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Experimental assessment of the replacement of a conventional fin-and-tube condenser by a minichannel heat exchanger in an air/water chiller for residential air conditioning

F. Illán-Gómez*, J.R. García-Cascales, F. Hidalgo-Mompeán, A. López-Belchí

Universidad Politécnica de Cartagena, DITF ETSII Dr. Fleming, s/n Cartagena, Murcia, 30202, Spain

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ABSTRACT

This paper analyses the performance of an air/water chiller typically used for residential air conditioning when a minichannel condenser is used in replacement of a conventional fin-and-tube condenser. The experimental facility, the data reduction process and the uncertainty analysis are briefly described and then the experimental results are presented and discussed, comparing the results obtained with both, the minichannel and the fin-and-tube condenser. Additionally, the chiller is numerically modelled using a commercial refrigeration system modelling software (IMST-ART). The good agreement between experimental and numerical results allows validating the model that is then used to calculate the mass of refrigerant contained in all the components of the system, as well as other operational parameters of interest not measured experimentally. The analysis of the results shows that replacing a conventional fin-and-tube condenser by a minichannel condenser allows, under almost any operating condition, reducing the mass of refrigerant increasing efficiency and cooling capacity.

1. Introduction

In the early 80s, Tuckerman and Pease [1] demonstrated the ability of microscopically narrow channels to provide efficient heat removal. Since then, micro and minichannel technology has been used in different industrial applications.

The transition between what it is considered a conventional channel and a narrow channel is not clear. Some authors like Kew and Cornwell [2] only distinguish between conventional channels and microchannels depending on the channel diameter being above or below a critical value given by $D_{\text{crit}} = \left[4\sigma/\left(g\left(\rho_\text{l} - \rho_\text{v}\right)\right)\right]^{1/2}$, where σ is the fluid surface tension, ρ_l and ρ_v are liquid and vapour densities and g is the acceleration due to gravity. Yarin et al. [3] also distinguish only between micro and conventional channels, but they proposed a simplest classification, considering microchannels those whose hydraulic diameter, D_h, ranges from 5 to 500 μm, and conventional size channels those with $D_\text{h} > 500\,\mu\text{m}$. Other authors like Kandlikar and Grande [4] proposed a more extensive classification based on the presence of rarefaction effects that affect fluid flow at hydraulic diameters below 200 μm, distinguishing between conventional channels ($D_\text{h} > 3$ mm), minichannels ($3\text{ mm} \geq D_\text{h} > 200\,\mu\text{m}$) and microchannels ($200\,\mu\text{m} \geq D_\text{h} > 10\,\mu\text{m}$).

Although there are a lot of emerging uses for micro and minichannel technology, including their use in cooling system of electronic devices and microreactors or automotive evaporators, their most important use is in compact condensers for automotive air conditioning systems [5,6]. They have been used extensively for many years in that field, even long before having a complete knowledge of the heat transfer and pressure drop processes in micro and minichannels.

Minichannel heat exchangers began to be used in mobile air conditioning equipment (especially as condenser in automotive industry) mainly due to weight and space restrictions in these applications. Nowadays, the main concerns of refrigeration industry are energy efficiency and environmental impact and minichannel technology is seen as an opportunity to improve refrigeration systems efficiency reducing refrigerant charge and thus their environmental impact.

First research works dealing with heat transfer and fluid flow in micro and minichannels were published in the early 90s. From then on, a strong research effort has been made in this topic, especially focused in analysing heat transfer and pressure drop in single-phase liquid flow, but also including boiling and condensing study in refrigeration and air conditioning applications.

* Corresponding author.
E-mail address: fernando.illan@upct.es (F. Illán-Gómez).

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Nomenclature

c_p	Specific heat at constant pressure (J kg^{-1} K^{-1})
D_{crit}	Critical diameter (m)
D_h	Hydraulic diameter (m)
EER	Coefficient of performance (–)
EER_{AI}	Coefficient of performance considering the consumption in evaporator fan (–)
f	Compressor frequency (Hz)
g	Acceleration due to gravity (m s^{-2})
h	Enthalpy (J kg^{-1})
$\dot{m}$	Mass flow (kg s^{-1})
$\dot{Q}$	Heat exchanged (W)
SC	Subcooling (K)
SH	Superheating (K)
T	Temperature (K)
v	Coil face velocity (m·s^{-1})
$\dot{V}$	volumetric flow rate (m^3·s^{-1})
W	Air humidity ratio (kg kg^{-1})
$\dot{W}$	Compressor electrical power input (W)

Greek symbols

ρ	Density (kg m^{-3})
σ	Fluid surface tension (kg s^{-2})

