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Performance Analysis of R410A in lieu of Ammonia in Milk Chilling Plant Employed with Plate Heat Exchangers

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ABSTRACT

Ammonia is used as the refrigerant for preserving milk in milk chilling plant. Since ammonia is toxic, usage of an alternate refrigerant is sought. Plate heat exchangers with 45 degree chevron angle are employed for transfer of heat between various media that circulate in the milk chilling plant. In this work the choice of the alternate refrigerant is only considered keeping the other existing system unchanged. Among the various choices of refrigerants, R410A is chosen and employed in lieu of ammonia. To ascertain the suitability of R410A, both theoretical CFD analysis and experimental analysis have been carried out. The analyses have been carried out for both the refrigerants, NH_3 and R410A with the same setup. Various parameters like LMTD, heat transfer coefficient, refrigerant effect, mass flux, pressure drop, effectiveness and temperatures at various locations have been recorded and the results have been compared. Comparative graphs have been drawn for CFD analysis and experimental analysis. It has been found that from all graphs, R410A proves to be a better alternative to the existing ammonia refrigerant.

Keywords: Refrigerant, Ammonia, R410A, mass flux, heat transfer coefficient, refrigerant effect, plate heat exchangers

1. INTRODUCTION

Milk chilling systems are employed worldwide to preserve milk as safe food for longer period. At present, ammonia (NH_3) is widely used as the refrigerant in milk chilling in dairy industries. Plate heat exchangers are used to transfer heat in between various media such as milk, ammonia and water. Water is used as an intermediary agent. Though ammonia is widely regarded as an environment-friendly natural refrigerant, it is toxic and inflammable. Hence it is dangerous to use ammonia in refrigeration systems that are employed in food processing industries. It might be highly unlikely for ammonia to get into milk circuit but, if it happens it will prove to be a disastrous event. Therefore, use of a safe and eco-friendly refrigerant is a compelling and mandatory requirement and hence this study is undertaken.

In order to find a suitable alternative for ammonia as refrigerant, the present ammonia refrigerant system is investigated both analytically and experimentally to know the parameters which influence the performance of milk chilling system. Analytical investigation is carried out using CFD. R410A, a food grade and eco-friendly refrigerant, is chosen as an alternative refrigerant and this work has been carried out. Both the CFD and experimental results are compared to arrive at a conclusion whether R410A will be a suitable replacement for the ammonia refrigerant.

1.1 Objectives:

The objectives of this work are given below.

1) Study the milk chilling system employed with plate heat exchangers with ammonia as refrigerant and develop CFD model to represent the present system.
2) Analyze using CFD model of the system with ammonia and R410A as refrigerants.
3) Arrive at the decision to replace ammonia with R410A by comparing the results obtained by performing experiments for validating the results obtained using CFD analysis with ammonia and R410A as refrigerants.

2. METHODOLOGY

An extensive literature survey has been done to find the features and performance of the milk chilling systems using ammonia as the refrigerant. The properties of ammonia, that prevent using ammonia as the refrigerant in food processing systems, have been identified. A theoretical analysis has been conducted to understand and estimate the characteristics of the milk chilling system using ammonia as refrigerant. CFD has been employed to find the performance of the systems in the theoretical analysis. The experimental values of the existing system have been obtained from an experimental setup. As an alternative refrigerant for ammonia, R410A has been identified and similar analyses have been done to find the characteristics of the modified system. In the experimental setup, ammonia has been replaced by R410A and an experimental analysis has been carried out and the findings are recorded. The performance of both the refrigerants in various analyses are then brought out and compared to arrive at the decision to replace ammonia with R410A.

