A_f$, $A_{f,c} = 0.5A_f$)
b	channel width (m)—($b = d$ for PCHE)
C_p	heat capacity (J/kg K)
C_{op}	cost ($) per wh
d	channel diameter (m)
d_e	equivalent diameter ($d_e = 4AL/S$)
f	friction factor
h_c	heat transfer of cold channel
h_h	heat transfer coefficient of hot channel
H	CHE height and width
k	thermal conductivity (W/m K)
L	CHE length
$\dot{m}$	mass flow rate (kg/s)
N_f	number of fins per meter
OP	operating cost of CHE
p	pitch of channel (m)
Q	total transferred heat
S	heat transfer surface area ($S = \beta V$, $S_h = 0.5S$, $S_c = 0.5S$)
t_f	fin thickness (m)
t_p	plate thickness (m)
U	overall heat transfer coefficient
V	volume of compact heat exchanger (CHE) ($V = H^2L$)
Y	total duration of operation

Greek symbols

β	surface area density
ΔP	pressure differential between hot and cold fluid; pressure drop (Pa)
θ_m	log mean temperature
Λ	wavelength (m)
μ	viscosity (Pa m)
σ	ratio of the free flow area to the frontal area ($\sigma = A/A_f$)
σ_D	maximum allowable stress
ρ	density of flow (kg/m^3)

of compact heat exchangers and provided experimental data on heat transfer and friction factors. Hesselgreaves (2001) improved the heat transfer and friction factor correlations and provided more generalized forms that considered the geometrical configurations. Dostal et al. (2004) performed simple cost estimation and design calculation for an IHX used with a supercritical CO_2 reactor, on the basis of the weight. In their study, a printed circuit heat exchanger (PCHE) manufactured by HEATRIC was employed and estimated extensively. A PCHE is a special type of compact heat exchanger that is manufactured in two steps. First, individual plates are chemically etched to form the flow channels, and then the plates are diffusion bonded together to form a monolithic block. The shapes of channels are generally wavy. Nikitin et al. (2006) experimentally investigated the performance of a PCHE using supercritical CO_2. They measured heat transfer and flow data and developed heat transfer and friction factor correlations. In addition, they compared the experimental data with CFD simulations for thermal hydraulic analysis. Song (2005) also performed experiments for a PCHE using air. He obtained data at low Reynolds numbers and developed heat transfer and friction factor correlations. He estimated the adaptability of Hesselgreaves (2001)'s universal correlation to PCHE type heat exchanger.

Generally, in the VHTR, the IHX influences plant economics due to its large size and costly materials. In the current study, we focused on the optimum sizing and cost for CHEs. The cost of a heat exchanger can be described as the summation of capital cost and operating cost. The capital cost is associated with the heat exchanger size while the operating cost is associated with pumping power. Generally, the capital and operating costs are negatively correlated. For example, if the size of a heat exchanger is reduced to lower capital cost, operating cost will tend to increase due to increased pressure drop. Therefore, the size of the heat exchanger should be carefully determined from the economic viewpoint. Until recently, much research has been carried out to estimate CHE heat transfer performance and friction loss, but little attention has been given to the optimum size and cost based on performance and economic considerations. In this study, we developed an analytic model for the optimum size of compact heat exchangers, and evaluated them in the context of VHTR systems.

2. Determination of CHE characteristic parameters

Kays and London (1984) characterized compact heat exchangers by the following geometrical parameters:

L: CHE length.
H: CHE height and width.
V: volume of CHE ($V = H^2L$).
A_f: frontal area ($A_f = H^2$, $A_{f,h} = 0.5A_f$, $A_{f,c} = 0.5A_f$).
A: flow area ($A_h = 0.5A$, $A_c = 0.5A$).
β: surface area density.
σ: ratio of the free flow area to the frontal area ($\sigma = A/A_f$).
S: heat transfer surface ($S = \beta V$, $S_h = 0.5S$, $S_c = 0.5S$).
d_e: equivalent diameter ($d_e = 4AL/S$).

All the heat transfer and friction factor calculations are based on the above geometrical parameters. Among the various types of compact heat exchangers, the PCHE manufactured by HEATRIC was investigated in this study. Fig. 1 shows the cut through cross-section of the typical PCHE which shows the shape of the channels.

Main configuration parameters for PCHE can be calculated by the basic geometrical variables of typical heat exchangers (Kakac and Liu, 2002; Bejan and Klaus, 2003).

Fig. 2 shows the front section and side view of PCHE channel. In this figure, each symbol represents the followings:

d: channel diameter (m).
p: pitch of channel (m).
t_p: plate thickness (m).
t_f: fin thickness (m)
Λ: wavelength (m).
b_w: channel width (m) ($b_w = d$ for PCHE).
P: perimeter of the channel (m).

2.1. Fin thickness (t_f) and pitch (p)

Hesselgreaves (2001) recommends the following formula for the fin thickness.

$$t_f = \frac{1}{((\sigma_D/\Delta P) + 1)N_f} \qquad (1)$$

where t_f is the fin thickness, σ_D is the maximum allowable stress, ΔP is the pressure differential between hot and cold fluid and N_f is the number of fins per meter.

In the PCHE, the number of fins per meter means the number of channel walls per meter (Dostal et al., 2004). Therefore,

$$N_f = \frac{1}{p} \qquad (2)$$