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Experimental investigation on flow boiling of R407C in plain horizontal copper tube

SheetalR.Thorat, Prof. M.D.Hambarde and OmkarP.Dale

Mechanical Engineering ,SavitribaiPhule Pune University, MIT Kothrud, India
Mechanical Engineering ,SavitribaiPhule Pune University, MIT Kothrud, India
Mechanical Engineering ,SavitribaiPhule Pune University, MIT Kothrud, India

Abstract

This paper aims at investigating the flow boiling heat transfer characteristics of zeotropic mixture R407C. Test section is plain horizontal copper tube with inner diameter13.386 mm and 2m long. The tests were carried out with same test section. Flow boiling characteristics of R407C was investigated by varying following parameters : i) Refrigerant mass flux within the range of 150 to210kgm^{-2}s^{-1} ii) the heat fluxes within 1.4 to 4.2 Kwm^{-2} iii) Pressure range in the evaporator 4.5 bar to 5.5 bar iv) The average quality of boiling refrigerant varied between 0.05 to 0.9.Present study shows the effect of all the parameters mentioned above on the heat transfer coefficient of refrigerant on flow boiling in copper tube.

Keywords:flow boiling, heat transfer coefficient, R407C,plain copper tube.

1.Introduction

Refrigerator and air conditioning systems are playing very important role in domestic and industrial area from last few decades. Because of their numerous application large amount of refrigerant have been used and exposed to the atmosphere inevitably. The use of HCFC and CFC as refrigerant is leading to new environmental issue due to the depletion of ozone layer because of chlorine content. Hence according to Montreal protocol, refrigerants containing chlorine such as CFC and HCFC's are needed to phase out by 2020.

Hence there is need to find out best substitutes for these refrigerants. The use of new refrigerants is restricted to detailed study of their heat transfer characteristics and thermodynamic properties. Heat transfer characteristics in condensation, boiling and related frictional pressure drop are very important in designing heat exchanger. The accurate knowledge of heat transfer coefficient and pressure drop and their behavior in plain horizontal tube is important to effectively design smaller size evaporator.Chlorine free compounds, such as hydro fluorocarbons (HFCs) and their mixtures, have been proposed as substitutes for HCFCs (S.Wellsandt and L.Vamling, 2005).Among all new refrigerants R407C can be accepted as substitute to R22. This is because of thermodynamic properties of R407C are very close to that of R22. R407C is a ternary zeotropic mixture of R32, R125, and R134a (23%, 25% and 52% by weight).It has no chlorine content (ODP = 0) and a modest direct global warming potential (GWP = 1650). It is non-flammable and non-toxic (C.Aprea,et al,2008) Zeotropic mixtures are characterized by temp glide i.e. difference between bubble and dew point temperature.R407C has temperature glide of 6^{0}C.At first from the blend of R407C more volatile mixture changes to vapor and then remaining phase i.e. liquid phase remains as richer in less volatile components due to temperature glide phenomenon during boiling (Julio Cesar Passos,et al,2003). It is used to match the pressure drop in heat exchangers, increasing their efficiency (Juan Garcia,et al,2016).The literature related to the present study is reviewed in the following:

(ArijitKundu, Ravi Kumar, Akhilesh Gupta,2014)shows that heat transfer coefficient of pure and mixed refrigerants always increases with mass velocity and heat transfer coefficients of R407C are always lower than pure refrigerant R134a.They also showed that tube inclination affects boiling heat transfer coefficient of R407C in significant manner and for same mass velocity, pressure drop increases with tube inclination.
(Julio Cesar Passos,et al,2003)used horizontal plain and microfin tubes with outside diameters (OD) of 7.0 and 12.7 mm and compared their performance showing that the heat transfer coefficient for the microfin tubes is higher (100%) than that for the plain tubes. The comparison between R407C and R417A is done by (C. Aprea, A. Greco , A. Rosato, 2008) tofind out best substitute for R22 and they found that The local pressure drops of R417A are always slightly lower than those of R407C by a factor ranging from7.8% to 48.1%, with a mean value of 25.8%.(S.Wellsandt and L.Vamling, 2005)used horizontal herringbone micro fin tube to compare the performance of R407C and R410A And compared the obtained data with existing three general flow boiling correlations.(P.Rollmann,K. Spindler,2016)developed a new correlation for the Nusselt number during flow boiling of R407C in a horizontal micro-fin tube.

