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Low-GWP refrigerants flow boiling heat transfer in a 5 PPI copper foam

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ABSTRACT

This paper reports an experimental investigation of the heat transfer performance of the new low-GWP refrigerants, R1234yf and R1234ze(E), during flow boiling heat transfer inside a horizontal high porosity copper foam with 5 Pores Per Inch (PPI). Metal foams are a class of cellular structured materials consisting of a stochastic distribution of interconnected pores; these materials have been proposed as effective solutions for heat transfer enhancement during both single and two-phase heat transfer. R1234yf and R1234ze(E) refrigerants are appealing alternatives of the more traditional R134a by virtue of their negligible values of GWP and normal boiling temperatures close to that of R134a, which make them suitable solution in several different applications, such as: refrigeration and air conditioning and electronic thermal management. This work compares the two-phase heat transfer behaviour of these new HFO refrigerants, studying the boiling process inside a porous medium and permitting to understand their effective heat transfer capabilities. The experimental measurements were carried out by imposing three different heat fluxes: 50, 75, and 100 kW m^{-2}, at a constant saturation temperature of 30 °C; the refrigerant mass velocity was varied between 50 and 200 kg m^{-2} s^{-1}, whilst the mean vapour quality varied from 0.2 to 0.95. The two-phase heat transfer and pressure drop performance of the two new HFO refrigerants is compared against that of the more traditional R134a.

Introduction

As the number of electrical and electronic systems increases, their physical sizes decrease, and the spacing between electrical components decreases, both the total amount of heat generated (hence to be dissipated) and the power density (the heat generated per volume unit) increase significantly. In this scenario, smart cooling solutions are more and more needed to cope with the continuous increasing of the heat loads that have to be rejected from the electronic equipment.

In the last decades, open-cell metal foams have received a lot of attention by virtue of their great attitude to be implemented in many different applications, amongst those: multifunctional heat exchangers, cryogenics, combustion chambers, cladding on buildings, strain isolation, buffer between a stiff structure and a fluctuating temperature field, geothermal operations, petroleum reservoirs, catalytic beds, compact heat exchangers for airborne equipment, air cooled condensers, and compact heat sinks for power electronics.

Open-cell metal foams present high surface area to volume ratio as well as enhanced flow mixing and attractive stiffness and strength. Most characteristic parameters are the size of the windows (or pore diameter) which correlates with the pore density (the number of pores per linear inch, PPI), the struts diameter and length, porosity ε (defined as the volume of void divided by the total volume of the foam, solid matrix and void volumes (Gibson and Ashby, 1997)) and relative density ρ^* (defined as the density of the foam divided the density of the metal).

This kind of stochastic cellular structured materials seems to present some interesting heat transfer capabilities as extended surface for single and two-phase heat transfer to face with the new challenging dissipation demands of the next generation of electronic devices.

Starting from the work proposed by Calmidi and Mahajan (2000), the air forced convection through the open-cell high porosity metal foam was extensively investigated and studied; recently, Mancin et al. (2010, 2012, 2013) presented the experimental measurements relative to air forced convection through 21 aluminium and copper foams. The same Authors also proposed two different models, which can be easily implemented to design compact and efficient heat sinks for any given application (Mancin et al., 2013).

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Unfortunately, the thermophysical properties of the air limit its future applicability to the thermal management of the next generation of electronic devices; on the other hand, it is well known that boiling is the heat transfer mechanism with the highest heat transfer coefficients, thus it can be used to spread high heat fluxes whilst maintaining the wall temperature at low values with compact heat sinks. Since the electronics devices call for non-dielectric fluids for safety and reliability issues, the possible implementation of synthetic refrigerants represents a viable solution.

The possible use of a low-GWP refrigerant as working fluid would be an important feature of an efficient, eco-friendly, and smart cooling system for electronic thermal management. Amongst the fluorinated propene isomers which have normal boiling point temperature data published in the public domain, several have low-GWP and normal boiling temperatures relatively close to R134a; amongst them, R1234yf and R1234ze(E) have normal boiling temperatures approximately 3.15 K and 7.3 K, respectively, lower than that of R134a. They present $GWP_{100years} < 1$ (Hodnebrog et al., 2013) and are being widely considered as possible substitutes of R134a in many different applications, including electronic thermal management, air conditioning and refrigeration systems.

Recently, the attention of the scientific community has been focused on the boiling in metal foams during both pool and flow boiling; however, the literature on this topic still remains limited. The pool boiling on metal foams was studied by several Authors, amongst those: Athreya et al. (2002), Moghaddam and Ohadi (2003), Coursey et al. (2005), Xu et al. (2008), Yang et al. (2010), Ji et al. (2011), Jin et al. (2011), Zhu et al. (2011), Pranoto et al. (2012), Qu et al. (2012), and Xu and Zhao (2013, 2014).

The study on flow boiling is a relatively recent topic; Kim et al. (2008) explored the possible viable use of metal foams inserted in a channel as a porous medium for a cold plate using water and FC72 as working fluid. They considered three different copper foam samples: one having 10 PPI and 95% of porosity, and two with 20 PPI with 92% and 95% of porosity. The 10 PPI copper foam was found to be the best choice in terms of heat transfer coefficient.

