INTERNATIONAL JOURNAL OF REFRIGERATION 34 (2011) 696–706

available at www.sciencedirect.com

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

Performance of residential air-conditioning systems with flow maldistribution in fin-and-tube evaporators

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ARTICLE INFO

Article history:
Received 18 October 2010
Received in revised form
23 November 2010
Accepted 15 December 2010
Available online 30 December 2010

Keywords:
Cooling
Air conditioning
Finned tube
Modeling
Simulation

ABSTRACT

Refrigerant and airflow maldistribution in fin-and-tube evaporators for residential air-conditioning was investigated with numerical modeling. Fin-and-tube heat exchangers usually have a pre-defined circuitry. However, the objective in this study was to perform a generic investigation of each individual maldistribution source in an independent manner. Therefore, the evaporator and the condenser were simplified to be straight tubes for the purposes of this study. The numerical model of the R410A system, its verification and an investigation of individual maldistribution sources are presented in this paper. The maldistribution sources of interest were: inlet liquid/vapor phase distribution, feeder tube bending and airflow distribution. The results show that maldistribution reduced the cooling capacity and the coefficient of performance of the system. In particular, different phase distribution and non-uniform airflow distribution reduced the performance significantly. Different feeder tube bendings only caused a minor decrease in performance.

Performance des systèmes de conditionnement d'air résidentiels avec une mauvaise distribution de l'écoulement dans les évaporateurs à tubes ailetés

Motsclés : Distribution ; Conditionnement d'air ; Tube aileté ; Modélisation ; Simulation

1. Introduction

Reduction of energy consumption and refrigerant charge in refrigeration systems is becoming increasingly important for environmental, legislative and economical reasons. Therefore, compact dry-expansion multi-channel heat exchangers are of interest for future refrigeration technology.

The use of multi-channels in evaporators gives rise to refrigerant maldistribution, which has been shown to reduce the cooling capacity and coefficient of performance (COP) of

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doi:10.1016/j.ijrefrig.2010.12.010

Nomenclature

Roman

A	Cross-sectional area (m^2)
C	Capacitance flow ($W\ K^{-1}$)
c_p	Specific heat capacity ($J\ kg^{-1}K^{-1}$)
F_w	Wall friction force ($N\ m^{-3}$)
F_x	Phase distribution parameter (–)
F_{air}	Airflow distribution parameter (–)
F_{ft}	Feeder tube bending parameter (–)
g	Gravitational acceleration ($m\ s^{-2}$)
$\bar{h}$	Specific in-situ mixture enthalpy ($J\ kg^{-1}$)
h	Specific enthalpy, mixed-cup enthalpy ($J\ kg^{-1}$)
M	Mass (kg)
$\dot{m}$	Mass flow rate ($kg\ s^{-1}$)
NTU	Number of transfer units (–)
P	Channel perimeter (m)
p	Pressure (Pa)
$\dot{Q}$	Heat flow rate (W)
q''_w	Wall heat flux ($W\ m^{-2}$)
T	Temperature (K)
t	Time (s)
V	Velocity ($m\ s^{-1}$)
x	Vapor quality (–)
z	Axial channel length (m)

Greek

α	Void fraction (–)
ϵ	Effectiveness (–)
ρ	Density ($kg\ m^{-3}$)
$\bar{\rho}$	Mixture density ($kg\ m^{-3}$)
ρ'	Momentum density ($kg\ m^{-3}$)
θ	Angle to horizontal plane (deg.)

Subscripts

a	Air
acc	Accelerational
fr	Frontal
$fric$	Friction
ft	Feeder tube
f	Saturated liquid
g	Saturated gas
H	Homogeneous
m	Mean
r	Refrigerant
sh	Superheat
w	Wall

cooling systems. Payne and Domanski (2003) showed that the capacity dropped as much as 41% and 32% for two different fin-and-tube evaporators due to variable superheat values between the circuits when circuit pressure drops were induced and the overall superheat was fixed at 5.6 °C.

Typically, fin-and-tube A-coils are employed in residential air-conditioning (RAC) systems as the indoor coil, which is the evaporator. Two coils form an A-shape, as the name indicates, in order to increase the frontal area of the evaporator. A drawback is that the airflow becomes non-uniform to the coil, resulting in airflow maldistribution. In a numerical study by Lee et al. (2003), non-uniform airflow profiles reduced the capacity of the evaporator up to 6%. The airflow might also create a recirculation zone in the lower part of the coil as pointed out by AbdelAziz et al. (2008), who carried out simulations of the airflow through an A-coil using computational fluid dynamics. These recirculation zones in the coil led to a reduction in the cooling capacity since the recirculated airflow was not exchanged.

Mixing of the refrigerant phases and orientation of the refrigerant distributor is also important in order to distribute the refrigerant phases equally. The density differences among the liquid and vapor phases indicate that the best flow orientation is vertical. However, this orientation does not always ensure optimal refrigerant distribution. Nakayama et al. (2000) studied a new type of distributor that had a capillary mixing space instead of the orifice of a conventional distributor. They showed that a vertical inclination angle of 15° reduced the capacity of the evaporator by 1.5% when they used the conventional distributor. However, the new type of distributor only had a reduction of 0.4%. The better mixing in the new type of distributor resulted in a capacity increase of 1.2% with the vertical orientation compared to the conventional distributor. Li et al. (2005) studied refrigerant flow distribution in distributors using computational fluid dynamics. In general, the authors reported that the spherical base distributor achieved the best distribution, and the orifice should be located close to the distributor base. Brix et al. (2009) studied maldistribution in an R134a mini-channel evaporator for an automotive air-conditioning system. Both inlet vapor quality and airflow non-uniformities were investigated numerically with simplified two-channel geometry. When only liquid entered into channel 2 and the remaining mixture entered channel 1, the cooling capacity was reduced by 23%. When the air velocity across channel 1 and 2 were 2.24 $m\ s^{-1}$ and 0.96 $m\ s^{-1}$, the cooling capacity decreased by 19%.

Furthermore, different feeder tube bendings give rise to refrigerant maldistribution due to different pressure drops in the multi-channels of the evaporator. Kim et al. (2009a,b) studied both refrigerant and airflow maldistribution on a fin-and-tube five channel R410A heat pump. Two and three of the channels, respectively, were treated similarly. Essentially, there were two circuits, where one had 50% larger area than the other. It was found that the cooling capacity and COP decreased by 12% and 8% as the feeder tube diameter decreased by 25%, or the inlet void fraction increased by 5.5% in one of the circuits, respectively. They also found that the cooling capacity and COP decreased by 16% and 11% when the airflow ratio between the circuits was 0.4, keeping the total volume flow constant.

Airflow maldistribution can be compensated for to some extent with smart refrigerant circuiting. However, the refrigerant circuiting does not ensure optimized refrigerant distribution under off-design conditions. Domanski and Yashar (2007) applied a novel optimization system called ISHED (intelligent system for heat exchanger design) to optimize refrigerant circuitry in order to compensate for airflow maldistribution. They measured the air velocity profile using particle image velocimetry (PIV). When the measurements