Copper tube of type K used in this experimentation for test section is thick walledand used for domestic water, service and distribution, fire protection, solar, fuel and oil, HVAC, compressed air, oxygen, LPG gas, snow melting, steam and vacuum systems. Most of the work for flow boiling is done on horizontal plain tube diameter ranging up to 12 mm. hence going further this experimentation uses test section of 13.386mm inside diameter.

Therefore the purpose of present study is to provide the effect of imposed heat flux, mass flux and operating pressure of refrigerant on two phase flow heat transfer characteristics for evaporation of R407C in plain tube.

Nomenclature*Subscripts*

D Diameter, mm i inner
AArea, m^2 in inlet
FS Full ScaleTSTest Section
FSD Full scale deflectionH Heater
URL Upper Range Limitwiinside wall
T Temperature*wo*outside wall
Q Heat, kW s surface
x Vapor quality o outer
G Mass flux, kg $m^{-2}s^{-1}$sat saturation
q Heat flux kw^{-2} tptwo phase
E Enthalpy L heat loss, kW
E_{fg}Enthalpy of*woz*outside
Evaporation wall location
h Heat transfer coefficient,
kW m^{-2} s^{-1}

2. Flow boiling test facility and procedure

The schematic of test setup is as shown in figure 1.The experimental facility consists of simple vapor compression cycle with R407C as a working fluid. The main components of the system are a semi hermetic compressor, air cooled condenser, pre heater, test evaporator, after heater, de-super heater and manually operated expansion valve. The refrigerant flows from pre heater to test section through expansion valve and gets heated by hot water which is electrically heated by two heaters from both the sides of annulus containing water glycol mixture.Electrical heaters supply the hot water with the power transferred to the refrigerant. The refrigerant enters to the tube as sub cooled liquid or saturated vapor and then it's get vaporized against the hot water in the annulus. The compressor is connected to air cooled condenser. The flow of refrigerant can be indirectly controlled through manually operated by pass valve and it is measured by oval gear flow meter. Dryer is provided to entrap the foreign particles from refrigerant flow.Preheater is generally designed and installed to control the vapor quality at the inlet of test section.Desuper heater is installed to meet vapor conditions same as after heater. Heat input to the preheater and test evaporator can be changed by varying power supply with variable voltage AC heat source.Heat flow to the heater is determined by the current flow and voltage drop across the heater measured by standard clamp meter. Accumulator to upstream of compressor is installed to ensure the refrigerant vapor should enter the compressor and receiver to downstream of condenser is installed to oil free refrigerant to enter the test section. A Metal frame structure is provided to ensure the correct location of every component for proper functioning of system.

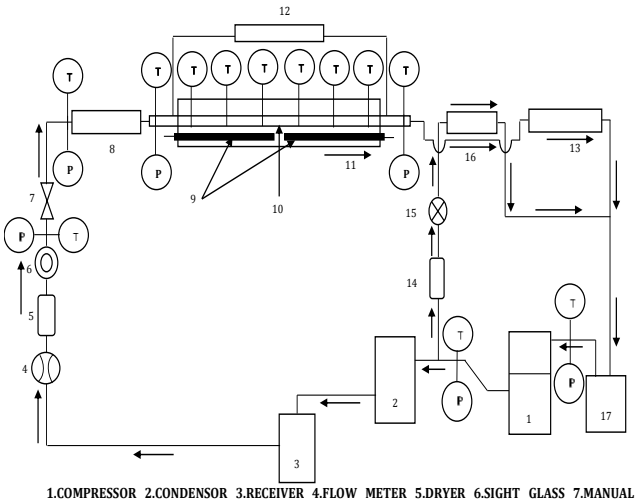

Fig.1 Schematic of test lay-out

The schematic of test section is presented in figure 2. The test section with inner diameter 13.386mm and outside diameter 15.875mm was considered for experimentation. The plain copper tube of test section was 2m in length.

