Annals of Nuclear Energy 94 (2016) 129–137

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Design study and cost assessment of straight, zigzag, S-shape, and OSF PCHEs for a FLiNaK–SCO_2 Secondary Heat Exchanger in FHRs

In Hun Kim *, Xiaoqin Zhang, Richard Christensen, Xiaodong Sun

Nuclear Engineering Program, Ohio State University, Columbus, OH 43210, USA

ARTICLE INFO

Article history:
Received 5 January 2016
Received in revised form 21 February 2016
Accepted 26 February 2016

Keywords:
PCHE
Optimization
FHR

ABSTRACT

This study focused on designing a cost-effective heat exchanger for a 20-MW FLiNaK–SCO_2 Secondary Heat Exchanger in Fluoride salt-cooled High-temperature Reactors. Specific Printed Circuit Heat Exchanger geometries were investigated for those cases where Fanning factor and Nusselt number correlations were available. Straight, S-shape, Offset Strip Fin, and zigzag 52° channels were considered for the SCO_2 side while straight, zigzag 15°, rectangle OSF 7.565 mm, and rectangle OSF 2.40 mm channels were considered for the FLiNaK side. Thermal-hydraulics, mechanical aspects, and corrosion rate were taken into account. A cost analysis was performed to combine the effects of heat transfer performance and pressure drop in heat exchangers. Single banking and double banking were also considered. Finally, the best PCHE channel configurations on SCO_2 and FLiNaK sides were proposed.

1. Introduction

The Fluoride salt-cooled High-temperature Reactor (FHR) adopts advantages of High Temperature Gas-cooled Reactors (HTGRs), Sodium Fast Reactors (SFRs), and Molten Salt Reactors (MSRs). Accordingly, graphite-matrix coated-fuels, a Direct Reactor Auxiliary Cooling System (DRACS), and liquid salt working fluids are applied to the FHR, where a three-loop system is currently considered. The primary coolant is FLiBe, which is a mixture of LiF and BeF_2, with a melting point of 459 °C and a boiling point of 1433 °C. LiF–NaF–KF (FLiNaK), KF–ZrF_4, and KCl–$MgCl_2$ are considered as potential secondary coolants. A helium Brayton cycle, a supercritical CO_2 Brayton cycle, a supercritical Rankine steam cycle, and a subcritical Rankine steam cycle are considered as potential candidates for the power conversion cycle.

In the FHR, the heat exchangers are some of the most important components. It is strongly pertinent to overall plant thermal efficiency. In addition, heat exchanger failure due to corrosive salts results in a significant economic loss due to purchasing a new heat exchanger, replacing the failed one with a new one, and generating no profit during the shut-down period. Therefore, more reliable and compact heat exchangers are required.

A Printed Circuit Heat Exchanger (PCHE) is currently considered as one of the most promising heat exchangers for the FHR. The PCHE is manufactured by chemical etching, stacking, and diffusion bonding processes. Compared to welding, diffusion bonding achieves higher structural integrity and corrosion resistance. Micro-wavy channels made by the chemical etching increase heat transfer performance as well as pressure drop.

Previous research evaluated thermal-hydraulic performance for specific PCHE channel geometries and suggested an improved PCHE design than a zigzag channel. Ngo et al. (2007) designed and constructed zigzag 52° and S-shape PCHEs for CO_2 and supercritical CO_2 (SCO_2) conditions. Their subsequent analysis resulted thermal-hydraulic correlations for both zigzag 52° and S-shape fin channels. They showed the S-shape fin channel has equivalent heat transfer performance and 1/6–1/7 pressure drop compared to the zigzag 52°. Kim et al. (2008) numerically investigated thermal-hydraulic performance under SCO_2 condition for a zigzag PCHE (Ishizuka et al., 2005) and an air-foil finned PCHE. Their results indicated that the air-foil PCHE has the same heat transfer performance and 1/20 smaller pressure drop compared to the reference zigzag PCHE. Kim et al. (2009) and Kim and No (2011, 2013) investigated thermal-hydraulic performance of a zigzag 15° channel through experiments and numerical analysis for He–He, He–water, and mixture–water conditions. Kim and No (2012)

Abbreviations: FHR, Fluoride salt-cooled High-temperature Reactor; HTGR, High Temperature Gas-cooled Reactor; MSR, Molten Salt Reactor; SFR, Sodium Fast Reactor; DRACS, Direct Reactor Auxiliary Cooling System; PCHE, Printed Circuit Heat Exchanger; SCO_2, Supercritical Carbon Dioxide; IHX, Intermediate Heat Exchanger; OSF, Offset-Strip Fin; SHX, Secondary Heat Exchanger.