3. LITERATURE SURVEY

Francisco *et al* (2010) found that for the selected operating conditions, the boiling heat transfer coefficient is highly dependent on the mass flux, whereas the influence of heat flux and pressure are negligible mainly at higher vapour qualities. Francisco *et al* (2011) compared the experimental data of a flow boiling of ammonia/water in a plate heat exchanger with the predicted values. Kayansayan (1994) brought out the effects on the performance of plate fin-tube cross flow heat exchangers due to outer surface geometry using R410A. Lottina *et al* (2003) highlighted the consequences of the oil rejected by the compressor of a vapour-compression refrigeration system on the operation of the evaporator and condenser with a modeled prototype using the mixture of HFC, R410A and synthetic polyolester (POE) oil. Kuo *et al* (2005) investigated experimentally, heat transfer and associated frictional pressure drop in the condensing flow of the ozone friendly refrigerant R-410A in a vertical plate heat exchanger (PHE). Longo *et al* (2007) presented the experimental heat transfer coefficients and pressure drop measured during HFC refrigerant 134a, 410A and 236a vaporisation inside a small brazed plate heat exchanger. The experimental results are reported in terms of refrigerant side heat transfer coefficients and frictional pressure drop. The heat transfer coefficients show great sensitivity to heat flux and outlet conditions and weak sensitivity to saturation temperature. Giovanni *et al* (2007) investigated HFC-410A vaporisation inside a commercial brazed plate heat exchanger. Simone *et al* (2012) investigated the condensation heat transfer of two refrigerants mixtures, R407C and R410A, in a brazed plate heat exchanger (BPHE) reporting the experimental measurements of the heat transfer coefficient.

Dong *et al* (2003) investigated the evaporative heat transfer and pressure drop in the brazed plate heat exchangers. They used plate heat exchangers with different 45^o, 35^o, and 20^o chevron angles. They measured varying the mass flux of refrigerant (13–34 kg/m^2 s), the evaporating temperature (5, 10 and 15^oC), the vapor quality (0.9–0.15) and heat flux (2.5, 5.5 and 8.5 kW/m^2), the evaporation heat transfer coefficients and pressure drops. The heat transfer coefficient increases with increasing vapor quality and decreasing evaporating temperature at a given mass flux in all plate heat exchangers. The pressure drop increases with increasing mass flux and quality and with decreasing evaporating temperature and chevron angle. It was found that the heat transfer coefficients of R410A were larger than those of R22 and the pressure drops of R410A were less than those of R22.

Zhe *et al* (2003) used a computational fluid dynamics (CFD) program FLUENT to predict the fluid flow distribution in plate-fin heat exchangers. It was found that the flow maldistribution was very serious in the y direction of header for the conventional header used in industry. Jian *et al* (2006) characterized the turbulent flow structure inside the entrance of plate-fin heat exchanger was by CFD simulation and PIV experiment under the similar conditions. The numerical and experimental results indicate that the performance of fluid maldistribution in conventional entrance is deteriorated, while the improved configuration with punched baffle can effectively improve the performance in both radial and axial direction. It is found that the baffle on which the small holes are distributed in staggered arrangement is the first choice for the improvement.

4. THEORETICAL ANALYSIS

The purpose of heat exchanger design is to relate the inlet and outlet temperatures, the overall heat transfer coefficient and the geometry of the heat exchanger to the rate of heat transfer between the two fluids. The two common problems in heat exchanger design are rating and sizing of the heat exchangers. This work is limited to the design of recuperators only. That is, the design of a two fluid heat exchanger used for the purpose of recovering waste heat.

The basic principles of heat transfer for a heat exchanger are discussed in this chapter. The enthalpy balance equation on either fluid stream can be written as

$$Q_c = m_c (h_{c2} - h_{c1}) \tag{1}$$

and

$$Q_h = m_h (h_{h1} - h_{h2}) \tag{2}$$

For constant specific heats with no change of phase, it may also be written as

$$Q_c = (mc_p)_c (T_{c2} - T_{c1}) \tag{3}$$

and

$$Q_h = (mc_p)_h (T_{h1} - T_{h2}) \tag{4}$$

Now from energy conservation, it is known that $Q_c = Q_h = Q$, and it may related to the heat transfer rate Q and the overall heat transfer coefficient U, to the mean temperature difference ΔT_m by means of

$$Q = UA\Delta T_m \tag{5}$$

where,

A is the total surface area for heat exchange
U is Overall heat transfer coefficient

$$\Delta Tm = f(T_{h1}, T_{h2}, T_{c1}, T_{c2}) \tag{6}$$

4.1 LMTD Method

The logarithmic mean temperature difference (LMTD) is used to determine the temperature driving force for heat transfer in flow systems, mostly in heat exchangers. The LMTD is a logarithmic average of the temperature difference between the hot and cold streams at each end of the exchanger.

$$\Delta T_{LMTD} = (\Delta T_2 - \Delta T_1) / \ln (\Delta T_2 / \Delta T_1) \tag{7}$$

where ΔT_1 andΔT_2 represent the temperature difference at each end of the heat exchanger.

