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Comparative analysis of compact heat exchangers for application as the intermediate heat exchanger for advanced nuclear reactors

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ABSTRACT

A comparative evaluation of alternative compact heat exchanger designs for use as the intermediate heat exchanger in advanced nuclear reactor systems is presented in this article. Candidate heat exchangers investigated included the Printed circuit heat exchanger (PCHE) and offset strip-fin heat exchanger (OSFHE). Both these heat exchangers offer high surface area to volume ratio (a measure of compactness [m^2/m^3]), high thermal effectiveness, and overall low pressure drop. Helium–helium heat exchanger designs for different heat exchanger types were developed for a 600 MW thermal advanced nuclear reactor. The wavy channel PCHE with a 15° pitch angle was found to offer optimum combination of heat transfer coefficient, compactness and pressure drop as compared to other alternatives. The principles of the comparative analysis presented here will be useful for heat exchanger evaluations in other applications as well.

1. Introduction

Advanced reactors, such as the High Temperature Gas-Cooled Reactor (HTGR) or Advanced High Temperature Reactor (AHTR) from the Generation IV Program, are required to deliver electricity and process heat with high efficiency. The electric power production may be through a high-pressure steam generator (Rankine Cycle) or a direct- or indirect-cycle gas turbine (Brayton Cycle). The process heat applications may include co-generation, coal-to-liquids conversion, and synthesis of chemical feedstock. The process heat applications of these advanced reactors are critically dependent upon an effective intermediate heat exchanger (IHX), which is a key component transferring heat from the primary coolant to a secondary coolant (Shultis and Faw, 2008). A schematic of the advanced reactor-IHX-power/heat application is shown in Fig. 1. The primary loop in the system conducts the thermal energy from the nuclear reactor to the IHX, and a secondary medium transfers this energy to the power generation or process application via the secondary loop. The overall performance of the system is highly dependent upon the IHX, requiring it to operate at high efficiency. The IHX also serves as the primary coolant boundary and must be robust enough to maintain system integrity under normal and off-normal conditions.

Several investigators have looked at various heat exchanger configurations for use as the IHX. Compact heat exchangers are particularly attractive candidates as they have high effectiveness and low heat loss due to their high heat transfer area per unit volume of the exchanger. In addition, compact heat exchangers, such as the printed circuit heat exchanger (PCHE) or offset strip-fin heat exchanger (OSFHE) operate in the laminar flow regime and have low pressure drops, minimizing the energy requirements for coolant circulation. Kim and No (2012) investigated the performance of a PCHE in a Helium-Helium test loop and found an effectiveness of 95%. Ishizuka et al. (2006) investigated the performance in a supercritical CO_2 loop and found an effectiveness of greater than 98%. The use of these heat exchangers can result in improved performance of the system shown in Fig. 1.

The objective of the present paper is to present a comparison of the steady state designs of a wavy-channel PCHE and an OSFHE for a 600 MWth nuclear reactor. These two types of heat exchangers are described briefly followed by the steady state models and resulting thermal-hydraulic designs. A comparative analysis of the two designs is also presented which would help in decision-making related to the advanced nuclear reactor systems.

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Nomenclature

A_s	heat transfer surface area
A_f	flow area
ch	channel height
c_p	specific heat capacity
D_h	hydraulic diameter
f	fanning friction factor
h	convection coefficient
j	Colburn factor
k	thermal conductivity
l	fin length
L_c	channel length
$\dot{m}$	mass flow rate
Nu	Nusselt number
ΔP	pressure drop
Pr	Prandtl number
P_x	pitch in span-wise direction
P_y	pitch in flow direction
$\dot{Q}$	thermal duty
Re	Reynolds number
t_f	OSFHE fin thickness
t_s	OSFHE plate thickness
t_w	wall thickness
T	temperature
ΔT_{LMTD}	log mean temperature difference
$\dot{Q}$	thermal duty
v	mean fluid velocity
Greek	
μ	fluid viscosity
ρ	fluid density
ϕ	wavy channel pitch angle

2. Heat exchanger geometry

2.1. Wavy-channel PCHE

A PCHE is a type of compact heat exchanger where the flow channels are photo-chemically etched on one side of thin plates. The fluid channels are typically semicircular in cross-section. These plates are then stacked on top of each other and formed into a heat exchanger core through a diffusion bonding process that includes a thermal soaking period to allow grain growth. This diffusion bonding process enables an interface-free join between the plates and gives the base material strength and a very high pressure containment capability (Hesselgreaves, 2001). A cross-section of a single-bank arrangement consists of hot and cold fluids flowing through the flow channels on alternate plates as shown in Fig. 2(a). It should be noted that the diffusion bonding process will eliminate the boundaries between the plates, forming a monolithic block with semicircular flow channels in it. The plenum arrangement to accomplish this flow configuration is shown in Fig. 2(b).

In the countercurrent flow arrangement, the cold and hot fluids flow in opposite directions on the adjacent plates. The individual channels are etched in a zig-zag configuration in the wavy channel PCHE as shown in Fig. 3. The geometry of the wavy channel is determined by the pitch angle ϕ and single pitch length as indicated in the figure.

A summary of the PCHE geometrical parameters investigated in this study is shown in Table 1. The channel pitch was maintained at 24.6 mm, while three different pitch angles of 10°, 15° and 20° were investigated.

2.2. OSFHE

An OSFHE consists of flow channels that have a number of rectangular fins of uniform thickness arrayed in the flow direction. Alternate fins along the flow direction are in a staggered configuration, with the offset between the upstream and downstream fins equal to half-fin spacing normal to the flow direction. The geometry of a unit cell of the offset strip-fin channel is shown in Fig. 4(a), with the characteristic dimensional parameters – fin length l, fin thickness t_f, fin spacing (pitch in span-wise direction P_x) – clearly identified. The height of the fin is same as the channel height ch, and the length of the unit cell is double the pitch in the flow direction (P_y), which is the center-to-center longitudinal distance between consecutive fins. The unit cell repeated in both the flow direction and the direction normal to the flow forms a single layer of flow channels. OSFHE is formed by stacking a number of such layers as shown in Fig. 4(b). As in the case of PCHE, cold and hot fluid flow through alternate layers of the OSFHE. The geometrical parameters of the OSFHE used in this study are shown in Table 2.

3. Design methodology

Alternative IHX designs for the two types of heat exchangers described above were developed for a high temperature gas reactor (HTGR). The basic design assumptions are as follows:

- the working fluid flow rates in the primary and secondary loops are equivalent and it thus is a balanced-flow heat exchanger,

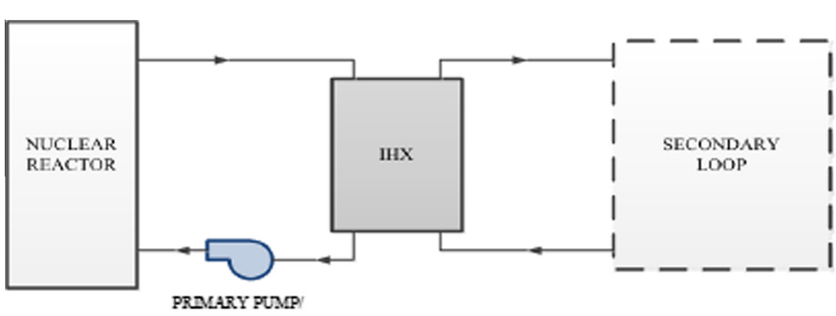

Fig. 1. Advanced reactor-IHX-secondary application system.