Zhao et al. (2009) experimentally studied the flow boiling in horizontal metal-foam filled tubes. The effects of mass velocity, vapour quality, heat flux, and operative pressure on heat transfer and pressure drop were also investigated. The Authors found that the heat transfer coefficient is almost doubled when increasing the number of Pores Per Inch (PPI) from 20 to 40.

Li and Leong (2011) investigated water and FC-72 flow boiling in aluminium foams. The heat transfer process prior to the onset of nucleate boiling and the critical heat flux for FC-72 were studied. Ji and Xu (2012) conducted experiments to study pressure drop in copper foams embedded in a rectangular copper channel. They used water as working fluid with mass velocity between 30 and 200 kg m^{-2} s^{-1}. Three copper foams with different linear porosity: 30, 60, and 90 PPI with porosity equal to 0.88 were tested. Effects of mass flux, vapour quality, and average pore diameter of metal foams on boiling were analysed; the pressure drops increase as the vapour quality, mass flux, and PPI values increase. In addition, an empirical correlation to estimate the two phase pressure drop was proposed.

Madani et al. (2010) characterised the hydraulic performance of a channel filled with a metallic foam during n-pentane flow boiling, by varying the mass velocity from 4 to 49 kg m^{-2} s^{-1}, and the heat flux up to 350 kW m^{-2}. The experimental results showed that the heat transfer mechanisms governing the phase change process in a channel provided with metallic foams are very similar to those for a channel without foams. The same Authors analysed the n-pentane upward flow boiling inside a 36 PPI copper foam with a porosity of 97% (2013). The mass velocity ranged between 10 and 100 kg m^{-2} s^{-1} and the heat flux up to 250 kW m^{-2}. Experimental results were also compared with values predicted by Gungor and Winterton (1987) and Shah (1982) correlations. The comparison with the correlation proposed by Gungor and Winterton (1987) revealed that the metallic foam enhances the heat transfer coefficient by a factor of 2–4 at low vapour quality.

More recently, Hu et al. (2013, 2014a, 2014b) have focused their attention on the effect of the oil (Hu et al., 2013) and tube diameter (Hu et al., 2014a,b) on the two-phase heat transfer and pressure drop of R410A flow boiling inside circular tubes filled with metal foams. Considering the effect of the oil, the Authors studied nominal oil concentrations up to 5%, metal foam structures of 5 PPI and 10 PPI, vapour qualities from 0.2 to 0.8, and mass fluxes from 30 to 90 kg m^{-2} s^{-1}. The test results showed that the pressure drop increases with the increase of oil concentration, mass flux or vapour quality (Hu et al., 2013).

Considering the effect of the tube diameter, the results showed that the heat transfer coefficient decreases maximally by 32% and 42% as the tube diameter decreases from 23.4 mm to 13.8 mm and from 13.8 mm to 7.9 mm, respectively, and the heat transfer coefficient decrement becomes smaller as the oil concentration increases. The pressure drop increases with increasing PPI, but the impact of PPI becomes insignificant as the tube diameter decreases. When the diameter decreases from 13.8 mm to 7.9 mm, the pressure drop decreases due to the incomplete cells and randomly chopped ligaments nearby the tube wall, and the maximum decrements are 22% and 35% for 5 and 10 PPI metal foam filled tubes, respectively (Hu et al., 2014a,b).

Pranoto and Leong (2014) studied the flow boiling heat transfer and bubble characteristics from low-porosity graphite foam structures in a channel. The flow boiling performance and phenomena for different coolant mass fluxes, evaporator gaps, and foam properties were investigated. It was found that the graphite foam structures enhance the boiling heat transfer coefficients by up to 2.5 and 1.9 times, respectively as compared to those of a smooth surface.

Zhu et al. (2014) investigated the flow boiling heat transfer characteristics of R410A in tubes filled with metal foams at a saturation temperature of 7 °C, by varying the mass velocity from 10 to 90 kg m^{-2} s^{-1}, vapour quality from 0.1 to 0.8, and heat flux from 3.1 to 18.3 kW m^{-2}. The experimental results revealed that metal foam enhances the flow boiling heat transfer by a maximum of 220% and promotes the flow pattern transition from stratified flow to stratified-wavy flow and from stratified-wavy flow to annular flow. The Authors also suggested a correlation to estimate the flow boiling heat transfer coefficient inside a foam filled circular tube.

Mancin et al. (2014) experimentally characterised the flow boiling heat transfer of R1234ze(E) and R134a inside a rectangular channel filled with a 5 PPI copper foam. The experimental results showed the interesting heat transfer capabilities of the metal foams as heat transfer medium for flow boiling enhancement. This paper extends and completes the previous work presenting additional experimental measurements relative to two low-GWP refrigerants R1234yf and R1234ze(E) and to the more traditional R134a during flow boiling inside the same high porosity copper foam. The measurements were carried out at 30 °C of saturation temperature, by varying refrigerant mass velocity, vapour quality, and heat flux. Furthermore, several videos recorded with a high speed video camera are presented to aid in explaining the measured heat transfer behaviour at different operating test conditions. The experimental results permit to compare the performance of these environmental friendly refrigerants against the current working fluid inside an innovative thermal solution for efficient cooling systems.