4.2 NTU Method

The effectiveness or number of transfer units (NTU) method was developed to simplify a number of heat exchanger design problems. The heat exchanger effectiveness is defined as the ratio of the actual heat transfer rate to the maximum possible heat transfer rate if there were infinite surface area. The heat exchanger effectiveness depends upon whether the hot fluid or cold fluid is a minimum fluid. That is the fluid which has the smaller capacity coefficient

$$C_h = m_h C_{ph} \text{ and } C_c = m_c C_{pc} \qquad (8)$$

If the cold fluid is the minimum fluid then the effectiveness is defined as:

$$€ = C_{max}(T_{H,in} - T_{H,out}) / C_{min}(T_{H,in} - T_{C,in}) \qquad (9)$$

otherwise, if the hot fluid is the minimum fluid, then the effectiveness is defined as:

$$€ = C_{max}(T_{C,out} - T_{C,in}) / C_{min}(T_{H,in} - T_{C,in}) \qquad (10)$$

The heat transfer rate may now be defined as:

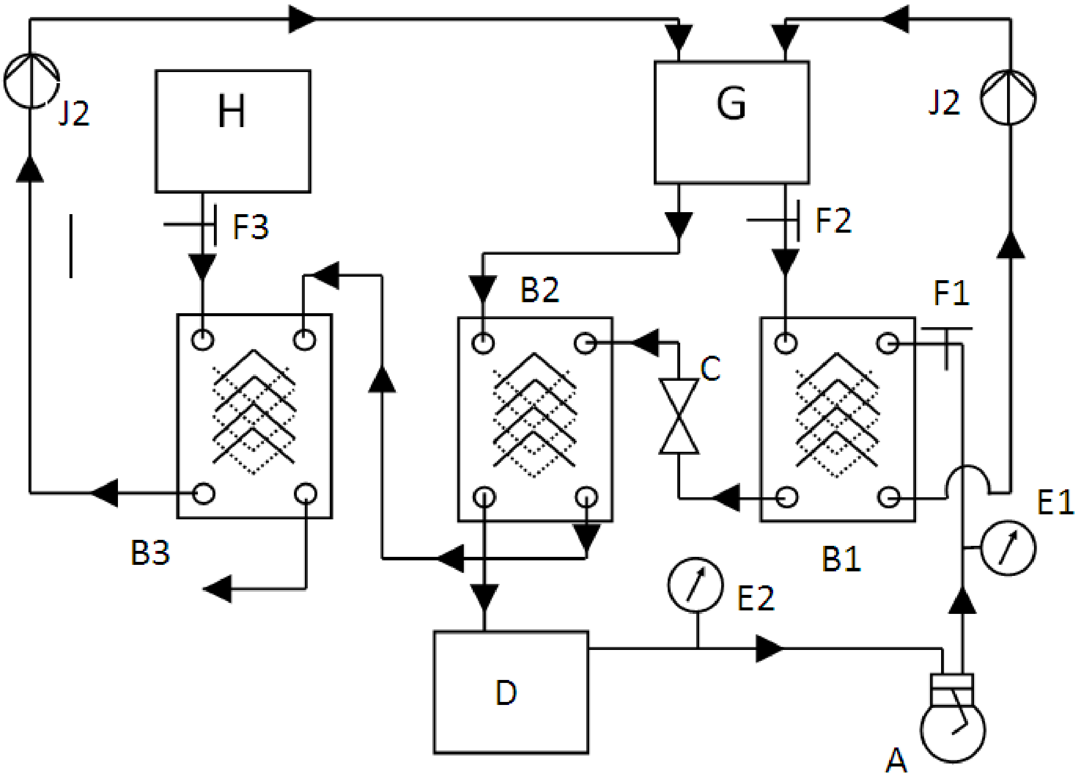
$$Q = € \, Cmin(T_{H,in} - T_{C,in}) \qquad (11)$$

