A Comparative Study on the Heat Transfer and Environmental Characteristics of R22 Replacements

Arijit Kundu, Ravi Kumar, and Akhilesh Gupta

***Abstract*—**To summarize the current canvas in the developing field of refrigeration and to identify the prospect of future research as well, a comprehensive review of the characteristics of environmentally friendly refrigerants and their comparative experimental results of heat transfer performances in evaporation is presented here. Azeotropic and quasi-Azeotropic refrigerant mixtures are the new feasible replacements to R22 which is being used by most of the existing refrigeration systems. This paper presents an experimental study on heat transfer characteristics in the evaporation of a pure fluid R134a and a refrigerant blend R410A through small diameter (ID 7.0 mm) smooth copper tube. Experimental data were acquired over an imposed heat flux range of 5-10 kW/m^2 and the refrigerant mass flux was varied from 100 to 300 kg/m^{2}s at an evaporating temperature range of 50 ^{o}C-80 ^{o}C.

***Index Terms*—**refrigeration, evaporation, azeotropic, quasi-azeotropic, R22, R134a, R410A.

I. Introduction

The air conditioning and refrigeration has a compelling growth in the recent past for inducing human comfort against the appalling effect of sweltering summer or intense cold in the winter season. Technology also has been used to take care of human soothe to explore this field for the past few decades. But the elevated electrical energy consumption, ozone depletion and global warming are the woeful adverse effects to the environment and living biota on the earth. The rich progression of the use of refrigerators, air conditioners and heat pumps increases the emission of greenhouse gases (GHGs) which are the main endorsers to the climate change. Thus to protect the environment, especially from global warming and to find solutions to socioeconomic favor for mankind, further study is essential.

Due to their stratospheric ozone layer depletion, hydrochlorofluorocarbon (HCFC) refrigerants, especially R22 which has been used by refrigeration household for many decades, will be phased out by 2020 as amendments had been strictly granted by Montreal protocol [1] and EEC regulation [2]. The Kyoto Protocol [3] in Japan was the same international climate treaty in the trail. Among all the refrigerants that can replace the HCFCs there are hydrocarbons (HCs), hydro-fluorocarbons (HFCs) and natural substances like CO_2, ammonia, air or water.

Manuscript received October 10, 2014.

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II. Environmental Impacts

Ozone is a greenhouse gas which absorbs solar ultraviolet (UV) radiation, thus, plays an important role in the climate system over the earth. Also the absorption of UV radiation protects the Earth's Biota from this potentially harmful short wavelength radiation. But the stratospheric ozone layer has been depleted in recent decades by the emission of various ozone-depleting substances (ODS), most of which are also greenhouse gases. The major anthropogenic depleting agents, CFCs and halocarbons, are now controlled under the Montreal Protocol [1]. They are being replaced by HFCs and HCFCs with lower ozone depletion potentials (ODPs) but those are still greenhouse gases, often with large global warming potentials (GWPs). In contrast to the reimbursement of the stratospheric ozone layer, high surface ozone values are unfavorable to human health. Stratospheric ozone depletion during recent decades has interpreted a negative radiative forcing of the climate system; in contrast, the increase in ODSs has been a positive radiative forcing. Human activities resulted in changes in the atmospheric concentrations of several greenhouse gases, including stratospheric ozone structure and ODSs and their substitutes. Changes in the engrossment of these gases amend the radiative balance of the Earth's atmosphere by changing the balance between incoming solar radiation and outgoing infrared radiation. Such a change in the Earth's radiative balance is called a radiative forcing. Positive radiative forcing are expected to warm the Earth's surface and negative radiative forcing are for cooling it beyond anticipation. Changes in carbon dioxide (CO_2) provide the largest radiative forcing effect and are estimated to be the largest overall contributor to climate change. Global warming rises because of greenhouse effects as described by McMullan [4] shown in Fig. 1.

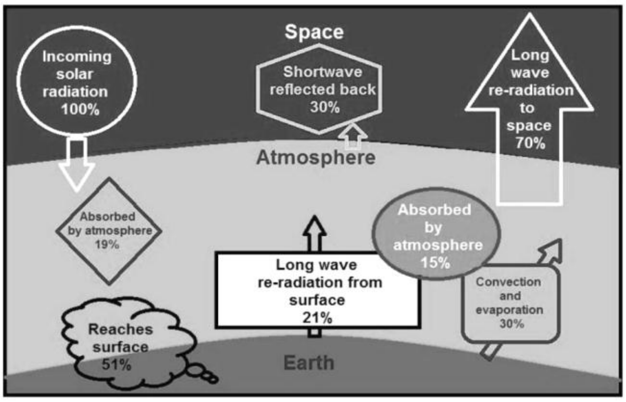


Fig. 1 The global warming and greenhouse effect.

