Prototype Design of a Printed Circuit Heat Exchanger for Na-sCO_2

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Abstract

For the application of heat exchange between two different heat transfer fluids (HTFs) in a concentrating solar power (CSP) plant or intermediate heat exchangers such as recuperators, printed circuit heat exchangers (PCHE) have been proposed [1]. The main advantages are the high ratio of heat transfer area to volume (compactness), high heat transfer coefficient, the lowest achievable pinch, and small footprint compared with the conventional shell and tube systems [2, 3] while diffusion bonding between the platelets is capable of providing high structural strength and integrity [4, 5]. This study aims to provide a preliminary design of a PCHE suitable for sodium and supercritical carbon dioxide (sCO_2) heat exchange.

A conventional PCHE consists of a semicircular or oval cross section in straight, zigzag or wavy channels as the flow passages (Fig. 1), arranged in a counter flow configuration. While zigzag channels enhance the heat transfer rate, the higher pressure drop and higher probability of blockage along the channels introduces new challenges [6-8]. The wavy channel has been proposed to address the issues of zigzag passages [9].

Figure1- Semicircular cross section in continuous channels; straight, zigzag and wavy

Additionally, PCHE‘s can be classified as continuous or discontinuous in relation to the fluid passages. In the conventional configurations mentioned above, fluids pass through continuous channels without further mixing between adjacent channels of the same fluid. The characteristic of this flow is similar to internal flow in tubes. Alternatively, in the discontinuous configuration, fluids pass between fins resembling an external flow where it is less restricted to a specific pass (as internal flow) and more mixing occurs [5] .

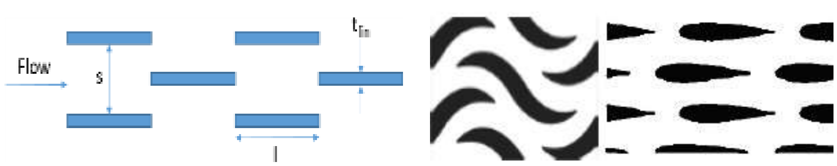


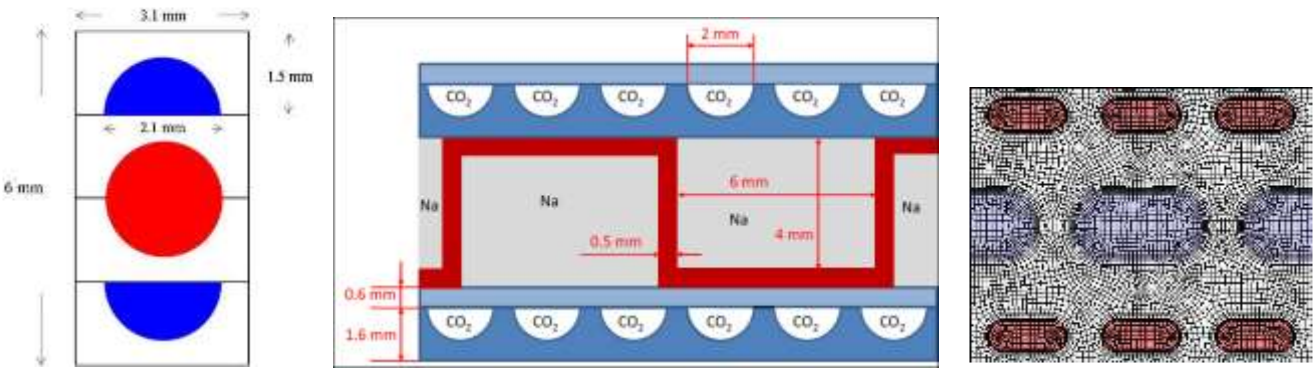
Figure2- Discontinuous fluid passages between fins; stripe, S shape and airfoil [10]

For the discontinuous configuration, different types of fins such as airfoil, oval, stripe, and S shape have been proposed (Fig. 2) [10-12]. The thermohydraulic performance of discontinuous channels is superior to the conventional continuous passages, however, the structural and mechanical integrity of the system may be compromised, particularly in conditions of high operating temperature and pressures [13].