It is now possible to develop expressions, which relate the heat exchanger effectiveness to another parameter referred to as the number of transfer units (NTU). The value of NTU is defined as:

$$NTU = UA / C_{min} \qquad (12)$$

5. EXPERIMENTAL ANALYSIS

The schematic of the experimental setup is shown in figure 1. The reciprocating compressor (A) is used to compress the high temperature and low pressure gaseous ammonia which is received from the evaporator (plate heat exchanger B2) via heater (D). The compressed high pressure and high temperature ammonia enters in the plate heat exchanger (B1) which acts as a condenser. This plate heat exchanger cools the ammonia by using water as a coolant. The cooled low temperature high pressure ammonia enters the expansion valve where it is throttled. The expanded ammonia is now in low pressure and lower temperature. This ammonia vapour enters in the plate heat exchanger (B2) which serves as the evaporator where ammonia vapour cools the water, which is at atmospheric temperature and pressure. This water flows from the storage tank which is mounted at an elevated position. After getting cooled, it goes to the plate heat exchanger (B3) where it cools the milk.



Symbol	Item Description
A	Compressor
B1, B2 and B3	Plate Heat Exchange (PHE)
C	Expansion Valve
D	Heater
E1 and E2	Pressure Gauge
F1, F2 and F3	Regulator
G	Water Tank
H	Milk Tank
J1 and J2	Pump

Figure 1. Schematic diagram of the experimental setup

Milk is stored in a tank at an elevated level and flows by gravity. It flows through the plate heat exchanger (B3) where it is cooled by low temperature water and leaves for further processing. The cooling water, after gaining heat from milk, leaves the plate heat exchanger (B3) goes to the water storage tank by means of a pump.

A series of experiments and simulation studies have been carried out on the milk chilling system in order to improve its performance using R410A as the refrigerant. Simulation studies have also been performed to study the influence of heat exchanger parameters on the system performance.

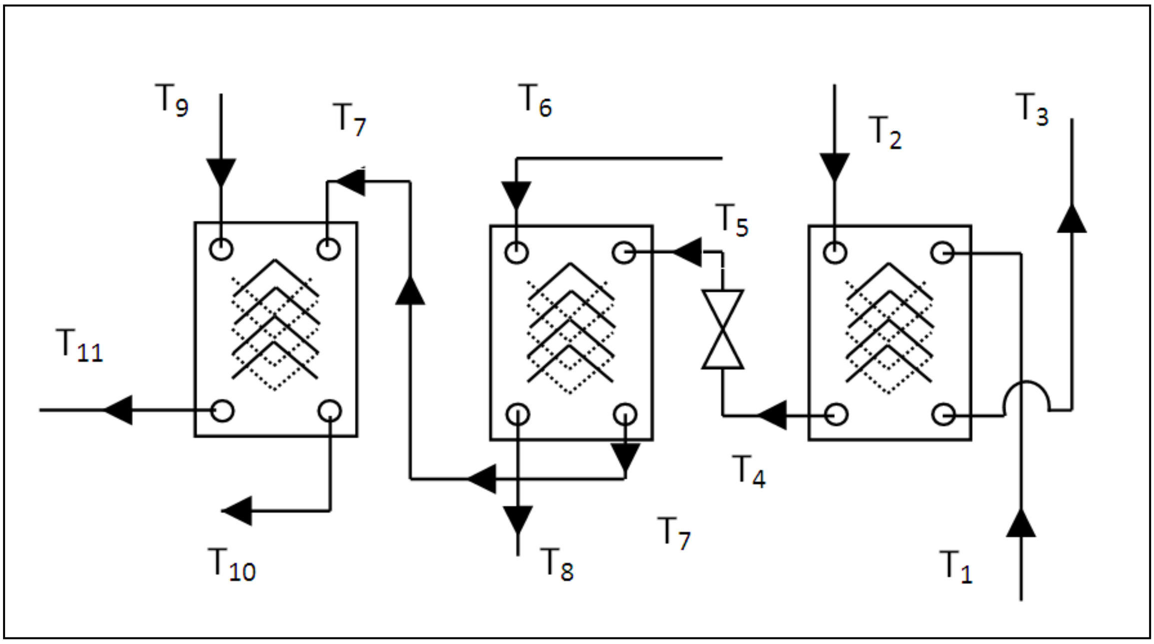


Figure 2. Temperature variables of Plate Heat Exchanger

Experiments have been conducted with NH_3 as refrigerant and various parameters are recorded. Table 1 shows the inlet and outlet temperature of working fluids. Table 2 and Table 3 show the observation data for NH3 and R410A respectively. The various locations at which the temperatures and pressures are measured are shown in figure 2.