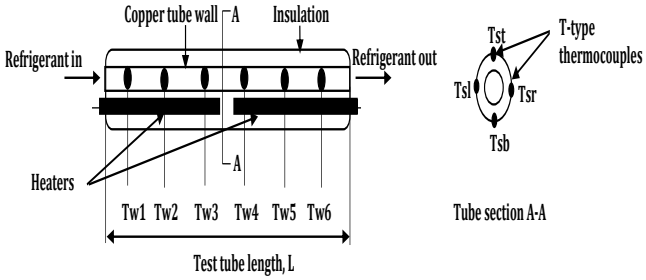

Fig.2 Schematic of test section

T-type copper-constantan thermo-couples placed at six axial positions to measure the surface temp of test section. For every location four thermocouples were placed at top, bottom, left andright side of tube. Averaging these temperatures gives the local wall temperatures. Saturation pressures at test section obtained by averaging inlet and outlet pressures at test evaporator. A differential pressure transducer across the inlet and outlet of test evaporator indicates the corresponding pressure drop. Two heaters wereinserted from both sides to heat the test evaporator. Insulation was provided outside to test evaporator to ensure adiabatic condition. Pressure transducer and thermocouple were fitted just before to pre heater to calculate enthalpy at entry to pre heater. Pressure and temperature measurement data was recorded by using data acquisition system connected to computer.

3. Data reduction

Mass flow rates are determined from measured mass flow rates and the real inner cross-section area based on the given tube dimensions:

$$G = \frac{\dot{m}}{A_s} \quad (1)$$

The local heat transfer coefficient is calculated by using newton's law of cooling as shown by following equation:

$$h = \frac{q}{(T_{wi} - T_{sat})} \quad (2)$$

Where,

$$q = \frac{Q_{TS}}{A_S} \quad (3)$$

$$Q_{TS} = Q_H - Q_L \quad (4)$$

Q_H, heat input from test evaporator heaters and it is a product of voltage and current across the heaters.
Q_L, heat loss from the test evaporator to the surrounding is estimated by heat leakage test of test evaporator.

$$T_{wi} = T_{wo} - \frac{Q_{TS}}{2\pi LK} ln \frac{D_o}{D_i} \quad (5)$$

Where,

$$T_{wo} = \frac{T_{woz1} + T_{woz2} + T_{woz3} + T_{woz4} + T_{woz5} + T_{woz6}}{6} \quad (6)$$

$$T_{woz} = \frac{T_{woz(Tst)} + T_{woz(Tsb)} + T_{woz(Tsl)} + T_{woz(Tsr)}}{4} \quad (7)$$

T_{wo} is the average outside tube wall temperature over the full length of test section.
T_{woz} is the average outside tube wall temperature at the given location 'Z' on the copper test section.
T_{sat} isthe saturation temperature taken as mean of dew and bubble temperature corresponding to pressure in the test section.
The vapor quality in test section is taken as the average of vapor quality at inlet and outlet of test section tube and expressed as:

$$X_{avg} = \frac{X_{in} + X_{out}}{2} \quad (8)$$

Where, X_{in} is the vapor quality at the inlet of test section and is calculated as:

$$X_{in} = \frac{E_{in} - E_{f,in}}{E_{fg,in}} \quad (9)$$

Similarly vapor quality at the outlet of the test section is calculated as:

$$X_{out} = \frac{E_{out} - E_{f,out}}{E_{fg,out}} \quad (10)$$

Enthalpies at inlet E_{in} and outlet E_{out} to test section are found from REFPROP 7.0 at temperature and pressure condition measured by thermocouples and pressure transducers at the inlet and outlet to test section.
The error in measurement depends on the operating conditionsand mostly on the accuracy of the wall temperature difference. The experimental uncertainty analysis was done by following Equation:

$$U_R = \left[\sum_{i=1}^{N} \left(\frac{\partial R}{\partial V_i} U_{V_i} \right)^2 \right]^{0.5} \quad (11)$$

Where, UR is the estimated uncertainty in calculating the value of desired variable R, due to the independent uncertainty U_{V_i} in the primary measurement of N number of variables Vi, affecting the result. The experimental uncertainties for the sensors are listed in Table 1.