Subscripts

a	Air
a,in	Air inlet
a,out	Air outlet
comp	Compressor
cond	Condenser
cond,in	Condenser inlet
cond,out	Condenser outlet
conf,r	Condenser, refrigerant side
cond,a	Condenser, air side
evap	Evaporator
evap,w	Evaporator, water side
evap,in	Evaporator inlet
evap,out	Evaporator outlet
evap,r	Evaporator, refrigerant side
in	Inlet
l	Liquid phase
out	Outlet
r	Refrigerant
v	Vapour phase
v,in	Water vapour inlet
v,out	Water vapour outlet
w	Water
w,in	Water inlet
w,out	Water outlet

This work is focused in the use of minichannel technology in the condenser of a domestic air conditioning system as a tool for improving energy efficiency while reducing refrigerant charge. There is a considerable amount of research papers published in this field that deal with the experimental characterisation of two-phase flow in a single port or multiport minichannels, including the study of pressure drop, heat transfer, flow pattern, etc., and in many cases proposing new prediction models that allow to determine pressure drop and heat transfer for different refrigerants and different channel geometries. However, the number of research papers that study the use of compact minichannel condenser in a whole refrigeration system is rather scarce and thus more effort is necessary in this field to assess the effective of compact minichannel heat exchangers under practical air conditioning operation conditions.

Fernando et al. [7] analysed a 5 kW heating power, water to water R290 heat pump where aluminium minichannel heat exchanger substituted the conventional plate heat exchangers used as condenser and evaporator. According to their results, at optimum charge conditions, a reduction of around 23% can be found in the charge of refrigerant in the condenser (decreasing from 125 to 96 g), with an increase higher than 60% in the overall heat transfer coefficient for the condenser (increasing from 897 to 1456 Wm^{-2} K^{-1}) and a 6% increase in refrigerant side pressure drop (increasing from 2.12 to 2.26 kPa, almost negligible in both cases). The reduction of charge was reached with a negligible reduction in the total heating power (decreasing from 5.16 to 5.14 kW) and an increase of 8% in the Coefficient of Performance (COP), that increased from 3.32 to 3.59.

Park & Hrnjak [6] developed a numerical and experimental study in which they compared the performance of two 10 kW R410A residential air conditioning systems, one with a minichannel condenser and the other with a round-tube condenser, both operated under three different ARI (Air-Conditioning & Refrigeration Institute) standard conditions (ARI A, B and C). They found that, in ARI A, the refrigeration capacity and COP of the system improved 3.4% and 13.1% respectively using the minichannel condenser, with even further improvement in ARI conditions B and C. They also found a reduction of the refrigerant charge of 9.2% for the whole system when using minichannel condenser (18.5% charge reduction in the condenser, with almost identical refrigerant charge for the rest of the system).

Hrnjak & Litch [8] studied a 13 kW prototype ammonia chiller with two different air cooled aluminium condensers, one with a single serpentine multiport macrochannels tube (D_h = 4.06 mm) and the other with a parallel multiport minichannel tube arrangement (D_h = 0.7 mm). They found that for the minichannel condenser, the overall heat transfer coefficient was between 60 and 80% higher, the refrigerant charge 53% lower, and the condenser charge per capacity ratio only 18 g/kW evaporator capacity, around 76% lower than for the macrochannels. The other smallest commercially available air cooled ammonia chillers have condenser charge per capacity ratio higher than 100 g/kW.

Cavallini et al. [9] studied a 100 kW R290 heat pump where the conventional brazed plate condenser was replaced by a shell and tube minichannel heat exchanger. According to their results, the minichannel condenser allows around 0.8 kg charge reduction (21% total charge reduction) with a slightly lower heating capacity and COP (around 2% average reduction).

The aim of the present work is to experimentally study an air/water chiller in which the conventional fin-and-tube condenser is replaced by an alternative compact heat exchanger with multiport minichannel tubes in a parallel flow arrangement provided by Modine Manufacturing Company.

2. Experimental facility

Fig. 1 shows the experimental facility developed at the Technical University of Cartagena for the test of reversible air/water heat pump systems. It is composed of a primary refrigerant loop represented in green lines, two auxiliary water loops represented in solid blue and solid red and an auxiliary air loop represented in dotted black lines in Fig. 1.

The chiller analysed is a reversible refrigeration system using R134a as refrigerant. The system is composed of: (1) a 34.38 cm^3 swept volume reciprocating compressor, (2) a four-way reversing valve, (3) an air/refrigerant heat exchanger, (4) a 3-l liquid refrigerant receiver, (5) a thermostatic expansion valve without external