Table 1. Inlet and Outlet temperature of working fluids

Plate Heat Exchanger	Working Fluids	Inlet Temperature (^oC)	Outlet Temperature (^oC)
Plate Heat Exchanger (B1)	Ammonia	90	20
	Water	32	36
Plate Heat Exchanger (B2)	Water	32	0.3
	Ammonia	-2	20
Plate Heat Exchanger (B3)	Milk	36	2
	Water	0.3	20

Table 2. Observation data for NH_3

Sl. No	T_1 (˚C)	T_2 (˚C)	T_3 (˚C)	T_4 (˚C)	P_1 (bar)	P_2 (bar)	P_3 (bar)	P_4 (bar)
1	-2	20	32	0.3	21.5	21.3	15	14.6
2	-2	21	32	0.4	21.5	21	15	14.2
3	-2	21.5	32	0.5	21.5	20.8	15	14
4	-2	22.4	32	0.6	21.5	20.6	15	13.7

Table 3. Observation data for R410A

Sl. No	T1 (˚C)	T2 (˚C)	T3 (˚C)	T4 (˚C)	P1 (bar)	P2 (bar)	P3 (bar)	P4 (bar)
1	-4	20	32	0.3	21.5	21.3	15	14.6
2	-4	20.2	32	0.4	21.5	21	15	14.2
3	-4	21.1	32	0.5	21.5	20.8	15	14
4	-4	22.2	32	0.6	21.5	20.6	15	13.7

where
T_1 - Inlet Temperature of Refrigerant
T_2 - Out let Temperature of Refrigerant
T_3 - Inlet Temperature of Water
T_4 - Out let Temperature of Water
P_1 - Inlet pressure of Refrigerant
P_2 - Out let pressure of Refrigerant
P_3 - Inlet pressure of Water
P_4 - Out let pressure of Water

5.1 COMPARISON OF CFD ANALYSES WITH EXPERIMENTAL STUDIES

Comparing the two refrigerants in this study, the results obtained using R410A and NH_3, are recorded and various graphs are drawn from which the following observations are made.

From the figure 3, it can be observed that for refrigerant R410A average heat transfer coefficient is high with respect to mass flux. The same is observed from the CFD analysis, the results of which are shown in figure 4.

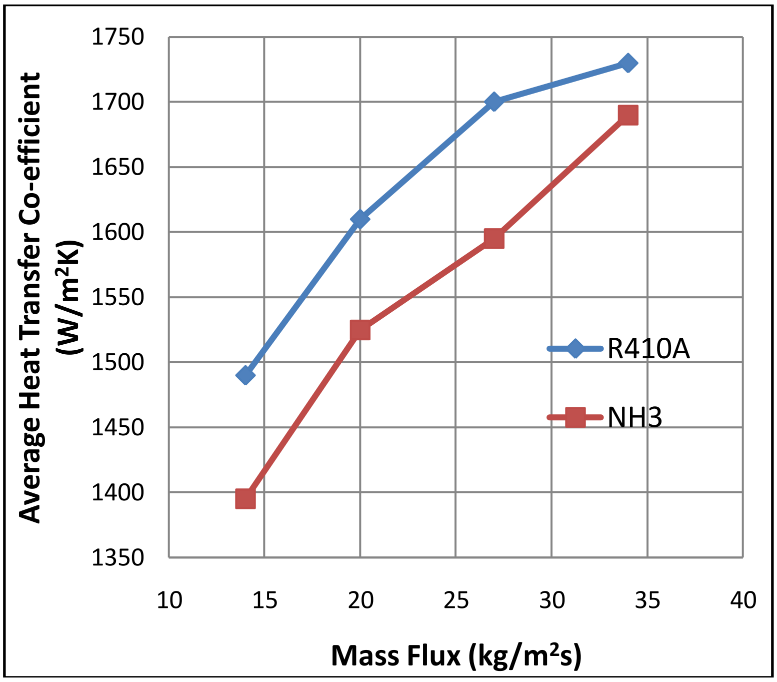


Figure 3. Average Heat Transfer Coefficient Vs. Mass Flux of NH_3 and R410A – Experimental values

