The Effects of the Tube Geometry and Mass flow Rate on the Fluid Parameters in a Compression Cooling System

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ABSTRACT

The air conditioning system works on the principle of vapour compression refrigeration cycle, and the effectiveness of the air conditioning system depends on the fluid parameter of the refrigerant. Several refrigerants ranging from Hydrofluorocarbon (HFC), Chlorofluorocarbon (CFCs), and some natural refrigerants have found application in the compression cooling system. However, HFC and CFCs refrigerants enhance the depletion of the ozone layer with a corresponding increase in global warming. Therefore, there is a need to study the fluid parameters of the refrigerants R410a currently in use for a typical compression cooling system and water as an alternative with respect to tube geometry and mass flow rate. The energy balance equations for mass flow rate, fluid properties and the heat transfer coefficient for R410a and water were used to examine the effect of varying tube diameter ranging from 0.01m to 0.03m, and mass flow rate on the fluid characteristics in a compression cooling system using water and R410a as working fluids. The Statistical Analysis Software (SAS) in Excel Package was used as the tool for numerical computation and graphical presentation to solve the characteristic governing energy balance equations, and the results were presented using the characteristic curves.

The results showed that the heat transfer coefficients and the fluid velocities for the two refrigerants decrease as the cross-sectional area of the tube increases. Reynolds number increase as the mass flow rate increases with R410a having a higher value. The effect of tube geometry shows that water has a higher heat transfer coefficient than R410a. This study revealed that water has a good potential of being a replacement for R410a as a refrigerant in a compression cooling system, thereby reducing the alarming effect of global warming.

Keyword: Fluid parameters, Refrigerants, Vapour compression system.

1. INTRODUCTION

Cooling is the process of comfortably making a confined environment free of heat, and this is usually achieved through refrigeration or air-conditioning. Many tropical places during the summer are relatively hot due to the excessive heat generated naturally by the sun. [1]. Refrigeration and air-conditioning is the subject that deals with the techniques to control the environments of the living and non-living items and thus provide them comforts to enable them to perform better and have longer lives [2].

Vapor-compression refrigeration is one of the many cooling cycles available for use, and it is the most widely used techniques for air-conditioning of large public buildings, offices, private residences, hotels, hospitals, theaters, restaurants, and automobiles, [3]. It is utilized in domestic and commercial refrigerators, large-scale warehouses for chilled or frozen storage of foods and meats, refrigerated trucks and railroad cars, and a host of other commercial and industrial services. Oil refineries, petrochemical, and chemical processing plants, and natural gas processing plants are among the many categories of industrial plants that often use large vapor-compression refrigeration systems, [1].
Among available refrigerants such as R-22, R140a has been extensively utilized for many years. It retains many desirable physical and thermodynamic characteristics which were used in a wide range of applications and temperatures with excellent system performance. It is harmless in terms of toxicity and flammability.

Nevertheless, in response to Montreal Protocol [4], R22, as the last remaining ozone depleting HCFC, will face the eventual phase-out in probably less than 5 to 10 years' time [4]. Many alternative refrigerants have been developed to replace R22 as well as many of those already phased out. The choice of alternative refrigerants is vast and it is not always easy to make the right decision, though many of the new refrigerants are expected to deliver the same or even better energy performance than those being phased out [4][5][6]. Many scenarios of refrigerant substitution can be embraced; these are “drop-in,” “retrofit,” and “new” systems. “Drop-in” - where the old refrigerant is taken out and the system charged with the alternative refrigerant and with some minor adjustments to the limit settings, “retrofit” - where the old refrigerant is exchanged with an alternative refrigerant often accompanied by oil and material changes due to compatibility issues, and “new system” - replacement of old systems with new ones designed for the alternative refrigerant [6].

Components can be developed for new systems to match individual refrigerants to accomplish the required system capacities at particular refrigerant temperatures [5]. Refrigerants with relatively weaker heat transfer characteristics will require a larger heat exchanger area [7] or better-designed heat exchangers [8][9] to achieve the same capacity. Also, refrigerants with a high volumetric refrigerating effect can use smaller compressors [10]. The capital cost per unit capacity and the COP will probably be one of the main interests of the comparison. In both the drop-in and retrofit scenarios, the same original performance and size may not be obtainable due to the use of the current heat exchangers and compressor, unless the two refrigerants have the same properties. For instance, when retrofitting an R22 system to R407C or R290, lower cooling capacities were obtained [11-13] due to their lower volumetric refrigerating effects.

