Applied Thermal Engineering 99 (2016) 790–801

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Thermal performance of a 10-kW phase-change plate heat exchanger with metal foam filled channels

Gholamreza Bamorovat Abadi [a], Dae Yeon Kim [a], Sang Youl Yoon [b], Kyung Chun Kim [a,*]

[a] School of Mechanical Engineering, Pusan National University, San 30, Jangjeon-dong, Geumjeong-gu, Busan 609-735, Republic of Korea
[b] Rolls-Royce and Pusan National University Technology Centre, Pusan National University, Busan 609-735, Republic of Korea

HIGHLIGHTS

- Thermal performance of a metal foam filled heat exchanger has been studied.
- The effect of pressure, metal foam configuration and PPI value is reported.
- 20 PPI metal foam proved to have the best performance.
- With 20 PPI metal foam the overall HTC increased by 2.3 times.
- ORC evaporator size can be reduced by using proper metal foam.

ARTICLE INFO

Article history:
Received 6 November 2015
Accepted 31 January 2016
Available online 6 February 2016

Keywords:
Open cell
Metal foam
Phase change
Heat exchanger
Convective heat transfer

ABSTRACT

Compact-sized organic Rankine cycle (ORC) power generators call for small-scale heat exchangers to work with them. Since the heat transfer area plays a direct role in the performance of heat exchangers, microcellular structures such as metal foams are proposed to increase the heat duty of heat exchangers by increasing the surface area while maintaining their small size. In this experimental study, the performance of a 10-kW heat exchanger with channels filled with copper metal foam was investigated. A hot water loop was designed for heat input. The cold side of the heat exchanger works with R245fa as the working fluid. Single-phase and two-phase experiments were performed with different mass fluxes ranging from 180 to 600 kg/m^{2}s. The effect of the pores per inch (PPI), working pressure, and different arrangements of metal foams was also investigated. Although the metal foam increases the pressure drop in the channel, it increases the recovered waste heat from the heat source and overall heat transfer coefficient of the heat exchanger by up to 2.3 times compared to a conventional heat exchanger without metal foams.

1. Introduction

High-porosity open-cell metal foams have gained attention due to their performance in various applications such as heat exchangers. Their high surface-to-volume ratio results in higher heat transfer coefficients and better performance of the system. Higher performance and small size are crucial in many applications, such as organic Rankine cycles (ORC), electronics, mini power generator cycles, heat exchangers [1], filtering [2], and heat sinks [3]. There have been numerous studies in the last decade that address different aspects of metal foams. Since the thermal conductivity of the metal foam is not the same as that of a block of metal or fluid media, effective thermal conductivity has been investigated extensively both numerically and experimentally [4–6].

Convective heat transfer and pressure drop data are vital for designing heat exchangers. Carpenter and da Silva [7] performed hydrothermal experiments and presented pressure drop and heat transfer coefficient data from single-phase tests with air as the fluid media. They used aluminum foams with 10, 20, and 40 pores per inch (PPI). They also performed experiments with different configurations of metal foams, such as a combination of 10-PPI metal foam with 40-PPI. But these combinations of metal foams have not been tested in phase change experiments. There have also been many attempts to accurately predict metal foam behavior with regard to heat transfer by using different methods such as computational fluid dynamics. Diani et al. [8] numerically studied the pressure drop and heat transfer in metal foams using non-destructive 3D imaging techniques. By employing micro-CT and CFD methods, they modeled metal foams with four different PPI values of 5, 10, 20, and 40 and compared the data with experimental results. Their model showed good agreement with experimental values.

New power generation methods call for new designs of heat exchangers. An extensive study on a supercritical CO_2-based organic

* Corresponding author. Tel.: +82-51-510-2324; fax: +82-51-512-9835.
E-mail address: kckim@pusan.ac.kr (K.C. Kim).

http://dx.doi.org/10.1016/j.applthermaleng.2016.01.156
1359-4311/

Rankine cycle by Liu et al. [9,10] documented the benefit of using metal foams in the heater section. They reported the heat transfer and pressure drop characteristics of supercritical CO_2 cooled in tubes partially filled with metal foam with PPI values of 20, 40, and 60 [9]. They concluded that the heat transfer coefficient decreases at first and then increases as porosity increases, and decreases as pore density decreases and finally approaches a nearly constant value. They also showed the improvement of a supercritical organic Rankine cycle (ORC) by using metal foams in a gas heater with supercritical CO_2 as the working media [9]. By partially filling the heater pipes with copper fibers, the performance of the system with metal foam was improved by 1.5 to 5 times.

Phase change in metal foams has also been studied numerically and experimentally. Su et al. [11] proposed a general heat transfer correlation based on experiments and numerical data for heat transfer in water-saturated metal foams. Experimental results were also obtained for thermal development in metal foams in Dukhan et al. [12]. Huisseune et al. [13] compared a heat exchanger with metal foam and a finned heat exchanger and concluded that the metal foam heat exchanger can outperform the conventional exchanger by up to six times. Convective flow has also been modeled in a partially filled channel with metal foam by Alhusseny et al., [14] and the model was compared to previous experimental data. Flow boiling of refrigerants in horizontal tubes filled with metal foam was visualized by Zhu et al. [15], who showed that the case with metal foam has annular flow in lower vapor qualities and that metal foams with higher PPI values promote the formation of annular flow.

