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Mathematical Modeling and Analysis of Household Air Conditioner with R1234yf as a Low GWP & Low ODP Refrigerant

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Abstract

HydrofluoroolefinR-1234yf has been introduced as a low global warming potential (GWP) replacement for R-134a in air conditioning applications. A large work on R-1234yf exists for mobile air conditioning (MAC) however recently interest in the use of R-1234yf in household air conditioning applications is growing. Refrigerant R-1234yf has low GWP value of 4, compared to R-134a which has GWP of 1340. R-1234yf has an ozone depletion potential (ODP) of zero.In this study heat transfer coefficient and pressure drop during condensation of R1234yf and R22 in horizontal circular tubes with inner diameter 9.488mm are compared.The local heat transfer coefficient and pressure drop is obtained for heat fluxes ranging 10 to 40 kW/m^2,mass fluxes ranging from 100 to 500 kg/m^{2}s,saturation temperature 5 to 15 for evaporator and 30 to 45 for condenser and vapour quality upto 1.Mass flow rate through capillary tube is calculated by varying inner diameter of tube from 1.6 to 1.9mm.Results of R1234yf are compared with R22.

Keywords:*R1234yf, R134a, R22, heat transfer coefficient, pressure drop, mass flow rate.*

1. Introduction

Montreal Protocol [1], was adopted by many nations to begin the phase out of both Chlorofluorocarbons(CFCs) and Hydro Chlorofluorocarbons (HCFCs) due to their ozone depleting potential (ODP). Hydro fluorocarbons (HFCs) were developed as long term alternative to substitute CFCs and HCFCs as they were non ozone depleting, but have large global warming potential (GWP). HFCs were considered as greenhouse gases and currently they are target compounds for greenhouse gases emission reduction under the Kyoto Protocol [2]. In this way, the growing international concern over relatively high GWP refrigerants has motivated the study of low GWP alternatives for HFCs in vapor compression systems [3].

In the EU the F-gas regulation was issued [4], and this will ban the use of refrigerants with GWPs of more than 150 for new mobile air conditioners from 2011 and for all mobile air conditioners from 2017. Therefore, R134a, which is now used for mobile air conditioners, with a GWP of 1430(GWP relative to CO_2 based on a 100-year time horizon [5]) will be regulated. Under these circumstances, HFO1234yf has been proposed as a substitute for R134a and mobile air conditioners using HFO1234yf are being developed. This is because HFO1234yf has a very low GWP of 4, as well as being low-toxic, low-flammable, and similar to R134a in thermodynamic properties. On the other hand, R410A, which is now used for room air conditioners, has a high GWP of 2088. Although HFO1234yf is greatly different to R410A in its thermodynamic properties, this can decrease the warming effect of the emission into the atmosphere [6].

The US Environmental Protection Agency (EPA) has recently released a proposed rule for HFO-1234yf as an automotive refrigerant [7]. According to EPA, HFO-1234yf has a 100 year direct GWP of 4 and an ozone depletion potential (ODP) of zero [8]. According to DuPont and Honeywell, the life cycle climate performance (LCCP) of HFO- 1234yf is the lowest one [9]. In terms of safety, HFO-1234yf has a low acute and chronic toxicity [9]. HFO-1234yf has a relatively high lower flammability limit, high minimum ignition energy, and very low burning velocity [10]. Furthermore, HFO-1234yf has a high auto-ignition temperature of 678.15K [11]. In the final report to EPA, Honeywell and Dupont state that HFO-1234yf is mildly flammable. HFO-1234yf is stated to be safe for use as a refrigerant in vehicles [10].

1.2 Properties of R1234yf:

Table.1: Comparison of physical properties of R1234yf with R134a and R410A

Property	R1234 yf	R134a	R22	R410A
Refrigerant classification	HFO	HFC	HCFC	HFC
Chemical Formula	$CF_3CF=CH_2$	CH_2FCF_3	$CHCLF_2$	CH_2F_2/CHF_2CF_3