A. Ozone depletion potential (ODP) is used as a simple quantifying tool for the measurement of the effect of various ozone-depleting compounds on the ozone layer, and have proved to be an important aspect of the formulation of the

http://dx.doi.org/10.15242/IAE.IAE1214204

Montreal Protocol [1] and its amendments. The ODP is defined as the integrated change in total ozone per unit mass emission of a specific ODS relative to the changes in total ozone per unit mass emission of chlorofluorocarbon-11 (R11) [5]. For the calculation of the ODP, Solomon et al. [6] have formulated a semi-empirical approach for which ODP is given by eq. (1) as

$$ODP = \emptyset \cdot \alpha \cdot \frac{\tau_{Gas}}{\tau_{CFC-11}} \frac{M_{CFC-11}}{M_{Gas}} \frac{N_{Gas}}{3} \tag{1}$$

Where $\emptyset$ is the factor of an inorganic halogen release in the stratosphere from observations relative to R11, α is the relative efficiency of any halogen compound compared with chlorine, τ is the global lifetime of the long-lived gas, M is the molecular weight, N is the number of halogen atoms. Global instantaneous lifetime τ is calculated from eq. (2) as shown below.

$$\tau = \int S dv / \int S \cdot f\, dv \tag{2}$$

$$\tau_{Local} = {}^{1}/_{f(x,y,z,t)} \tag{3}$$

Local lifetime, τ_{Local} is the reciprocal of total loss frequency $f(x,y,z,t)$, v is atmospheric volume and $S(x,y,z,t)$ is the trace gas distribution.

B. Global warming potential (GWP) is a relative index used to compare the climate impact of an emitted greenhouse gas, relative to an equal amount of CO_2 and calculated by the ratio of the time-integrated radiative forcing from a pulse emission of 1 kg of a substance, relative to that of 1 kg of CO_2, over a fixed time horizon. The direct GWP of a gas is calculated by eq. (4).

$$GWP = \int_0^{th} \Delta A_{Gas} dt \Big/ \int_0^{th} \Delta A_{CO_2} dt \tag{4}$$

Where Houghton et al. [7] explained that th is the time horizon over which the calculation is performed, $\Delta B_{Gas}(t)$ is the change in burden due to emission pulse, and the absolute GWP with respect to radiative forcing (RF) due to a unit mass increase of the gas according to its expected steady-state distribution for continuous emission is given by eq. (5).

$$\int_0^{th} \Delta A_{Gas} dt = RF_{Gas} \cdot \Delta B_{Gas_{t=0}} \cdot \tau_{Gas} \cdot \left(1 - exp^{th/\tau_{Gas}}\right) \tag{5}$$

C. Total equivalent warming impact (TEWI) is analyzed by Benhadid-Dib and Benzaoui [8] calculating the direct emissions of the refrigerants contained in each system from leakage over its entire lifetime. It can carry a high uncertainty associated with the assumptions taken for the calculation as shown in eqs. (6-8).

TEWI(kg of CO_2) = direct effect + indirect effect (6)

Direct effect = [(make-up rate × service life) + end of life-loss]× charge × GWP (7)

Indirect effect = op. power × service life ×CO_2 emission (8)

III. Recent Literature

The overall exposure on the historical declination of the use of CFCs in near past has been described by Kim *et al.* [9]. They imparted that the most widely employed in aerosol propellant mixture R11 had been preferred in refrigeration over its neighborhood R113, R115 and others due to low toxicity, low flammability, low gas-phase thermal conductivity, good chemical stability and low corrosiveness. Kuijpers *et al.* [10] has experimentally affirmed that CFC-12 was recommended to be replaced by HFC-134a though its volumetric refrigeration capacity and energetic efficiency was better. Suleiman *et al.* [11] has talked about the theoretical differences in performances between R12 and R22 and suggested in a case study that R12 can be replaced successfully to reciprocating air conditioner by R22. Archie McCullocha [12] showed that use and emissions of fluorocarbon arises the end products halogen acids and trifluoro-acetic acid, all of which pre-exist in the environment in quantities greater than they are expected. By this time, HCFCs have replaced less than one third of CFCs and are, themselves, ozone depleting substances that will be phased out under the international protocols. The growth in HFCs amounts to about 10% of the fall in CFCs. It is likely that the impact of new fluorocarbons on climate change will be a very small fraction of the total impact, which comes mainly from the accumulation of carbon dioxide in the atmosphere. The atmospheric concentrations for R12 and R134a have been observed by McCullocha *et al.* [13], calculated from the emissions anticipated and those are in near consort with observances. They also included that the agreement between observation and calculation is deficient for R22, if its atmospheric lifetime is 12 years, but becomes much closer with a lifetime of 10 years.