Table 1 Accuracy of measuring instruments

Variable	Instrument	Accuracy	Range
Temperature	T-type thermocouple	±0.375 ^{0}C	-40^{0}C to 150^{0}C
Pressure	Piezo resistive	±0.25%FS	0 to 20bar (Abs)
Differential Pressure	Piezo resistive	±0.1%of URL	0 to 0.3 Bar
Mass Flow Rate	Oval gear-Positive displacement	±0.15% FSD	20 to 300 LPH
Voltage	Clamp meter	±1.2%	0 to 250V
Current	Clamp meter	±2.5% FS	0 to 200A

Table 2 Uncertainty of variables

Primary measurements		Derived quantities	
Parameter	Uncertainty	Parameter	Uncertainty
Diameter	±0.02 mm	Mass velocity	±0.6 - 2%
Pressure	±0.5%	Heat transfer coefficient	±3.9-11%
Temperature	±0.2 C	Vapor quality	±2.0 - 9.5%
Mass flow rate	±0.2%	Electrical power	±0.80%
Heat flux	±2.1-3.6%	-	-

4.Result and discussion

The present work aims at investigating the effect of imposed heat flux, mass flux and operating pressure of refrigerant on two phase flow heat transfer characteristics for evaporation of R407C in plain tube. This mainly focuses the effect of the above parameters on heat transfer coefficient and vapor quality.

A. *Effect of heat flux:*

From figure 3, heat transfer coefficient is presented as function of vapor quality for R407C to investigate the effect of vapor quality on heat transfer. The heat transfer coefficients of R407C is reported in two different operating heat fluxes. Both are achieved withalmost constant refrigerant mass flux of 160kgm^{-2}s^{-1}.Figure 3, shows that heat transfer coefficient increases with increase in heat flux. From figure, initially heat transfer coefficient increases in low quality region up to vapor quality at 0.4 showing nucleation boiling is dominating at the same region. Just after that, heat transfer coefficient start decreasing at high vapor quality region.This because of the low thermal conductivity of vapor in dry out region of test tube during convective boiling.

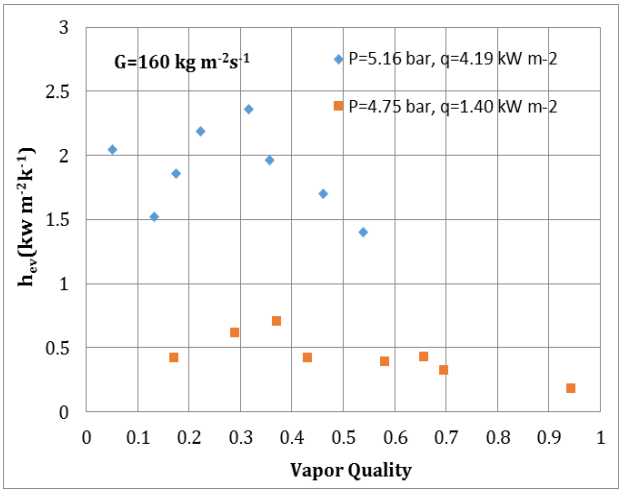

Figure 3.Heat transfer coefficient of R407C varying with different heat flux and pressure at G=160kg m^{-2}s^{-1}.

B. *Effect of mass flux:*

Figure 4. Shows effect of mass flux on flow boiling heat transfer with almost constant heat flux of 1.4 kW/m^2 and two different operating pressures at two different mass flux values. The experimental data clearly show that the heat transfer coefficients increase with increasing the refrigerant mass flux. Increase in mass flux accelerates fluid flow which results in increased mass velocity leading to overcome the mass transfer resistance due to mixture composition. Thus enhancing the convective boiling due to increase in mass flux.