Molecular weight (g/mol)	114.04	102.03	86.47	72.58
Boiling point(°C)	-29.45	-26.06	-40.9	-51.58
Critical temperature (°C)	94.70	101.08	96.15	72.13
Critical pressure (kPa)	3382.2	4060.3	4990	4926.1
Critical density (kg/m^3)	475.55	515.3	523.8	488.90
Critical volume (m^3/kg)	0.0021	0.00194	0.0019	0.00205
Ozone depletion potential	0	0	0.055	0
Global warming potential	4	1430	1810	2088
ASHRAE standard 34 safety rating	A2L	A1	A1	A1

2. Literature Review

Endoh, K. [6] "Evaluation of Cycle Performance of Room Air Conditioner Using HFO-1234yf as Refrigerant", International Refrigeration and Air Conditioning Conference, Purdue University, 2010. An R-410A room air conditioner with a rated cooling capacity of 4 kW was used for the tests. Baseline tests were run with R-410A. Then drop-in and optimized system tests were conducted with R-1234yf. Cooling mode test conditions were 27°C dry bulb, 19°C wet bulb, and 35°C outdoor air. Heating mode test conditions were 20°C dry bulb, 15°C wet bulb (indoors), and 7°C outdoor air.

J.M.Mendoza-Miranda[13] "Experimental analysis of R1234yf as a drop-in replacement for R134a in a vapor compression system".In this paper, an experimental analysis of a vapor compression system using R1234yf as a drop-in replacement for R134a has been presented. In order to obtain a wide range of working conditions a total of 104 steady state tests have been carried out. The tests have been performed varying the condensing pressure, evaporating pressure, superheating degree, the compressor speed and the IHX use.Finally, it can be concluded, from the experimental results, that the energy performance parameters of R1234yf in a drop-in replacement are close to those obtained with R134a at high condensing temperatures and making use of an IHX.

ZhaogangQi[15], "Performance Improvement Potentials of R1234yf Mobile Air Conditioning System". In this the thermodynamic analysis for R1234yf mobile air condition system was performed association with R134a system under three typical vehicle operation conditions. The performance improvement potentials by superheat, subcooling and compressor performance were mainly focused and discussed.The analysis results revealed that the R1234yf system COP and cooling capacity were lower by 4.8~7.0% and 7.7~10.6% than that of R134a system under all three conditions (idle, city and high speed), respectively. Increasing subcooling temperature from 1K to 10K could improve system COP and cooling capacity by 15.0%. And the effect of superheat on COP and cooling capacity was tiny and was adverse for larger refrigerant mass flow rate. R1234yf system cooling capacity could increase by 72.8% with compressor volumetric efficiency (η_{vol}) from 0.55 to 0.95 if the other compressor efficiency and state points were fixed.

Joaquin Navarro-Esbri[17]. "Experimental analysis of the internal heat exchanger influence on a vapour compression system performance working with R1234yf as a drop-in replacement for R134a".In this work, an experimental analysis of the influence of the IHX adoption on the overall plant energy efficiency using the refrigerant R134a and the substitute fluid R1234yf has been addressed. This analysis has been carried out using the results obtained from an experimental compression vapour plant, where the main energy parameters of which were compared when the IHX is used or not. In this way, varying the condensing temperature and the evaporating temperature, a total of 36 steady-state tests have been obtained as experimental data for the work. The influence on the main energy variables of the plant when the IHX is adopted has been analysed.

Claudio Zilio , J. Steven Brownb [17] "The refrigerant R1234yf in air conditioning systems"., Experiments were conducted for a typical R134a compact European automotive air conditioning system equipped with an internally controlled variable displacement compressor, minichannel condenser, TXV, and minichannel evaporator Experiments were conducted for a typical R134a compact European automotive air conditioning system having a nominal cooling capacity of 5.8 kW at a compressor volumetric flow rate of 7.8 m3/h Three R1234yf systems were tested using the baseline hardware with some modifications.The numerical simulations show that enhancing the face area of the condenser by 20%, the oneof the evaporator by 10%, and using the overridden compressor, theR1234yf system showed higher COP values than the baseline R134afor equal cooling capacities.

Linlin Wang, Chaobin Dang, EijiHihara [19] "Experimental study on condensation heat transfer and pressure drop of low GWP refrigerant HFO1234yf in a horizontal tube". The condensation experiments were carried out in a horizontal tube with an inner diameter of 4 mm, mass flux ranging from 100 to 400 kg m^{-2} s^{-1} and saturation temperatures of 40°C, 45°C, 50°C using HFO1234yf ,R134a and R32 as the working fluid. Main conclusions are the Haraguchi correlation for predicting the local frictional pressure drop can predict the measured pressure drop best compared to the Lockhart-Martinelli correlation and Huang correlation. Haraguchi correlation agrees reasonably with the

experimental data values with a mean deviation of 10.8%.

3. Objectives

The primary objective of this current work is to study the household air conditioner having capacity of 1TR with refrigerant R-1234yf as the working fluid.

1. Mathematical modeling of Vapour compression refrigeration cycle using Mathcad.
2. The individual component modeling of compressor, condenser, evaporator, expansion valve from manufactures catalogue.
3. Arrangement of components according to VCR cycle.
4. Testing of model for actual atmospheric conditions by using R1234yf as a refrigerant.
5. The performance of model is tested according to ARI 210 standards.

4. Methodology

Phase 1: This will be preparatory phase which includes the study of existing literature about refrigerant R1234yf.
Phase 2: In this phase study of properties, scope of the refrigerant and also the basic VCR cycle and its components will be done.
Phase3: Mathematical modeling of Vapour compression refrigeration cycle using MathCAD and also the individual component modeling of compressor, condenser, evaporator, expansion valve from manufactures catalogue will be done.
Phase 4: Testing of model for actual atmospheric conditions by using R1234yf as a refrigerant.
Phase 5: The performance model is testing according to ARI 210 standards will be done.

5. Experimental set up

Experimental set up is shown in fig.1. Window air conditioner of 1 ton refrigeration capacity was selected for testing the performance of system with R1234yf and R22.The window air conditioner is composed of the basic components of a vapour compression system: a rotary compressor, a condenser, a capillary tube and an evaporator, and fans.The unit will be retrofitted with R-1234yf.The evaporator and condenser of the refrigeration unit were tube-fin air heat exchangers.
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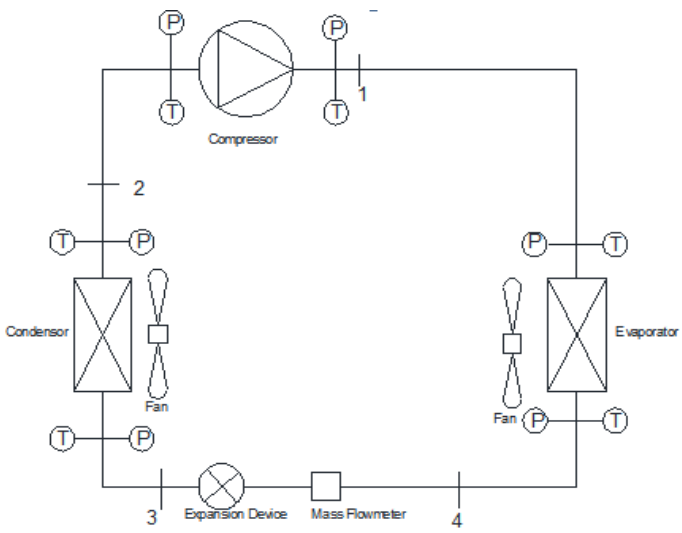


Fig1. Experimental set up

6. Mathematical modeling

Mathematical modeling of these components is done by using Mathcad.

6.1 Condensor

ShahCorrelation is used for calculation of two phaseheat transfer coefficient:

$$htp = hlo \times \left[(1-x)^{0.8} + \frac{[3.8 \times x^{0.76} \times (1-x)^{0.04}]}{Pr^{0.38}}\right]$$

To calculate single phase heat transfer coefficient Dittus-Boelter equation is used which is given by

$$hlo = \frac{Kl}{di} \times 0.023 \times Relo^{0.8} \times Prl^{0.4}$$

Pressure drop is calculated by using Haraguchicorrelation:

$$\Delta P = \Phi v^2 \times \left(\frac{2 \times fg \times G^2 \times x^2}{\rho g \times d}\right)$$

$$\Phi v = 1 + 0.5 \times \left[\frac{G}{\sqrt{g \times d \times \rho g \times (\rho l - \rho g}}\right]^{0.75} \times Xtt^{0.35}$$