Devotta *et al.* [14] has concluded with an experimental performance presentation of propane (R290) as a drop-in substitute to R22 with lower cooling capacity of 6.6-7.9%, but better COP of 2.8-7.9% and lesser energy consumption of 12.4-13.5% than that of R22. Improvement of about 4% on cooling capacity and 13.9% on coefficient of performance has been achieved by Chen [15] replacing R22 with R410A in a comparative study between near-azeotrope R410A and R22 residential air conditioner. Chaichana *et al.* [16] demonstrated the comparative assessment of natural working fluids like CO_2 and ammonia with R22 in terms of their thermo-physical properties and performances. They have shown that R744 (CO_2) is not suitable for solar-boosted heat pumps because of its low critical temperature and high operating pressures where ammonia seems to be a more suitable substitute in terms of overall performance. Alberto Dopazo and Fernandez-Seara [17] have dealt with the design, construction and experimental evaluation of a stationary prototype of a cascade refrigeration system with CO_2 and NH_3 to supply a horizontal plate freezer of 9 kW refrigeration capacities. They showed that the volumetric flow of NH_3 had been always higher, reaching differences of up to 840% at -50^{0}C evaporating temperature. Kim and Kim [18] investigated the performance of an auto-cascade refrigeration system using zeotropic refrigerant mixtures of R744 / R134a and R744 / R290. Experimental and similarly simulation results show that as the composition of R744 in the refrigerant mixture increases, cooling capacity is enhanced, but COP tends to decrease while the system pressure rises. Messineo [19] has presented a thermodynamic analysis of a cascade refrigeration system using carbon dioxide and ammonia as refrigerant. They reported that in low- temperature applications including rapid freezing and the storage of frozen foods a carbon dioxide-ammonia cascade refrigeration system is an interesting alternative to R404A two-stage refrigeration system for energy, security and environmental reasons. It was also noticed a decrease by 27% of the COP as the condensing temperature increases from 30°C to 45°C.

Karagoz *et al.* [20] experimentally investigated the performance of an air to water vapor compression heat pump with pure R22, pure R134a and some binary mixtures of R22/R134a as working fluids. Payne and Domanski [21] compared an R22 and an R410A air conditioner operating at high ambient temperatures and noticed that when outdoor temperature increased, the R410A system performance degraded more than the R22 system performance. Babu *et al.* [22] made attempts to find new alternatives for R22 by considering performance parameters of window air-conditioner. By comparing the performance parameters, they recommended to use the binary mixture R32/R134a with POE oil or ternary mixture R32/R134a/R290 with mineral oil as a drop in alternate for R22 in window air-conditioner.

IV. Refrigerant Predilection

The thermodynamic, physical, and chemical properties specify a refrigerant's application, either it is industrial, commercial or domestic and also fulfilling the requirement of low or higher cooling effect, but environmental safety in general is an essential requirement to accredit it in current situation. High boiling refrigerants, as R11 or R123, generally low pressure fluid require large suction volumes and are accommodated for large capacity refrigerating units. R22, propane, ammonia or CO_2 are low boiling high pressure refrigerants and require smaller suction volume suited for medium capacity refrigeration appliances. R12, R134a or isobutene requires quite small suction volumes, thus, has been used in small capacity units like domestic refrigerators or in cars. Generally, any refrigerant should be non-toxic and non-flammable in its use though no fluid in existence is just the thing to these touchstones. Refrigerants preferred depending on its picky application with better thermodynamic and chemical possibilities under safety precautions with limited perniciousness.

HFCs and HFOs are being well thought-out for future use as refrigerants. They are replacing the use of CFCs and HCFCs, and some of HFCs which are being prohibited due to their noteworthy smack to climate as ODSs. The resulting changes in historic emissions from CFCs, HCFCs and HFCs are shown in Table 1**.** Direct and indirect emissions need to be quantified to account for the full inventory of emissions from products and equipment using HFCs or HCFCs. Indirect emissions are usually associated with the amount of energy assimilated for the operation of the equipment loaded with the fluid. Direct emissions are reasonable throughout the lifetime of the refrigerant, from the commencement of fluid manufacture through use, to its demolition. The identification of emissions from these various stages is necessary for both the environmental and safety appraisals of its applications. The manufacture of fluids requires feedstock materials, which are sourced, produced and used universally. Emissions from these feedstock materials, their intermediates and the end substance can occur in chemical processing plants. The well design and cognitive process of the plant can show the way to lower emissions. The emissions of GHGs are significantly less for alternative fluids. The operational stage of the product lifetime tends to result in the largest emissions for most applications. The multiple factors contributing to the emissions of refrigerants often lead to a fairly broad distribution of net leakage rates for equipment individually. Unfortunately, it is difficult to measure the field leakage for most applications and even where possible, the measurement may be inexact. To predict emissions associated with a particular system different approaches can be employed. The least accurate but the simplest approach is to apply annual leak rates (% per year) for the appropriate sector to the weight of the fluid used. The IPCC Good Practice Guidance on National Green house Gas Inventories published in 2000 includes three methods for estimating emissions of ODS substitutes. The tier1 method that equates emissions to consumption (potential emissions), the tier2a bottom-up method that applies country specific emission factors to estimates of equipment stock at different life cycle stages, and the tier2b top-down method that uses a country-level, mass-balance approach.