The current diffusion bond technology provides reliable structural integrity for the conventional continuous channels which have been proven up to 650 °C and 100 bar pressure for certain types of platelet materials with fluids such as steam, sCO2, helium, and molten salt [2, 3]. High temperature gradients, particularly in transient operations, result in high thermal stresses where thermo-mechanical performance and structural integrity become more important compared with thermohydraulic performance [4, 5, 13]. This is complicated further when considering corrosion and compatibility issues between fluids such as sodium, sCO_2 and platelet materials.

Sodium-sCO_2 configurations

Research in the nuclear sector covers the investigation of PCHE's for sodium-cooled fast reactors (SFR) and high temperature gas-cooled reactors (HTGR); sodium-sCO2, helium-water, and helium-helium [11, 14, 15]. Cha et al. [14] proposed a sCO_2 – sodium energy conversion cycle for a sodium cooled fast reactor. Yoon et al. [11] numerically studied hydrothermal performance of PCHE with different channels for HTGR and SFR. Considering the fouling problem, the authors proposed a circular straight channel for hot sodium, and semicircular zigzag channels for sCO_2 (Fig.3a)



(a) (b) (c)

Figure 3- Circular straight channel for sodium and semicircular zigzag for sCO_2 [11], (b) rectangular straight channels for sodium and semicircular wavy channels for sCO_2 [16], (c) Oval cross section in straight channels for sodium and straight or wavy channels for sCO_2 [this study]

Moisseytsev and Sienicki [16] conducted system level modelling on the transient hydrothermal behaviour of a sodium-sCO_2 PCHE within a range of operating conditions including severe accidents. In collaboration with Heatric [3], and for a total duty of 250 MW_{th}, the authors considered a rectangular straight passage for sodium and a semicircular wavy channel for sCO_2 (Fig. 3b). The temperature range considered was 356 °C to 528 °C with a nearly atmospheric operating pressure on the sodium side and 25 MPa at the sCO_2.

While the above numerical investigations provide valuable insights, more experimental examinations are required, particularly for higher operating temperatures up to 800 °C expected for the CSP system being considered by ASTRI. Modelling and experimental work at small scale are planned for the future. Working in close collaboration with HEXCES [2], previous modelling work will be extended. Working with a manufacturer provides insight into the technological limitations and what is best practice for small scale PCHE's and for testing purposes.

Findings from the literature regarding the technological maturity of the continuous patterns compared with the discontinuous configuration [2, 13] are shown in Fig. 3. The configuration presented in Fig. 3c is a preliminary sketch of an alternative version of the pattern and was used in a superheater manufactured and tested by HEXCES [2]. The oval cross section is considered for both fluids, however, a straight channel for sodium and a wavy channel for sCO_2 has been selected. The proposed oval section is supposed to provide a streamlined channel for both fluids compared with a rectangular cross section which may introduce a greater fouling rate on the sodium side. In this regard, the circular cross section (Fig. 3a) may potentially be the best for the sodium side, however, it might not be practical considering the limitations of diffusion bonding. In regard to the limitations of manufacturing, the same cross section of oval shape is thought to be achievable. The high thermal conductivity of sodium might provide a chance to have a larger cross section on the sodium side as proposed by Heatric [3] and is shown in Fig. 3b. However, all critical assumptions will be examined with modelling and close collaboration with HEXCES [2]. Considering the required size and operating conditions of the PCHE for the ASTRI CSP demonstration project, the design criteria of the small scale PCHE for the purpose of testing can be defined using dimensional analysis. This will be followed by modelling of a module of the small scale PCHE which will provide insight into the hydrothermal performance of the proposed configuration in Fig. 3c.

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