Φv, two phase flow multiplier for frictional pressure drop

$$Xtt = \left(\frac{1-x}{x}\right)^{0.9} \times \left(\frac{\rho g}{\rho l}\right)^{0.5} \left(\frac{\mu l}{\mu g}\right)^{0.1}$$

Xtt,-Lockhart-Martinelli parameter

$$fg = \frac{0.046}{Reg^{0.2}}$$

Air Side

Air side heat transfer coefficient and pressure drop:

$$h = \frac{j \times G \times Cp}{Pr^{\left(\frac{2}{3}\right)}}$$

$$\Delta P = \frac{G^2 \times f \times Ar}{2 \times \rho}$$

j is colburn factor
f is friction factor

6.2 Capillary tube
The Length of an increment:

$$\Delta L = [(P1 - P2) \times A - m.(V2 - V1) \times \left(\frac{2 \times d}{fm \times Vm \times m}\right)$$

P1, V1 values at point 1 which is known at entrance condition
P2, V2 values for an arbitrarily selected temperature at point 2

$$fm = \frac{f1 + f2}{2} \qquad Vm = \frac{V1 + V2}{2}$$

fm, Vm are the mean values at point 1 and point 2.

Mass flow rate through the capillary tube is calculated by using Buckingham's π theorem,

$$m = \Pi 7 \times d \times \mu f$$

Where,

$$\Pi 7 = 1.5104 \times \Pi 1^{0.5351} \times \Pi 2^{-0.3785} \times \Pi 3^{0.1074} \times \Pi 4^{-0.1596} \times \Pi 5^{0.0962} \times Fcoil$$

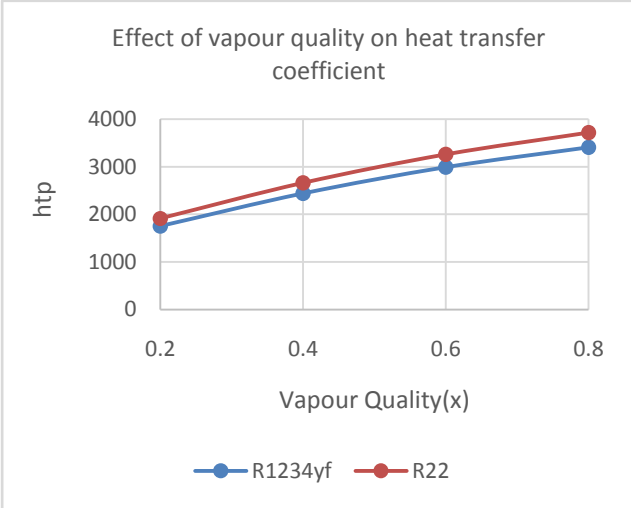
$$Fcoil = 0.7887 \times \Pi 6^{0.0424}$$

Table.2 Definition of dimensionless π parameters

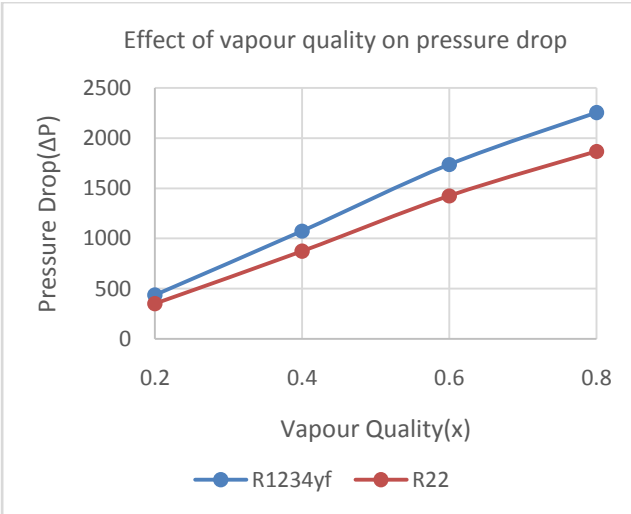
Πgroup	Definition	Consideration
Π1	$\Pi 1 = \frac{Pin \times d^2}{\mu f^2 \times vf}$	Inlet pressure
Π2	$\Pi 2 = \frac{L}{d}$	Tube geometry
Π3	$\Pi 3 = \frac{d^2 \times Cpf \times Tsub}{vf^2 \times \mu f^2}$	Inlet condition
Π4	$\Pi 4 = \frac{d^2 \times hfg}{vf^2 \times \mu f^2}$	Heat of vaporization
Π5	$\Pi 5 = \frac{d \times \sigma}{vf \times \mu f^2}$	Bubble growth
Π6	$\Pi 6 = \frac{D}{d}$	Coiled diameter
Π7	$\Pi 7 = \frac{m}{d \times \mu f}$	Mass flow rate