Prapainop and Suen presented the effects of thermophysical properties and derived parameters of refrigerants on system performance [14]. It was noted that the evaluation of parameters influences system performance. Derisazadeh and Monte studied the fluid flow and heat transfer characteristics of nanofluids as advanced coolants for the cooling system of electric motors [15]. It was found that the increase in the Reynolds number yields a corresponding increase in heat transfer coefficient with the wall temperature decreases, which enhances cooling.

The vapor-compression uses a circulating liquid refrigerant as the medium which absorbs and removes heat from the space to be cooled and subsequently rejects that heat elsewhere. In a compression cooling system, different refrigerants are used as a working fluid in the system. It is now of interest to study the behaviour of some selected refrigerants through their characteristics under set conditions and to know which is better preferred to others with the reasons to justify this preference. The key refrigerant parameters are the fluid velocity, the heat transfer coefficient, fluid flow rate, and the Reynolds number. This work presents the study fluid parameters of the refrigerants R410a currently in use in a typical compression cooling system and water as an alternative, a non-ozone depleting and a non-global warming refrigerant with respect to mass flow rate, the cross-sectional area and diameter of the tube through which the refrigerants flow in a compression cooling system.

These refrigerant fluid parameters were studied numerically and analyzed to describe the effects of mass flow rate, cross-sectional area and diameter of the tube through which the refrigerants flow in the compression cooling system on fluid velocity, heat transfer coefficient, and Reynolds number.

2. METHODOLOGY

The governing equations for the fluid parameters of R410a and water as refrigerants suitable for application in a vapour compression cooling system were examined. SAS in Microsoft excel package was used to carry out a computational analysis of the combined values of the constants and the variables to solve the energy balance governing equations to analyze the effect of mass flow rate and geometry of the tube on the heat transfer coefficient, the velocity of flow and the Reynolds number of R410a and water as refrigerants suitable for the application in vapour compression cooling system. The governing equations for the fluid parameters were described in equations (1 – 6).
**Velocity of Refrigerant:** The speed of refrigerant flowing through the tube of condenser and evaporator is derived from the continuity equation (1) [16]

\[
u = \frac{m}{\rho A}
\]

Where, \(\nu\) is the fluid velocity in ms\(^{-1}\), \(m\) is the mass flow rate in kg/s, \(\rho\) is the fluid density in kg/m\(^3\) and \(A\) is the cross-sectional area of the tube in m\(^2\).

**Reynolds Number:** The Reynolds number for flow through the tube can be determined using equation (2) [16]

\[\text{Re} = \frac{\rho u D}{\mu}
\]

Where \(\text{Re}\) is the Reynolds number, \(D\) is the diameter of the tube, \(\mu\) is the coefficient of dynamic viscosity in Ns/m\(^2\), \(u\) is the fluid velocity in m/s.

**Heat Transfer Coefficient:** The heat transfer coefficient for secondary fluid (water) flowing through the tube of a heat exchanger is correlated by equation (3) [16]

\[H_{\text{water}} = \frac{0.023 K_{\text{water}} \text{Re}^{0.8} \text{Pr}^{0.4}}{D_{\text{e,water}}}
\]

Where: \(H_{\text{water}}\) is the heat transfer coefficient for water, \(K_{\text{water}}\) is the thermal conductivity for water which is obtained as 0.58 W/mK and \(K_{\text{R410a}}\) is the thermal conductivity for R410a, and its value is 0.08 W/mK. Re is the Reynolds number, Pr is the Prandtl number. It is a dimensionless number, the ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity [17].

\[\text{Pr} = \frac{\nu}{\alpha} = \frac{\text{Viscous diffusion rate}}{\text{thermal diffusion rate}} = \frac{C_p \mu}{k}
\]

Where: \(\nu\) : kinematic viscosity, \(\nu = \mu/\rho\) in m\(^2\)/s, \(\alpha\) : thermal diffusivity, \(\alpha = k/(\rho C_p)\) in m\(^2\)/s, \(\mu\) : dynamic viscosity in Pa s, \(k\) : thermal conductivity, in W/(m K), \(C_p\) : specific heat in J/(kg K). \(\rho\) : density in kg/m\(^3\). For water, is 1000 kg/m\(^3\) and for R410a is 1040 kg/m\(^3\). Pr for water is obtained as 7 at 20°C and 72.58 for R410a (engineering toolbox), \(D_e\) is the hydraulic diameter is obtained using equation (5) [18].

\[D_e = \frac{4A}{P}
\]

Where \(A\) is the cross-sectional area of the tube, and \(P\) is the wetted perimeter of the tube. For a circular tube, the hydraulic diameter is simply the diameter of the tube [17]. Therefore, for this work, \(D_e = D_h\), it is the diameter of the tube.