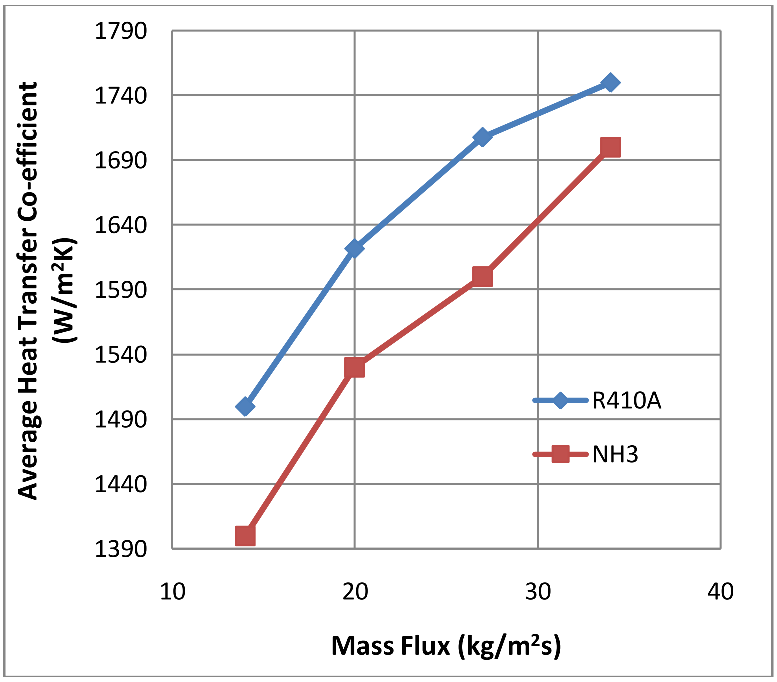


Figure 4. Average Heat Transfer Coefficient Vs. Mass Flux of NH_3 and R410A - CFD analysis

The heat transfer coefficient for R410A is considerably high for lesser refrigerating effect compared to NH_3. However, it is still high for higher refrigerating effects. This is shown in the figure 5 experimentally and figure 6 using CFD analysis.

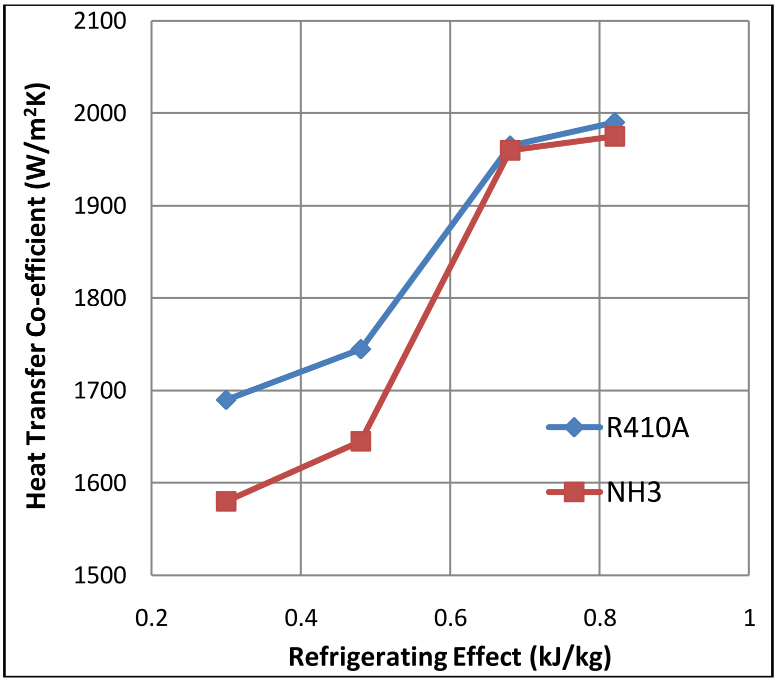


Figure 5. Heat Transfer Coefficient Vs. Refrigerating Effect of NH_3 and R410A – Experimental values