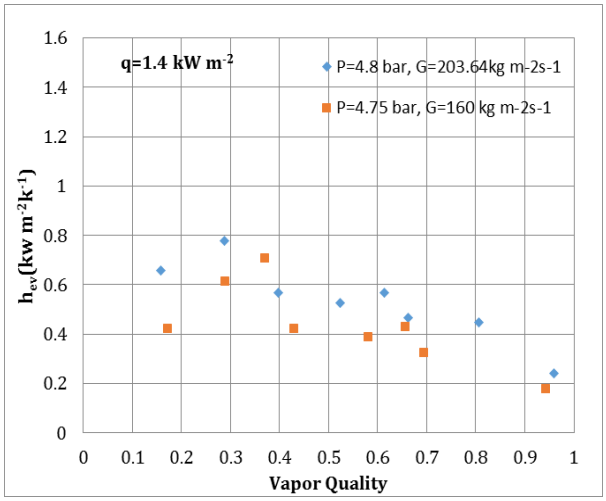

Figure 4. Heat transfer coefficient of R407C varying with different mass flux and pressure at 1.4 kW m^{-2}.

C. *Effect of operating pressure*

Figure5. Shows the effect of different operating pressures on flow boiling heat transfer with constant mass flux of 203.64kg m^{-2} s^{-1} and heat flux of1.4kWm $^{-2}$. From Figure 5 it is clear that heat transfer coefficient increases with increase in operating pressure value. This is due todominating nucleation boiling at low quality region. Convective boiling region shows decrease in heat transfer coefficient at high quality region because of the mass transfer resistance in the same region.

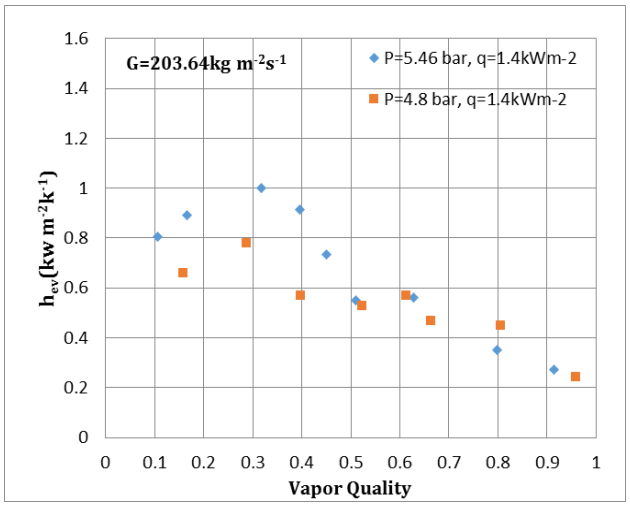

Figure5.Heat transfer coefficient of R407C varying with different pressure at G=203.64kg m^{-2}s^{-1}andq=1.4kWm^{-2}

5. Conclusion

In this work flow boiling characteristics of R407C are investigated by varying following parameters:
i) Refrigerant mass flux within the range of 150 to 210kgm^{-2}s^{-1} ii) the heat fluxes within 1.4 to 4.2 Kwm^{-2} iii)Pressure range in the evaporator 4.5 bar to 5.5 bar iv) The average quality of boiling refrigerant varied between 0.05 to 0.9.Present study shows the effect of all the parameters mentioned above on the heat

transfer coefficient of refrigerant on flow boiling in copper tube.

From the experimental results, following conclusions can be delineated:

1. Heat transfer coefficient increases with increasing heat flux at fixed mass flux. The increase in heat transfer coefficient can be observed upto vapor quality at 0.4 in low quality region. At high quality region, decrease in heat transfer coefficient can be seen due to low thermal conductivity of vapor at this region due to presence of dry spots.

2. Heat transfer coefficient increases with increase in mass flux in nucleate boiling region first and then start decreasing in convective boiling region. This decrease in heat transfer coefficient is related to mass velocity.This is because of increase in mass flux accelerates the two phase flow by increasing fluid velocity which leads to overcome the mass transfer resistance due to mixture composition.

   Thus enhancing the convective boiling due to increase in mass flux.

3. Increase in operating pressure, increases the heat transfer coefficient for fixed mass flux. Increase in operating pressure increases the relative importance of the nucleate boiling contribution to the heat transfer coefficient. Hence heat transfer coefficient increases in nucleate boiling region.

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