The heat transfer coefficient for the refrigerant, R410a flowing through the tube of a heat exchanger is correlated using equation (6) [16, 17]

\[H_{\text{R410a}} = \frac{0.023 K_{\text{R410a}} \text{Re}^{0.8} \text{Pr}^{0.4}}{D_{e,\text{R410a}}}
\]
3. RESULTS

A computational model is developed through the Microsoft Excel package to determine the velocity, Reynolds number and heat transfer coefficient of the water and R410a Refrigerants flow in the compression cooling system with different mass flow rate varied between 0.1kg/s to 0.5kg/s and different diameter of the tube varied between 0.01m to 0.03m. The results were presented using the characteristics curve.

Figure 1 presents the effect of the fluid mass flow rate on fluid velocity. It shows that the two refrigerants have their velocities reduced as the mass flow rate increases. However, water as a refrigerant has a higher velocity of flow than R410a refrigerant at the same flow rate. Hence water has a higher preference over R410a as the working fluid in a compression cooling system where the coolant is required to operate at a higher velocity.

Figure 2 displays the effect of Reynolds number (Re) on the heat transfer coefficient. It reveals that as Reynolds number increases, the heat transfer coefficient reduces for each of the refrigerants. Since the refrigerants flow is forced through the compressor, and the range of values of the Reynolds number showed that the fluid flow is turbulent (i.e., Re > 4000), then the more the Reynolds number, the lower the heat transfer coefficient of the Refrigerant.

Therefore, for an application where the flow required is turbulent in nature, water is preferred over R410a because it has a higher heat transfer coefficient and can absorb heat more even at a higher Reynolds number where the flow becomes turbulent. For a Laminar flow application, R410a should be selected over water.

Figure 3 presents the effect of mass flow rate m on Reynolds number Re, and Figure 4 shows that as the mass flow rate of the refrigerants increases, the Reynolds number also increases, and this shows a direct proportion in the mass flow rate and the Reynolds number. R410a will be a better choice over water when a cooling system requires refrigerant, which highly agrees with the proportionate relationship between mass flow rate and Reynolds number.
Figure 4 describes the effect of the cross-sectional area (A) on the heat transfer coefficient (h). It reveals that the heat transfer coefficient of the two refrigerants under consideration decreases as the cross-sectional of the tube through which they flow increases. The heat transfer coefficient for R410a falls faster than that of water when they flow through a tube of equal cross-sectional area. Therefore for a tube whose cross-sectional area falls between 0.0008m$^2$ and 0.0031m$^2$ water can be used as the working fluid in such an application because even in a tube of lower cross-sectional area, it has a higher heat transfer coefficient. But where a tube of more upper cross-sectional area is required, R410a is preferred over water as it can be seen from Fig 4.

Figure 5 explains the effect of the cross-sectional area of the tube on the velocity of flow. It shows that the velocity of the flow of the fluid is higher when the cross-sectional area of the tube through which the refrigerant flows is small. Water and R410a have a similar response to the variation in the size of the cross-sectional area of the tube through which the refrigerants flow. The cross-sectional area of the tube may not be of high importance when it comes to choosing between water and R410a as a refrigerant in a compression cooling system, though water has a higher value, there is little difference between it and R410a.

Figure 6 presents the effect of the cross-sectional area (A) of the tube on Reynolds numbers of the Refrigerants. It reveals that as the cross-sectional area of the tube increases, the Refrigerants Reynolds number also increases and R410a has a very high rise above the water. Water should be used to avoid high turbulence in a compression cooling system using a tube of the more top cross-sectional area because it has a steady increase and its value is lower than that of R410a.
Figure 7 describes the effect of the diameter of the tube on the velocity of the Refrigerants. It shows that an increase in the width of the tube through which the refrigerant's flow causes a corresponding decrease in the speed of the refrigerants with R410a decreasing at a faster rate than water. For an application in which a tube of smaller diameter is required for the transmission of refrigerants in a compression system at a high velocity, water should be chosen ahead of R410a.