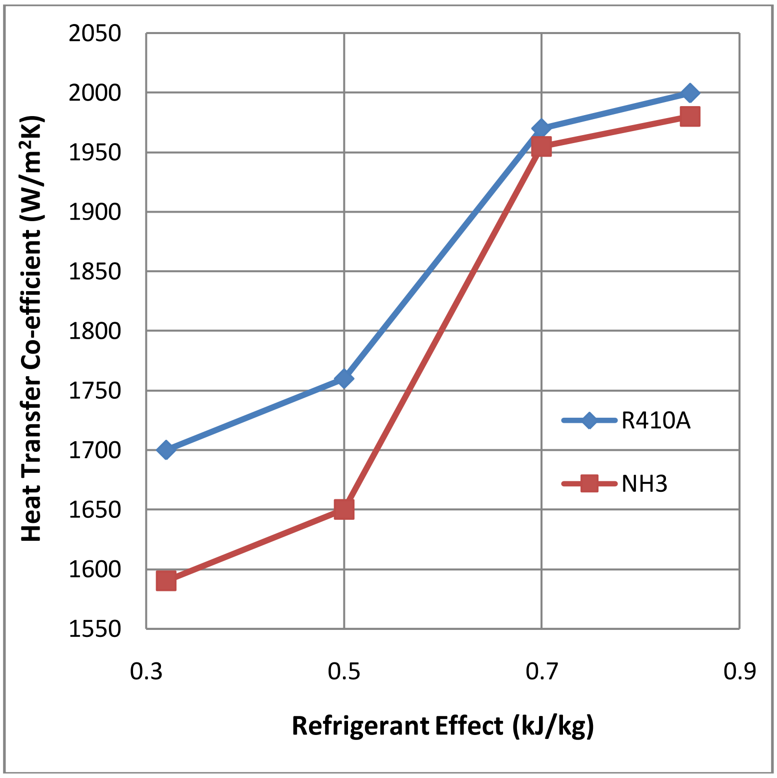


Figure 6. Heat Transfer Coefficient Vs. Refrigerating Effect of NH_3 and R410A – CFD values

A graph is drawn using the values of mass flux and average pressure drop. From the figure 7 and figure 8, it can be observed that for refrigerant R410A average pressure drop is low with respect to mass flux. This reduces the load on the compressor.

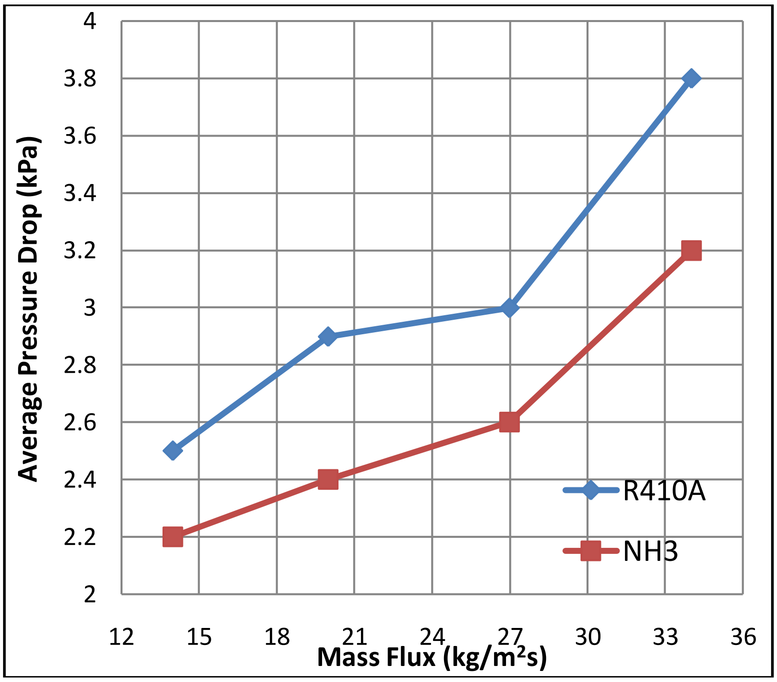


Figure 7. Average Pressure Drop Vs. Mass Flux of NH_3 and R410A – