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Thermal hydraulic performance testing of printed circuit heat exchangers in a high-temperature helium test facility

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HIGHLIGHTS

- *T–H* performance of Alloy 617 PCHEs at HTGR operating temperatures.
- PCHE heat transfer surface performance data compared with correlations in the literature.
- Numerical investigation of developing laminar flow in a semicircular duct.
- Entrance region parameters & pressure drop relation for laminar flow in semicircular duct.

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ABSTRACT

In high-temperature gas-cooled reactors, such as a very high temperature reactor (VHTR), an intermediate heat exchanger (IHX) is required to efficiently transfer the core thermal output to a secondary fluid for electricity generation with an indirect power cycle and/or process heat applications. Currently, there is no proven high-temperature (750–800 °C or higher) compact heat exchanger technology for high-temperature reactor design concepts. In this study, printed circuit heat exchanger (PCHE), a potential IHX concept for high-temperature applications, has been investigated for their heat transfer and pressure drop characteristics under high operating temperatures and pressures.

Two PCHEs, each having 10 hot and 10 cold plates with 12 channels (semicircular cross-section) in each plate are fabricated using Alloy 617 plates and tested for their performance in a high-temperature helium test facility (HTHF). The PCHE inlet temperature and pressure were varied from 85 to 390 °C/1.0–2.7 MPa for the cold side and 208–790 °C/1.0–2.7 MPa for the hot side, respectively, while the mass flow rate of helium was varied from 15 to 49 kg/h. This range of mass flow rates corresponds to PCHE channel Reynolds numbers of 950 to 4100 for the cold side and 900 to 3900 for the hot side (corresponding to the laminar and laminar-to-turbulent transition flow regimes). The obtained experimental data have been analyzed for the pressure drop and heat transfer characteristics of the heat transfer surface of the PCHEs and compared with the available models and correlations in the literature. In addition, a numerical treatment of hydrodynamically developing and hydrodynamically fully-developed laminar flow through a semicircular duct is presented. Relations developed for determining the hydrodynamic entrance length in a semicircular duct and the friction factor (or pressure drop) in the hydrodynamic entry length region for laminar flow through a semicircular duct are given. Various hydrodynamic entrance region parameters, such as incremental pressure drop number, apparent Fanning friction factor, and hydrodynamic entrance length in a semicircular duct have been numerically estimated.

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1. Introduction

The very high temperature reactor (VHTR), using gas-cooled reactor technology, is the primary candidate reactor concept for the next generation nuclear plant (NGNP) initiative [1]. In this reactor, a high-temperature (750–800 °C or higher) and high integrity intermediate heat exchanger (IHX) is indispensable to

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efficiently transfer the core thermal output to a secondary fluid for electricity generation in an indirect power cycle setting and/or process heat applications [2]. At present, there is no proven high-temperature compact heat exchanger technology for VHTRs. In the current study, a promising high-temperature compact heat exchanger concept, namely, the printed circuit heat exchanger (PCHE) was tested for its heat transfer and pressure drop characteristics.

In the literature, some research work was performed with the PCHEs. Nikitin et al. [3] and Ishizuka et al. [4] investigated, both numerically and experimentally, the heat transfer and pressure drop characteristics of a 3-kW PCHE in a supercritical CO_2 loop with mass flow rates varying from 40 to 80 kg/h. The PCHE employed in their study consisted of herringbone type channel flow passages, with a cold channel plate sandwiched between two hot channel plates. In their study, the hot and cold side inlet temperatures were varied from 280 to 300 °C and 90–108 °C, respectively while the hot and cold side inlet pressures were varied from 2.2 to 3.2 MPa and 6.5–10.5 MPa, respectively. For the PCHE tested, they correlated local heat transfer coefficient and pressure drop as a function of the Reynolds number. However, their experimental operating temperatures only reached 300 °C and are far from high-temperature reactor (HTR) requirements. Song et al. [5] performed experiments at low Reynolds numbers with a commercial PCHE using air as the working fluid. For the PCHE tested, they developed heat transfer and friction factor correlations and examined the adaptability of a Hesselgreaves correlation [6] to PCHE type heat exchangers.