TABLE 1: Estimated Emissions Of Ods (in tons/year) [23, 24].

Refrigerant	Year		
	1990	1995	2000
R11	258,000	106,000	75,000
R12	367,000	256,000	134,000
R22	217,000	252,000	286,000
R32	0	0	230
R123	0	2,100	4,200
R125	0	200	5,150
R134a	180	17,500	73,700

R134a intended to swap R12 for the high and medium pressures. R404A is proposed to replace definitely R502 and R12 for low pressures. R407C and R410A are intended to replace R22 in air conditioning applications. Several researches [25, 26] have been published showing quite weak heat transfer performances of zeotropic mixture R407C over R404A, R410A or R134a where environmental deportment of R410A or R134a is quite comparable with respect to the others except HFO refrigerants which have cost concern to be used in large scale in underdeveloped and developing countries. Also the test results for heat transfer performances for HFO refrigerants are very scarce in open literature, though they are reportedly environmentally friendly beyond expectations. This study only concentrates on the flow boiling performances of R410A and R134a in different experimental parameters.

V. Experimental Observations

The objective of the experimental study is to determine how the vapor-compression refrigeration plant actually deports when the refrigerant is used. The tests are anticipated to afford indications on the performance of the refrigeration system designed and constructed to operate with both R22 and replacement pure fluid R134a and blend R410A.

A. Experimental rig and test procedure

Fig. 2 shows the schematic of experimental rig. The test apparatus consists of a semi-hermetic compressor, water-cool condenser, filter-dryer, thermostatic expansion device, accumulator, oil separator, mass flow meter, pre-heater, post-heater and test-evaporator.

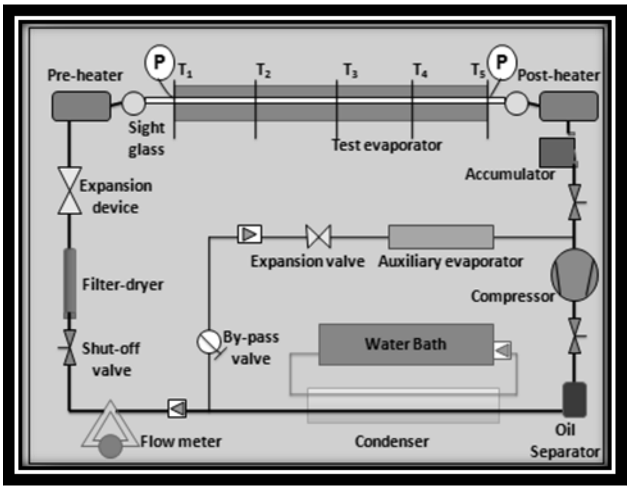


Fig. 2 Schematic diagram of experimental rig.

The mass flow rate has been controlled through the bypass valve fitted with auxiliary evaporator and expansion valve on the bypass line. The test section is made of copper circular smooth tube with inner diameter of 7 mm and outside diameter of 9.52 mm. The outside tube wall temperatures have been measured by T-type thermocouples (with a calibrated accuracy of $\pm 0.2^0$C) at five axial positions (T_1, T_2, T_3, T_4 and T_5) including inlet and exit to the test evaporator tube. In each section, the temperatures were measured at the top, two sides of the middle and bottom of the tube. The average of these temperatures indicates the local wall temperature. The local saturation pressures at the inlet and outlet of test evaporator are measured by piezoelectric pressure transducers (P). Test evaporator tube is heated by flexible Nichrome heater wire (2 kW capacity, calibrated accuracy of 2.5W) wrapped around the tube over full test length of 1.2 m. Heat flow to the heater has been conducted using a variable voltage controller and current flow is measured by standard clamp meter (accuracy ±2.0% of reading ±5digits) to determine applied heat flux. To calculate enthalpy at entry to pre-heater, another pressure transducer and T-type thermocouple are fitted at a section just prior to pre-heater.

The temperature and pressure measurement data have been recorded through the precise data acquisition system. The thermodynamic properties of refrigerants have been obtained from REFPROP 8.0 [27].