7.Results

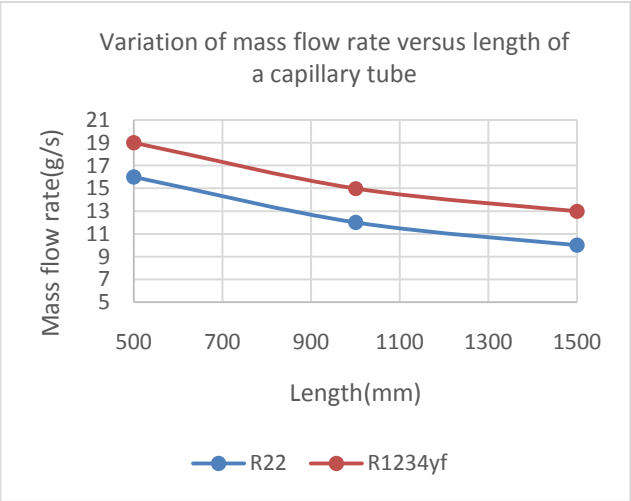
Condenser:
7.1 Comparison of effect of vapour quality on two phase heat transfer coefficient with R1234yf and R22
di =9.488mm
G =300kg/m²s
T =40°C



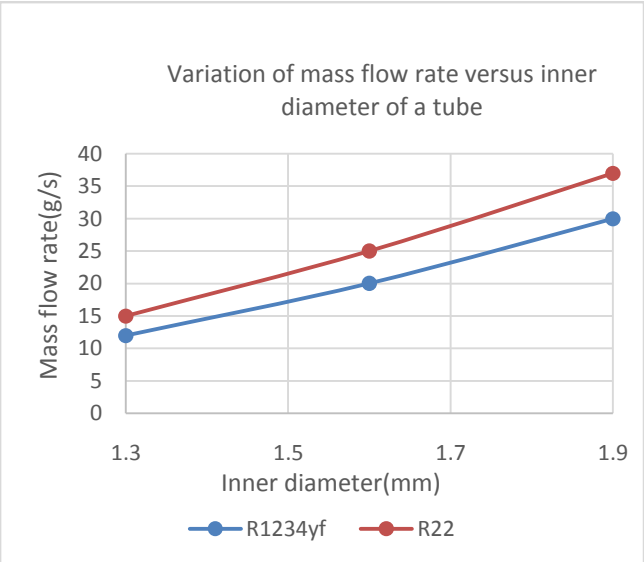
7.2Comparison of effect of vapour quality on pressure drop with R1234yf and R22
di =9.488mm
G =300kg/m²s
T =40°C



Capillary Tube:
7.3 Comparison of effect of variation of mass flow rate versus length of a capillary tube
d =1.3mm
T_{Ccond}=40°C
T_{sub} =5°C



7.4 Comparison of effect of variation of mass flow rate versus inner diameter of capillary tube
L =1000mm
T_{Ccond}=40°C
T_{sub} =5°C



8. Conclusion

This work investigates the comparison of pressure drop and heat transfer coefficient of R1234yf and R22 in condenser by varying vapour quality. Calculation of air side heat transfer coefficient and pressure drop and also comparison of length of capillary tube, mass flow rate with R1234yf and R22.The following important points emerge from the study.

1.Two phase heat transfer coefficient of R1234yf and R22 increases as the vapour quality increases.

2. Two phase heat transfer coefficient of R1234yf is less than R22 in condenser.

3. Condenser side pressure drop of R1234yf is more than R22.

4.As the length of capillary tube increases, mass flow rate for both the refrigerants decreases.

5.For equal length of capillary tube, mass flow rate required for R1234yf is more than R22

6.For same inner diameter, mass flow rate of R1234yf is less than R22.

From the above discussion, it is revealed that to meet the properties of HFO1234yf we have to modify a room air conditioner that had been using R22.

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