* Corresponding author. Tel.: +1 614 247 4684; fax: +1 614 247 3163.
E-mail addresses: ihkim0730@gmail.com (I.H. Kim), zhang.3836@osu.edu (X. Zhang), christensen.3@osu.edu (R. Christensen), sun.200@osu.edu (X. Sun).

http://dx.doi.org/10.1016/j.anucene.2016.02.031
0306-4549/

Nomenclature

Re	Reynolds number
Nu	Nusselt number
ρ	density [kg/m^3]
v	velocity [m/s]
D_h	hydraulic diameter [m]
μ	viscosity [Pa·s]
$\dot{m}$	mass flow rate [kg/s]
A_f	flow area [m^2]
T	temperature [K]
p	pressure [Pa]
σ_D	allowable stress [Pa]
r	radius [m]
t_m	required metal thickness [m]
t_{m-m}	required thickness determined by mechanical aspect [m]
t_{m-c}	required thickness determined by corrosion aspect [m]
t_f	fin thickness = distance between two neighboring channels [m]
Δp	pressure difference [Pa]
P	pitch [m]
P_{w_hot}	pitch in the hot side [m]
P_{w_cold}	pitch in the cold side [m]
d	diameter [m]
t_{f_hot}	fin thickness in the hot side [m]
t_{f_cold}	fin thickness in the cold side [m]
w_f	channel width [m]
d_f	channel height [m]
U	overall heat transfer coefficient [W/m^{2}K]
h	heat transfer coefficient [W/m^{2}K]
A_s	surface area [m^2]
Q	heat exchanger thermal load [W]
ΔT_{lm}	log mean temperature difference [K]
L	transparent length [m]
N	the total number of channels
N_s	the number of plate stacks
f	Fanning factor
C_t	total cost per year [$/y]
C_{cp}	payback cost per year for the capital cost [$/y]
C_o	operating cost per year [$/y]
C_M	material cost per kg [$/kg]
M	total material mass [kg]
ρ_M	material density [kg/m^3]
V	total heat exchanger material volume [m^3]
IR	interest rate
W_p	pumping power [W]
C_E	average retail price of electricity to customers [$/W-h]

Subscripts

i	inside
o	outside
in	inlet
out	outlet
FLiNaK or _FLiNaK	FLiNaK side
SCO_2 or $\_SCO_2$	SCO_2 side
w	metal wall

suggested thermal-hydraulic correlations for various zigzag channels (5°–45°) based on a numerical analysis. Through a cost analysis, they showed a 10°–15° zigzag channel has the lowest total cost for the Intermediate Heat Exchanger (IHX) in the PBMR among 5°–45° zigzag channels. Yoon et al. (2014) accomplished a cost assessment of straight channel, zigzag channel, S-shape fin, and airfoil fin PCHEs for the IHX in HTGRs and SFRs. For the IHX (He–He) in HTGRS, their results showed laminar flow operation of a zigzag PCHE is the most promising. For the IHX (Sodium–SCO_2) in SFRs, their results indicated turbulence flow operation of a straight channel PCHE is the most promising. Manglik and Bergles (1995) proposed generalized correlations of friction factor and Colburn factor for Offset-Strip Fin (OSF) heat exchangers.

However, Ngo et al. (2007) and Kim et al. (2008) did not combine both heat transfer performance effect and pressure drop effect as a same unit. Kim and No (2012) did not consider different geometries other than zigzag channels when the optimized design was proposed. Yoon et al. (2014) did not calculate required plate thickness and displacement based on mechanical strength and corrosion, which were located between the two neighboring channels on the same plate.

Now, when an optimized PCHE channel design for a specific inlet/outlet operating condition is suggested, it is still not clear on how to optimize PCHE channel geometries among different channels. In this study, we focus on developing an optimized PCHE design for a 20-MW FLiNaK–SCO_2 Secondary Heat Exchanger (SHX) in FHRs. Heat transfer and pressure drop correlations for straight, S-shape, OSF, and zigzag channels were investigated. Considering those geometries for which thermal-hydraulic correlations are available, we determined PCHE cross-sectional dimensions. Thermal-hydraulics, mechanical aspect, and corrosion characteristics were considered for the PCHE design. Single banking and double banking are considered for the current design study. A cost analysis, which mainly consider capital cost and operating cost due to material cost and pumping power, is performed to down select the most cost-effective PCHE channel geometry for both the SCO_2 and FLiNaK sides.

2. Considerations for PCHE designs

A reference operating condition of the 20-MW FLiNaK–SCO_2 SHX in the FHR, Sabharwall et al. (2011), was selected as design parameters. Details are presented in Table 1. FLiNaK and SCO_2 properties were obtained from Williams et al. (2006) and a NIST chemistry web-book (NIST website). Single banking and double banking were considered.

2.1. PCHE correlations for FLiNaK and SCO_2

Heat transfer and pressure drop correlations could be obtained for a limited number of PCHE channel geometries from literature: straight (Incropera and Dewitt, 2002), zigzag 52° and S-shape (Ngo et al., 2007), zigzag 15° (Kim and No, 2013), and OSF (Manglik and Bergles, 1995). They are summarized in Table 2. Correlations for straight, zigzag 15°, and OSF channels are available in laminar region, while those for straight, S shape, zigzag 52°, and OSF channels are available in turbulence region.

Table 1
20-MW SHX operating conditions (Sabharwall et al., 2011).

SHX	T_{in} (°C)	T_{out} (°C)	p (MPa)	Mass flow rate (kg/s)
FLiNaK	676.2	575.0	0.153	102.2
SCO_2	494.0	651.2	20.8	102.2