B. *Data reduction*

An analysis is needed to calculate the heat transfer coefficient, pressure drop and vapor quality from the experimental data and the data reduction process is discussed below. The local heat transfer coefficient, h is calculated using eq. (9).

$$h = \left[\frac{\pi D_i L\left(T_{w_0} - T_{Sat}\right)}{q} - \frac{D_i}{2}\left(\frac{\ln[D_o/D_i]}{k}\right)\right]^{-1} \tag{9}$$

The vapor quality, x has been estimated by an energy balance over the evaporator using eq. (10).

$$x = \frac{1}{H_{lv}}\left[\frac{4Q}{\pi D_i^2 G} + \left(H_{l,i} - H_{l,o}\right)\right] \tag{10}$$

Here D is the tube diameter, L is the test length of the tube, *k* is the thermal conductivity of copper in W/mK, G is the mass velocity in kg/m^{2}s, H is specific enthalpy of refrigerant in J/kg, *h* is heat transfer coefficient in W/m^{2}K and x is vapor quality. Subscript i indicates inside or inlet and o indicates outside or outlet condition; where w denotes at tube wall, Sat means saturation state, *l* denotes for liquid state, *v* denotes vapor state and *lv* indicates latent heat. q is heat flux supplied to the test evaporator measured by input voltage (*V*) and current (*I*) shown in eq. (11) where Q ($V \cdot I$) is the heat supplied to the evaporator and heaters.

$$q = V \cdot I / \pi D_0 L \tag{11}$$

The difference of the inlet and outlet quality of the test section was varied with test conditions. Kim et al. [28] have explained the procedure with an example as when the inlet quality of the test section was 0.15 at a mass flux of 100 kg/m^{2}s and heat flux of 5 kW/m^2, the outlet quality of the test section was approximately 0.3. Therefore, to obtain the quality of 0.8 at the outlet of the test section, 8 consecutive experiments (40 local stations) were conducted with different inlet qualities. The average heat transfer coefficient ($\bar{h}$) was calculated by eq. (12).

$$\bar{h} = \frac{\int_{x_{in}}^{x_{out}} h\,dx}{(x_{out} - x_{in})} \tag{12}$$

The local pressure drops were also measured from 8 consecutive experiments with different inlet qualities at each mass velocity with corresponding heat flux. The uncertainty in the determination of the flow boiling heat-transfer coefficients and pressure drops of the present study is found to be within ±11% of all test runs using the method proposed by Schultz and Cole [29].

C. *Experimental results*

The refrigeration plant has been running with R22, R134a and R410A separately under various working conditions. Tests are conducted varying different experimental parameters to evaluate the flow evaporation heat transfer coefficient and the pressure drop gradient to compare the heat transfer performances of refrigerants selected. The test parameters are given in Table 2. R22, R134a and R410A heat transfer coefficients and pressure gradient trends are experimentally examined, compared and expressed with a variation of vapor quality in the present study.

TABLE II: EXPERIMENTAL PARAMETERS.

Parameters	**Range**
Refrigerant mass flux (G)	100-300 kg/m^{2}s
Heat flux (q)	5000-10000 W/m^2
Vapor quality	0.15-0.85
Evaporative pressure	5-6.5 bar
Inlet temperature	5^0C to 8^0C

Experiments have been performed varying the mass flux of 100-300 kg/m^{2}s where heat flux is varied from 5 kW/m^2 to 10 kW/m^2 at different evaporating pressures p = 5.0 bar to 6.5 bar where the inlet temperatures are maintained at 5^0C to 8^0C. Totally 81 test runs include 288 data points which have been obtained in the current study. Flow pattern map [30] has been used for evaluation of flow regime.

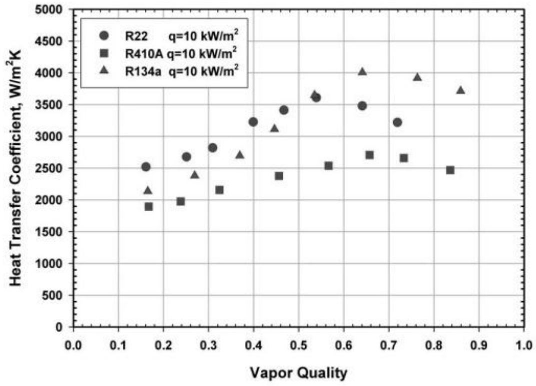


Fig. 3 Heat transfer coefficients comparison at G = 100 kg/m^{2}s.

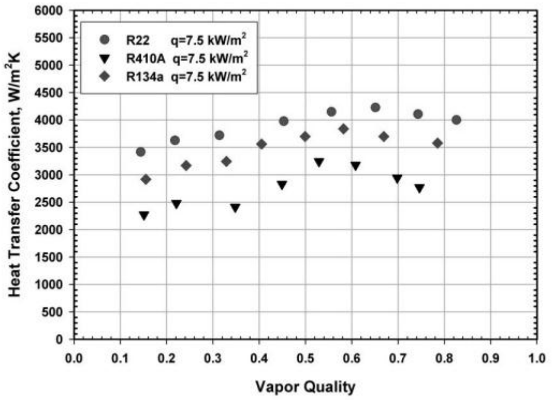


Fig. 4 Comparison of heat transfer coefficients at G = 200 kg/m^{2}s.

