Applied Energy 136 (2014) 968–978

Contents lists available at ScienceDirect

Applied Energy

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

In-tube performance evaluation of an air-cooled condenser with liquid–vapor separator

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HIGHLIGHTS

- Improving quality can greatly enhance the in-tube heat transfer of the LSC.
- The heat flux affects the result of liquid–vapor separation on heat transfer.
- The LSC has a marked advantage on lower pressure drop over common condensers.
- The friction power and penalty factor of the LSC are lowest among the condensers.
- The lowest inside irreversibility loss benefits the thermal performance of the LSC.

ARTICLE INFO

Article history:
Received 14 October 2013
Received in revised form 5 July 2014
Accepted 10 July 2014
Available online 29 July 2014

Keywords:
Heat transfer
Pressure drop
Liquid–vapor separation condenser
Comprehensive performance evaluation

ABSTRACT

This study evaluates the thermal hydraulic performance of a novel liquid–vapor separation condenser (LSC). A series of experiments was performed to investigate the in-tube heat transfer coefficient and pressure drop of the LSC with varying average refrigerant quality at constant mass flux. The results were compared with the performance of a serpentine condenser (SC) and a parallel-flow condenser (PFC), with R134a as the refrigerant. Findings showed a very small change in the wall temperature of the LSC. The LSC had the lowest average condensation heat transfer coefficient among the three condensers at lower heat flux, but exceeded that of the PFC at higher heat flux. The pressure drop of the LSC was 77.1–81.4% lower than that of the SC and 57.5–64.6% lower than that of the PFC at a heat flux of 6.45 kWm^{-2}. Moreover, heat flux and condensing temperature had little influence on the pressure drop of the LSC. Based on these experimental data, the three evaluation criteria (friction power ratio, penalty factor, and minimum entropy generation number) applied to the three condensers proved that the LSC had the best thermal hydraulic performance. The lowest irreversibility of the LSC resulted from the entropy generation rate of the refrigerant side, which was the lowest among the three condensers.

1. Introduction

Condenser selection in refrigeration and air conditioning engineering is a critical factor in system efficiency and physical size. Conventional finned round tubes are usually used for air-cooled condensers in residential air-conditioning systems. Researchers and engineers have struggled to improve the overall performance of finned tube condensers for the sake of cutting material costs, reducing occupied space, and protecting the environment. In essence, all means are being sought to balance heat transfer and pressure drop behaviors.

In the condensation process, mass flux and vapor quality are the main factors influencing in-tube condensation heat transfer and pressure drop. Berrada [1] investigated the condensation heat transfer of R134a in a smooth copper tube with an inside diameter of 8.92 mm. He found that the condensation heat transfer coefficients for a vapor quality of 0.8 were nearly twice that for a vapor quality of 0.3 at experimental mass flux. Cavallini et al. [2] investigated the condensation heat transfer and pressure drop of R134a, R125, R236ea, and R32 inside a smooth tube. Condensation heat transfer coefficients were found to increase faster in regions with high vapor quality at a mass flux ranging from 300 $kg/(m^2\,s)$ to 750 $kg/(m^2\,s)$. Wongwises [3] and Laohalertdecha [4] found that the condensation heat transfer coefficients of R134a increase in an approximately linear manner with vapor quality, and that pressure drop increases noticeably as vapor quality and mass flux increase. Later, several scholars (Hossain [5], Zhang [6], and Son CH

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http://dx.doi.org/10.1016/j.apenergy.2014.07.032
0306-2619/

Nomenclature

Abbreviation

LSC	liquid–vapor separated condenser
PFC	parallel-flow condenser
SC	serpentine condenser
PF	penalty factor
AHTC	average heat transfer coefficient
FPR	friction power ratio

