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Shell-and-tube evaporator model performance with different two-phase flow heat transfer correlations. Experimental analysis using R134a and R1234yf

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HIGHLIGHTS

- A model for a shell-and-tube evaporator using R1234yf and R134a is presented.
- The ε-NTU is used method to predict evaporating pressure and outlet temperatures.
- A set of different two-phase flow heat transfer correlations is compared.
- The performance of the model is studied comparing predicted and experimental data.
- The model using Kandlikar's correlation obtains the best predictions.

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ABSTRACT

This work presents a model of a shell-and-tube evaporator using R1234yf and R134a as working fluids. The model uses the effectiveness-NTU method to predict the evaporation pressure and the refrigerant and secondary fluid temperatures at the evaporator outlet, using as inputs the geometry of the evaporator, the refrigerant mass flow rate and evaporator inlet enthalpy, and the secondary fluid volumetric flow rate and evaporator inlet temperature. The model performance is evaluated using different two-phase flow heat transfer correlations through model outputs, comparing predicted and experimental data. The output parameter with maximum deviations between the predicted and experimental data is the evaporating pressure, being the deviations in outlet temperatures less than 3%. The evaporator model using Kandlikar's correlation obtains the highest precision and the lowest absolute mean error, with 4.87% in the evaporating pressure, 0.45% in the refrigerant outlet temperature and 0.03% in the secondary fluid outlet temperature.

1. Introduction

In recent years, chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) refrigerants have been replaced by hydrofluorocarbons (HFCs) refrigerants, due to their ozone depletion potential (ODP), according to the Montreal Protocol [1]. However, HFC refrigerants (such as R134a, R410A, R407C and R404A), which are entirely harmless to ozone layer, have high global warming potential (GWP) and they are considered as greenhouse gases under the Kyoto Protocol [2]. Moreover, the European Parliament established a ban for F-gases with a GWP of more than 150 for new models coming out of factories in 2011 and for all cars in 2017 [3]. As a result of all this process, efforts are made to search for refrigerant replacements for the actual fluids. One of those refrigerants to be replaced is R134a, with 100 years GWP of 1430, and extensively used in refrigeration and air conditioning, especially in mobile air conditioning (MAC). The possible refrigerants considered to replace R134a in vapour compression systems are natural refrigerants like ammonia, carbon dioxide or hydrocarbons (HC) mixtures; low GWP HFCs, highlighting R32 and R152a; and hydrofluoroolefins (HFO), specifically R1234yf, recently proposed as an alternative refrigerant for R134a in automotive air conditioning systems [4].

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Nomenclature

$\dot{m}$	mass flow rate (kg/s)
h	enthalpy (kJ/kg)
T	temperature (K)
P	pressure (kPa)
$\dot{V}$	volumetric flow rate (m^3/h)
c_p	specific heat capacity at constant pressure (kJ/kg K)
C	heat capacity (kW/K)
NTU	number of heat transfer units
C_r	heat capacity rate
A	heat transfer surface (m^2)
R_f	fouling resistance (m^2 K/W)
U	overall heat transfer coefficient (W/m^2 K)
d	diameter (m)
Q	thermal power (kW)
k	thermal conductivity (W/m K)
Re	Reynolds number
Pr	Prandtl number
Bo	boiling number
Co	convective number
S	suppression factor
F	Reynolds number factor
X	Martinelly parameter
M	molecular mass (kg/mol)
q	heat flux (W/m^2)
f	friction factor
x	vapour quality
var	variable
P_r	reduced pressure

Greek symbols

ρ	density (kg/m^3)
ε	heat exchanger effectiveness
α	heat transfer coefficient (W/m^2 K)
σ	surface tension (N/m)
δ	error
θ	standard deviation
λ	error bandwidth

Subscripts

r	refrigerant
b	brine
out	output
in	input
int	intermediate
1	boiling zone
2	superheating zone
min	minimum
max	maximum
i	inside
o	outside
w	wall
t	turbulent
tp	two-phase
l	liquid
v	vapour
nb	nucleate boiling
cb	convective boiling
lo	total flow as liquid
sat	saturated
fg	vaporisation

Focussing on R1234yf, this refrigerant has an ODP of zero [5] and its GWP is as low as 4 [6,7]. Hence, it can be accepted by the recent environmental requirements and polices. The thermophysical properties of R1234yf have been reported to be similar to those of R134a [8], thereby offering an opportunity as a drop-in replacement for R134a in current mobile air conditioners. The main thermophysical properties of R1234yf are summarized in Table 1 compared with those of R134a. About security characteristics, R1234yf has low toxicity, similar to R134a, and mild flammability, significantly less than R152a [9]. Analysing the case of R1234yf would be released into the atmosphere, it is almost completely transformed to the trifluoroacetic acid (TFA), and predicted consequences of some studies of using R1234yf [10,11] show that future emissions would not cause significant increase in TFA rainwater concentrations. Several works can be found in the literature presenting theoretical and experimental studies to determine the feasibility of direct substitution (or with slight modifications) using R1234yf in vapour compression facilities working with R134a in mobile air conditioning [12], air conditioning [13] and refrigeration systems [14,15]. These works show a reduction in the coefficient of performance (COP) and the cooling capacity when using R1234yf as drop-in alternative.

For optimizing the system performance, both in its design and its operation, it is interesting to model the heat transfer processes that take place in vapour compression systems. Information about the two-phase heat transfer coefficient in heat exchangers (condenser and evaporator) has an important role in the performance of heat exchangers models. Park and Jung [16] reported that R1234yf and R134a have very similar nucleate boiling transfer coefficients. Del Col et al. [17] revealed that R1234yf exhibits slightly lower heat transfer coefficients during condensation. Focussing on the evaporation, numerous correlations have been proposed for predicting the heat transfer coefficient of two-phase flow. The evaporator model could be developed using the most appropriate two-phase flow heat transfer correlations. However, limited information is available on evaporator models with R1234yf as working fluid.

So, in the present work a shell-and-tube evaporator model with different two-phase flow heat transfer correlations is presented, experimentally analysing the performance of the model when using R1234yf and R134a. The rest of the paper is organized as follows. In Section 2, the refrigerant test facility used to obtain the experimental data is described. In Section 3, the presented model is developed and explained. In Section 4, the experimental and predicted results are presented and discussed. Finally, in Section 5, the main conclusions of the paper are summarized.

2. Experimental setup

The experimental tests are carried out in a monitored test bench that consists of a refrigeration vapour compression system, shown in Fig. 1, using R1234yf and R134a as working fluids.

Table 1
Main thermophysical properties of R1234yf and R134a.

Thermophysical property	R1234yf	R134a
Chemical formula	$CF_3CF{=}CH_2$	$C_2H_2F_4$
Boiling point (K)	244.15	247.15
Critical point (K)	368.15	375.15
Liquid density at 298.15 K (kg m^{-3})	1094	1207
Vapor density at 298.15 K (kg m^{-3})	37.6	32.4
ODP	0	0
GWP	4	1430