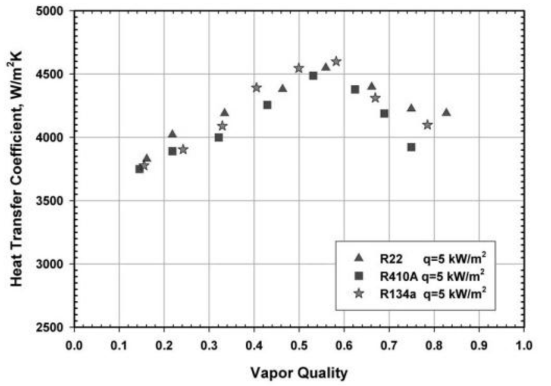


Fig. 5 Comparison of heat transfer coefficients at G = 300 kg/m^{2}s.

Fig. 3, 4 and 5 shows the variation of the heat transfer coefficient of R22, R410A and R134a as a function of vapor quality with different imposed heat fluxes at mass flux of 100 kg/m^{2}s, 200 kg/m^{2}s and 300 kg/m^{2}s, respectively. Generally heat transfer coefficient increases with increasing mass flux and vapor quality for all the refrigerants. About 100% increase in mass flux, average heat transfer coefficients increase of 51-97% for R22; 50-96% for R410A and for R134a, increments are 20-67% when imposed heat flux was 10 kW/m^2. It is also revealed from the figures that the average heat transfer coefficient for R22 is 24% more than that of R410A at 10 kW/m^2 fixed heat flux and mass flux of 100 kg/m^{2}s, but the average heat transfer coefficient of R134a is 22% less than that of pure fluid R22 at mass flux of 200 kg/m^{2}s with 7.5 kW/m^2 of heat flux.

Heat transfer coefficient increases with vapor quality up to a certain value in each case; then it decreases because of dry-out. Heat transfer mechanism in flow boiling is the combination of nucleate boiling and convective boiling. At high heat fluxes, nucleate boiling dominates over convective boiling; where at high mass flux, an increase in fluid velocity enhances convective boiling. Due to mass transfer resistance in nucleate boiling and high temperature glide, heat transfer coefficients of refrigerant mixtures are always lower than pure single component refrigerants. Liquid film on the tube wall disappears at dry out condition leaving the tube wall totally or partially dry, thus sharp drop in heat transfer coefficient. In the present investigation, at low mass velocity and low imposed heat flux inside the evaporator tube, heat transfer coefficient increases with vapor quality up to 60% to 70% of the tube for R22 or R134a, but only 45-54% for R410A. It is also seen from Fig. 6 that at high mass velocities of 300 kg/m^{2}s, when the annular flow regime persists, the variation of heat transfer coefficient in vapor quality nearly same for pure refrigerants R22, R134a or azeotropic blend R410A because of the lower temperature glide for R410A nearly diminishes the flow pattern differences with pure fluid at the thin layer of fluid around the tube wall when fluid velocities are very high; and it makes R410A a comparable replacement to HCFC fluids in refrigeration.

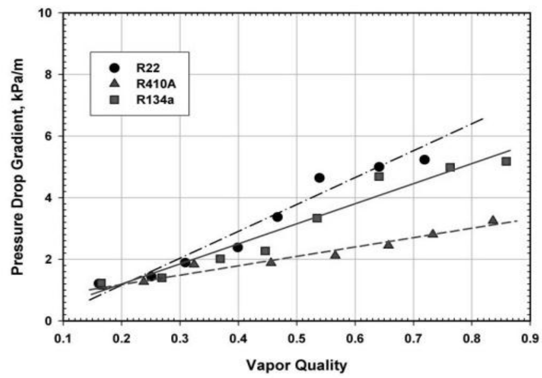


Fig. 6 Comparison of pressure drop gradient at G = 100 kg/m^{2}s.

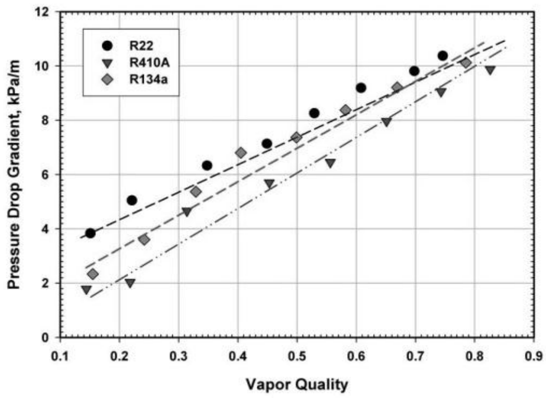


Fig. 7 Comparison of pressure drop gradient at G = 300 kg/m^{2}s.