Symbols

x	vapor quality
q	heat flux (W m^{-2})
h	specific enthalpy (J kg^{-1})
c_p	specific heat capacity (J kg^{-1} K^{-1})
T	thermodynamic temperature (K)
$\overline{T}$	mean thermodynamic temperature (K)
ρ	density (kg m^{-3})
V	volume flow rate (m^3 s^{-1})
m	mass flow rate (kg s^{-1})
α_i	in-tube heat transfer coefficient (W m^{-2} K^{-1})
A_i	in-tube heat transfer area (m^2)
N	total tube number
n	tube number in one tube pass
P''	friction power (W)
Q	heat load (W)
f	friction factor
DT_s	condensing temperature drop
DT_d	driving temperature difference
G	mass flux (kg m^{-2} s^{-1})
d	diameter of tube (mm)
p	pressure drop (kPa)
$\triangle P$	pressure difference (kPa)
z	coordinate of flow direction (m)
S	entropy (W/K)
L	tube length in a tube pass
Ns	minimum entropy generation number

Subscripts

k	tube pass number
pre	pre-cooler
sub	sub-cooler
LSC	liquid–vapor separated condenser
com	the compared condenser
TC	measured by thermocouple
IFR	measured by infrared thermal imager
s	smooth tube
finned	equipped with fins
r	refrigerant
i	tube side
sat	saturate
a	air
v; l	vapor; liquid
in; out	inlet; outlet
gen	generation
w	tube wall

[7] et al.) also conducted studies on the effects of high vapor quality on condensation heat transfer coefficients by using varied refrigerants, and observed the presence of large pressure drops. These studies showed that although high vapor quality and high mass flux help improve condensation heat transfer coefficients, they also lead to serious pressure drops.

PFCs are an emerging technology used to enhance condensation in domestic units, particularly flat extruded aluminum multiport micro-channels in automobile air conditioning. PFCs have several advantages over traditional fin-and-tube condensers, such as compactness, reduced pressure drop, and reduced refrigerant charge. Multiple short parallel circuits are favorable to pressure drop, which could result in a low heat transfer coefficient.

Peng et al. [8] presented LSCs, which adopt a short heat transfer tube in a parallel arrangement and use liquid–vapor separators to drain away condensate intermittently during the condensation process. They reduced the amount of refrigerant condensation to gain droplets or unsteady thin film patterns in short tubes by keeping high quality throughout the whole condenser. Chen et al. [9,10] measured the improvement in the performance of an R22 air conditioner equipped with an LSC instead of the original tube-and-fin condenser. However, the thermal performance of this condenser has yet to be explored, and requires further evidence to verify its superiority over other common condensers in current applications.

Evaluating the thermal performance of heat transfer exchangers should cover the link between the heat transfer coefficient and frictional pressure gradient that exists when refrigerant condenses under operating conditions. The appropriate Performance Evaluation Criteria (PEC) provide a method for selecting the optimum geometry of the specified operating conditions.

Based on the first law of thermodynamics, Webb [11] presented a heat exchanger evaluation criterion called the Stanton friction factor ratio. This ratio has three parameters for three application cases. Friction power ratio (FPR) is used to evaluate the friction power reduction of two heat exchangers with equal heat flux and equal total heat transfer area. Cavallini et al. [12] reported that in two-phase heat transfer, frictional pressure drop affects the fluid temperature profile in the exchanger, with related effects on its thermal performance. They introduced a parameter, the penalty factor (PF), which fully considers the saturation temperature drop of the refrigerant across the full condensation process and the driving temperature difference (saturation minus tube wall) of the heat transfer process. The PF value is suitable for the two-phase heat transfer exchanger. Another common way of studying a whole heat exchanger is using the second law of thermodynamics. Bejan [13] proposed a design of minimum irreversibility in the form of an entropy generation number (Ns). Saechan [14] developed the method for analyzing two-phase condensers. He noted that the minimum total entropy generation rate of the condenser indicates the minimum losses in the condenser.

This paper discusses and compares the thermodynamic performance of the LSC with the PFC and the SC, including the in-tube condensation heat transfer coefficients and pressure drops, using an SC and a PFC with the same heat transfer area under fixed working conditions. Authoritative PECs, such as FPR, PF, and minimum entropy generation numbers, were used to rank these factors.

2. Experiments

2.1. Test condensers

Fig. 1a shows the LSC, which consists of a finned tube bank and a pair of headers at both ends. Several baffles are set in the headers. The refrigerant route is divided into several tube passes. This arrangement differs from those of other parallel heat exchangers