Figley [7] developed a numerical model of a straight channel PCHE and performed numerical analysis to investigate its thermal–hydraulic performance for varied operating conditions and generate predictive data for the PCHEs fabricated at The Ohio State University. The PCHE model dimensions are representative of the PCHEs fabricated and installed in the high-temperature helium test facility. The operating conditions are representative of the maximum design operating temperature and pressure for the high-temperature helium test facility. The computational results of the convective heat transfer coefficient and pressure drop from the PCHE model agree well with the available models in the literature. Kim et al. [8] investigated, both numerically and experimentally, the thermal–hydraulic performance of the PCHE using the KAIST Helium Test Loop with mass flow rates varying from 40 to 100 kg/h. The PCHE employed in their experimental study is of Alloy 800H construction and fabricated by a commercial vendor. In their study, the operating pressure range was 1.5–1.9 MPa and the hot and cold side inlet temperatures were varied from 25 to 550 °C and 25–100 °C, respectively. Based on the experiments, a global fanning factor and a global Nusselt number were proposed for the PCHE tested. Furthermore, they validated their 3-D numerical model against the KAIST helium experimental data.

Pra et al. [9] performed steady and transient tests on a PCHE recuperator mock-up in an air test facility to investigate its thermal–mechanical behavior at conditions typical of High Temperature Reactor (510 °C). The PCHE employed in their study was supplied by a commercial vendor and had convoluted flow passages (wavy or herringbone type). The steady-state analysis of the PCHE was performed to evaluate its thermal–hydraulic performance and examine its ability to reach HTR recuperator specifications. An effectiveness of 95% was reported in their study. Furthermore, transient tests were performed to determine the number of thermal load cycles required to generate a failure in the heat exchanger. For the transient tests, the PCHE mock-up was subjected to severe temperature variations or thermal shocks representative of an HTR recuperator. During the cold shock, the temperature was varied from 510 to 108 °C within 5 s. In a similar manner, a hot shock was generated by varying the temperature from 180 to 510 °C within 3 min. This process was repeated 100 times and no fatigue failure of the mock-up was noticed. Although these tests are less stringent compared to the IHX requirements for NGNP, they however show that PCHE has a good potential for high temperature applications.

Kim et al. [10] performed a three-dimensional numerical analysis to investigate heat transfer and pressure drop characteristics of supercritical CO_2 flow in a PCHE model that incorporates airfoil shaped fins instead of zigzag or herringbone type channels. Numerical comparisons between the airfoil fin and zigzag PCHE channel configurations indicated an appreciable reduction in pressure drop in the case of the airfoil fin PCHE. However, the heat transfer rate per unit volume is comparable in both the configurations. The reduction in pressure drop was attributed to the streamlined shape of airfoil fins that help suppress generation of separated flow.

In light of the above discussion, it can be concluded that much of the work on PCHEs is computational and there are very limited experimental data on their thermal-hydraulic performance under very high operating temperatures and pressures. Notwithstanding the aforementioned works on PCHEs, to the authors' knowledge, however, a detailed thermal-hydraulic performance of the PCHEs with helium as the working fluid has not been experimentally investigated for the temperatures and pressures typical of VHTRs.

In the current study, two PCHEs, each having 10 hot and 10 cold plates with 12 channels (semicircular cross-section) in each plate were fabricated from Alloy 617 plates and were investigated for their thermal–hydraulic performance in a *h*igh-*t*emperature *h*elium test *f*acility (HTHF) [11,12]. Table 1 summarizes the PCHE configuration parameters [11]. The PCHE inlet temperature and pressure were varied from 85 to 390 °C/1.0–2.7 MPa for the cold side and 208–790 °C/1.0–2.7 MPa for the hot side, respectively, while the mass flow rate of helium was varied from 15 to 49 kg/h. This range of mass flow rates corresponds to PCHE channel Reynolds numbers of 950 to 4100 for the cold side and 900 to 3900 for the hot side (corresponding to the laminar and laminar-to-turbulent transition flow regimes). The experimental data were analyzed for the pressure drop and heat transfer characteristics of the heat transfer surface of the PCHEs and compared with the available models and correlations in the literature. In addition, a numerical treatment of hydrodynamically developing and hydrodynamically fully-developed laminar flow through a semicircular duct is presented. Relations for determining the hydrodynamic entrance length in a semicircular duct and the friction factor (or pressure drop) in the hydrodynamic entry length region for laminar flow through a semicircular duct are given. Various hydrodynamic entrance region parameters, such as incremental pressure drop number, apparent Fanning friction factor, and hydrodynamic entrance length in a semicircular duct have been numerically estimated.

Table 1
Basic geometric and characteristic parameters for the PCHEs tested.

Parameter	Hot side	Cold side
Channel pitch (p), mm	2.5	2.5
Channel width (d), mm	2.0	2.0
Plate thickness (t_p), mm	1.63	1.63
Channel hydraulic diameter (D_h), mm	1.22	1.22
Channel travel length (l), mm	305	272
Number of plates	10	10
Number of channels in each plate	12	12
Channel cross section (A_c), mm^2	1.57	1.57
Free flow area, mm^2	188	188

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