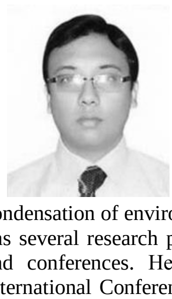
The variation of pressure drop gradients with respect to vapor quality for mass flux of 100 kg/m^{2}s and 300 kg/m^{2}s are shown in Fig. 6 and Fig. 7, respectively. Pressure drop increases significantly with both mass flux and vapor quality. Pressure drop gradients for R22 are higher than both of R134a and R410A. The difference increases with the increase in mass flux. The delay in flow pattern can be explained by the mixture property of refrigerant blend. The density difference in volatile elements may cause lower mean liquid velocity [31] and thus, delay in flow pattern transitions for refrigerant mixtures.

VI. Conclusion

Massive utilization of refrigeration and air conditioning in the present life, either domestic, commercial or industrial, has threatened the environment now through ozone depletion and global warming forcing us to acknowledge the time on the verge of finding positive solution immediately. The HCFC refrigerants, mainly R22 used in the refrigeration systems have become a subject of great concern for the last few decades in the same squad. HFCs and their mixture refrigerants which are currently the leading replacements for HCFC refrigerants; however, they are equally damaging in nature similar to HCFCs. This paper discusses the problems and causes of global warming and shows the experimental results with comparison in thermodynamic performances between R22, its replacement pure fluid R134a and near-azeotropic replacement R410A. Based on the results regarding the energy performance in flow boiling, it can be understood that R410A is found to be comparable substitutes for R22 and R134a.