Figure 8 explains the effect of the diameter of the tube on the heat transfer coefficient (h) of the Refrigerants. It shows that as the diameter of the tube increases, the heat transfer coefficient of the refrigerant falls accordingly. Water is seen to have a higher heat transfer coefficient, even with the tube of larger diameter. Therefore, cooling is better achieved in a compression cooling system when a tube of smaller diameter is used because of the proportionate relationship between the heat transfer coefficient and the width of the tube.

Figure 9 presents the effect of the diameter of the tube on the Reynolds number (Re) of the refrigerants. It reveals that an increase in the diameter of the tube yields an increase in the Reynolds number of the refrigerant. To avoid using a refrigerant that will be approaching turbulence at a faster rate for a large diameter tube, water should be chosen in place of R410a. The two refrigerants tend to have a higher Reynolds number, thereby making the flow in the compression cooling process turbulent, and there is variation in the rate at which both refrigerants approach turbulence as water has a lower rate and R410a has a higher rate.
Figure 10 describes the effect of the mass flow rate on the heat transfer coefficient. It shows that the heat transfer coefficients of the two refrigerants decrease as the mass flow rate increases. Water, having a higher value over R410a, shows that it can still maintain to a certain extent its heat transfer coefficient as its mass flow rate increases. For an application where a refrigerant that can steadily retain its heat transfer coefficient at a little rise in the mass flow rate is required, water is recommended over R410a.

4. CONCLUSION

The air conditioning system works on the principle of vapour compression refrigeration cycle. The effectiveness of the air conditioning system depends on the fluid parameter of the refrigerant. But currently used refrigerants (HCFCs) such as R410a, R12, R123 has a large amount of Global Warming Potential (GWP) and Ozone Depletion Potential (ODP). According to the Montreal Protocol and Kyoto protocol, these refrigerants are promised to be banned after 2020. One of the ways to reduce GWP and ODP is the use of alternative eco-friendly refrigerant. In this study, analysis of fluid parameters of two refrigerants, R140, and water in vapour compression refrigeration system were conducted. The effects of mass flow rate and tube geometry through which the refrigerants flow in the compression cooling system on fluid velocity, heat transfer coefficient and Reynolds number were analyzed using the governing equations.

The following conclusions were drawn from analyzing the two refrigerants of R410a and water, that the fluid velocity decreases as the geometry of the tube through which the refrigerants flow increases. The coefficients of heat transfer for the two refrigerants decrease as the geometry of the tube increases. However, water has a higher heat transfer coefficient than R410a flowing through a tube of the same geometry. Reynolds number increases as the mass flow rate and geometry of the tube increases for both water and R410 but to avoid higher turbulence, water should be chosen over R410a as it has a lower Reynolds number than R410a with the same tube geometry.

The influence of the tube geometry on the fluid parameters is favouring water ahead of R410a as a working fluid in a compression cooling system, and it is deduced that water has a higher preference over R410a. Furthermore, water is readily available, causes no harm to the environment, does not deplete the ozone layer, and does not cause global warming. And for its high corrosive tendency, corrosion preventive materials like a tin can be used in coating the inner walls of the tube to prevent corrosion when water is used as a refrigerant in a compression cooling system.

NOMENCLATURE

GWP  global warming potential
\( h \)  enthalpy (kJ \text{ kg}^{-1} )
\( h_{fg} \)  latent heat (kJ \text{ kg}^{-1} )
\( k \)  thermal conductivity (W m\text{ m}^{-1} K^{-1} )
\( \dot{m} \)  mass flow rate (kgs\text{ }^{-1} )
\( P \)  pressure (kPa)
\( Q \)  total capacity (kW)
\( A \)  Cross sectional area of the tube
\( Pr \)  Prandtl’s Number
\( W \)  power (W)
\( x \)  vapor quality
\( \mu \)  dynamic viscosity (μPa s)
\( p \)  density (kg m\text{ m}^{-3} )
\( \eta \)  efficiency
\( Re \)  Renolds Number
\( D_h \)  Hydraulic diameter
\( \dot{h}_{\text{water}} \)  heat transfer coefficient of water (kW/m-k)
\( \dot{h}_{water} \)  heat transfer coefficient of water (kW/m-k)
\( U \)  fluid velocity (m/s)
\( v \)  Kinematic viscosity (m\text{ m}^{-2} )
\( \alpha \)  Thermal diffusivity (m\text{ m}^{-2} )
\( C_p \)  Specific heat (J/kg K)
REFERENCES


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