One of the applications of metal foams is in heat exchangers. Filling the channels with metal foams will increase the pressure drop in the channel but will also increase the overall heat transfer coefficient of the heat exchanger. Finding the best porosity and size of metal foam is crucial and needs extensive experiments. Phase change in metal foams is a complicated phenomenon. This study focuses on a 10-kW phase-change heat exchanger design with metal-foam-filled channels; 10-kW heat exchangers like this design are used in many applications, such as 1-kW organic Rankine cycles, which have around 10% efficiency and need around 10-kW heat input.

A complete customized heat exchanger test section with five channels (three for the hot side and two for the cold side) has been manufactured. All the channels are filled with the metal foams and the performance of the heat exchanger is compared to a case where there is no metal foam in the channels. The effect of metal foams with different PPI has been studied under different working conditions and different configurations of metal foams. Metal foams of copper with PPI values of 20, 30, and 60 and different sizes were made. The results show a significant improvement in recovered waste heat when the metal foams are used, even if they are not brazed or soldered to the channel walls.

2. Test rig

2.1. Cycle

Three different loops are used together for this experiment, as shown in Fig. 1. The heat exchanger test section is installed in the middle loop, which uses R245fa as the working fluid on the cold side of the heat exchanger. This closed loop consists of a reservoir tank before the pump to ensure smooth flow and stability. A gear pump moves the refrigerant in this loop and is powered by a 170-W motor operating at 2000 RPM. The pump is powered by 220 volts of electricity and is controlled by a frequency control.

Immediately after the pump, there is a positive displacement flowmeter with a digital indicator. After the test section and before the condenser, a globe valve was used to control the pressure in the system. When changing the flow rate of the refrigerant, the pressure inside the test section is corrected and fixed to the desired value by adjusting this valve. Next to this, there is a condenser in the form of a plate heat exchanger connected to an air-cooled chiller. The fluid cools down and condenses in this heat exchanger and returns to the reservoir tank, which completes one loop.

The cooling water loop is a closed loop that provides cooling water and works separately. This loop has its own pump and flowmeter to measure the amount of cooling water provided to the condenser and its heat duty. The cooling water enters the condenser and goes through the chiller tubes after receiving heat from the refrigerant. The tubes are cooled by a combination of air flow and a refrigeration cycle. The temperature of the cooling water is measured by a thermometer and is controlled by the automatic on/off switch on the refrigerant cycle inside the chiller.

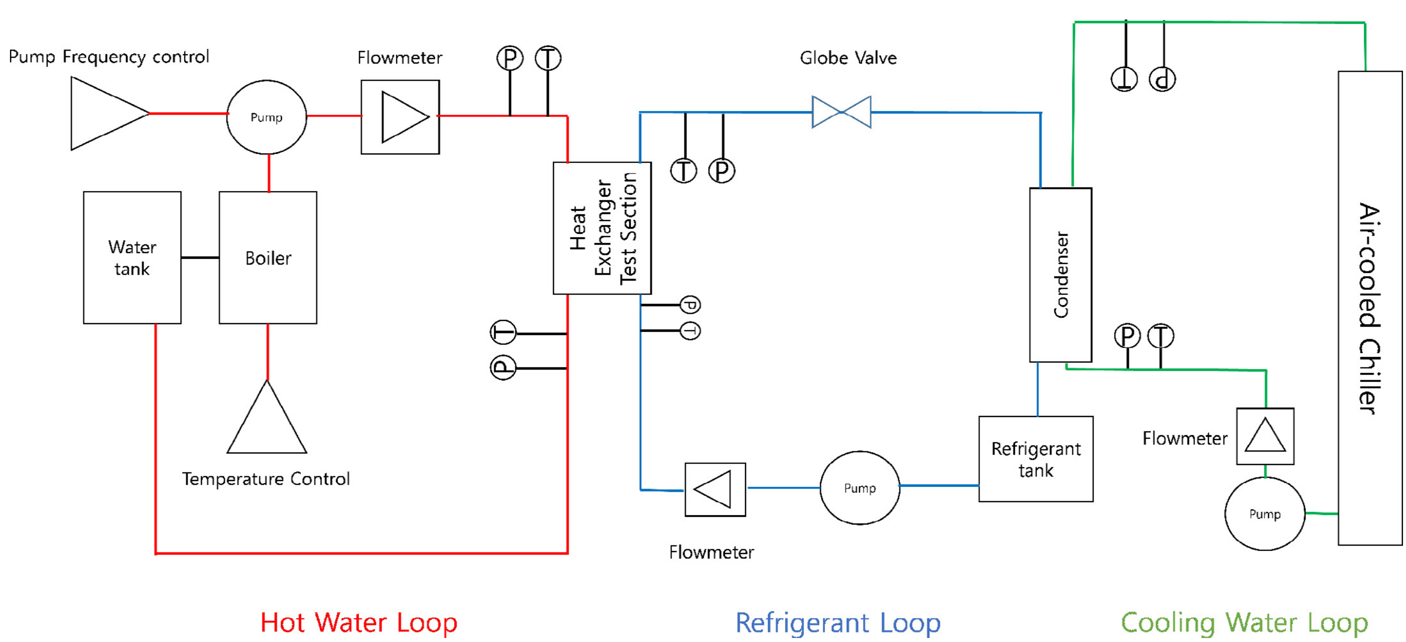

Fig. 1. Diagram of test rig showing different loops.