REFERENCES

[1] Copenhagen amendments to the Montreal Protocol, 1992.
[2] EEC Regulation 3093/94, 1994.
[3] The Kyoto Protocol, "Kyoto Protocol to the United Nations framework convention on climate change", *Climate Change Secretariat*, Kyoto, Japan, UNFCCC, from http://unfccc.int, (1997).
[4] McMullan, J.T., "Refrigeration and the environment-issues and strategies for the future", *Int. J. Refrig.*, vol. 25, pp. 89-99, (2002). http://dx.doi.org/10.1016/S0140-7007(01)00007-X
[5] WMO, "Scientific Assessment of Ozone Depletion: 1994, Global Ozone Research and Monitoring Project", Report No. 37, World Meteorological Organization, Geneva, (1995).
[6] Solomon, S., Mills, M., Heidt, L.E., Pollock, W.H., Tuck, A.F., "On the evaluation of ozone depletion potentials", *J. Geophy. Res. Atm.*, pp. 825-842, (1992).
[7] Houghton, J.T., Meira Filho, L.G. Bruce, J., Lee, H., Callander, B. A., Haites, E., Harris, N., Maskell, K., "Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emissions Scenarios", *Cambridge Univ. Press*, Cambridge, pp. 339, (1994).
[8] Benhadid-Dib, S., Benzaoui, A., "Refrigerants and their environmental impact substitution of hydro chlorofluorocarbon HCFC and HFC hydro-fluorocarbon. Search for an adequate refrigerant", *Energy Procedia*, vol. 18, pp. 807-816, (2012). http://dx.doi.org/10.1016/j.egypro.2012.05.096
[9] Kim, K.H., Shon, Z.H., Nguyen, H.T., Jeon, E.C., "A review of major chlorofluorocarbons and their halocarbon alternatives in the air", *Atmospheric Environment*, vol. 45, pp. 1369-1382, (2011). http://dx.doi.org/10.1016/j.atmosenv.2010.12.029
[10] Kuijpers, L.J.M., De Wit, J.A., Janssen, M.J.P., "Possibilities for the replacement of CFC-12 in domestic equipment", *Int. J Refrig.*, vol. 11, pp. 284-291, (1988). http://dx.doi.org/10.1016/0140-7007(88)90088-6
[11] Suleiman, Y.M., Said, S.A.M., Ismail, B., "HCFC 22 as a Replacement for CFC 12", *Applied Energy*, vol. 49, pp. 1-8, (1994). http://dx.doi.org/10.1016/0306-2619(94)90053-1
[12] McCullocha, A. (1999) CFC and Halon replacements in the environment, *J Fluorine Chemistry*, 100, pp. 163-173, (1994).
[13] McCullocha, A., Midgley, P.M., Ashford, P., "Releases of refrigerant gases (CFC-12, HCFC-22 and HFC-134a) to the atmosphere", *Atmos. Envr.*, vol. 37, pp. 889–902, (2003). http://dx.doi.org/10.1016/S1352-2310(02)00975-5
[14] Devotta, S., Padalkar, A.S., Sane, N.K., "Performance assessment of HC-290 as a drop-in substitute to HCFC-22 in a window air conditioner", *Int. J Refrig.*, vol. 28, pp. 594-604, (2005). http://dx.doi.org/10.1016/j.ijrefrig.2004.09.013
[15] Chen, W., "A comparative study on the performance and environmental characteristics of R410A and R22 residential air conditioner", *App. Therm. Eng.*, vol. 28, pp. 1-7, (2008). http://dx.doi.org/10.1016/j.applthermaleng.2007.07.018
[16] Chaichanaa, C., Ayea, L., Charters, W.W.S., "Natural working fluids for solar-boosted heat pumps", *Int. J Refrig.*, vol. 26, pp. 637-643, (2003). http://dx.doi.org/10.1016/S0140-7007(03)00046-X
[17] Dopazo, J.A., Seara, J.F., "Experimental evaluation of a cascade refrigeration system prototype with CO_2 and NH_3 for freezing process applications", *Int. J Refrig.*, vol. 34, pp. 257-267, (2011). http://dx.doi.org/10.1016/j.ijrefrig.2010.07.010
[18] Kim, S.G., Kim, M.S., "Experiment and simulation on the performance of an autocascade refrigeration system using carbon dioxide as a refrigerant", *Int. J Refrig.*, vol. 25, pp. 1093-1101, (2002). http://dx.doi.org/10.1016/S0140-7007(01)00110-4
[19] Messineo, A., "R744-R717 Cascade Refrigeration System: Performance Evaluation compared with a HFC Two-Stage System", *Energy Procedia*, vol. 14, pp. 56-65, (2012). http://dx.doi.org/10.1016/j.egypro.2011.12.896
[20] Karagoz, S., Yilmaz, M., Comakli, O., Ozyurt, O., "R134a and various mixtures of R22/R134a as an alternative to R22 in vapor compression heat pumps", *Energy Conversion and Management*, vol. 45, pp. 181–196, (2004). http://dx.doi.org/10.1016/S0196-8904(03)00144-4
[21] Payne, W.V., Domanski, P.A., "A Comparison of an R22 and an R410A Air Conditioner Operating at High Ambient Temperatures", *Int. Refrig. Air Cond. Conference Proceedings*, vol. 2, pp. 1-8, (2002).
[22] Ashok Babu, T.P., Samaje, V.V., Rajeev, R., "Development of zero ODP, less TEWI, binary, ternary and quaternary mixtures to replace HCFC-22 in window air-conditioner", *Int. Refrig. Air Cond. Conference Proceedings*, vol. 854, pp. 1-8, (2006).
[23] Ashford, P., Clodic, D., McCulloch, A., Kuijpers, L., "Emission profiles from the foam and refrigeration sectors comparison with atmospheric concentrations. part 1: methodology and data", *Int. J Refrig., vol.* 27, pp. 687-700, (2004a). http://dx.doi.org/10.1016/j.ijrefrig.2004.07.025
[24] Ashford, P. , Clodic, D., McCulloch, A., Kuijpers, L., "Emission profiles from the foam and refrigeration sectors comparison with atmospheric concentrations. Part 2: results and discussion", *Int. J Refrig.*, vol. 27, pp. 701-716, (2004b). http://dx.doi.org/10.1016/j.ijrefrig.2004.08.003
[25]Wang, C., Chiang, S., Chang, Y., Chung, T., "Two-phase flow resistance of refrigerants R22, R410a and R407c in small diameter tubes", *Trans. IChemE*, vol. 79, pp. 553-560, (2001). http://dx.doi.org/10.1205/02638760152424325
[26] Greco, A., "Convective boiling of pure and mixed refrigerants: An experimental study of the major parameters affecting heat transfer", *Int. J Heat Mass Trans.*, vol. 51, pp. 896–909, (2008). http://dx.doi.org/10.1016/j.ijheatmasstransfer.2007.11.002
[27] REFPROP, Thermodynamic Properties of Refrigerants and Refrigerant Mixtures, Version 8.0, National Institute of Standards and Technology, Gaithersburg, MD, (2007).
[28] Kim, Y., Seo, K. , Chung, J.T., "Evaporation heat transfer characteristics of R-410A in 7 and 9.52 mm smooth/micro-fin tubes", *Int. J Refrig.*, vol. 25, pp. 716-730, (2002). http://dx.doi.org/10.1016/S0140-7007(01)00070-6
[29] Schultz, R.R., Cole, R., "Uncertainty analysis in boiling nucleation", *AIChE Symp. Series*, vol. 75(189), pp. 32-38, (1979).
[30] Wojtan, L., Ursenbacher, T., Thome, J.R., "Investigation of flow boiling in horizontal tubes: Part II –Development of a new heat transfer model for stratified-wavy, dryout and mist flow regimes", *Int. J Heat Mass Trans.*, vol. 48, pp. 2970-2985, (2005). http://dx.doi.org/10.1016/j.ijheatmasstransfer.2004.12.013
[31] Wang, C., Chiang, C., "Two phase heat transfer characteristics of R22/R407C in a 6.5-mm smooth tube", *Int. J Heat Fluid Flow*, vol. 18, pp. 550-558, (1997). http://dx.doi.org/10.1016/S0142-727X(97)00017-9



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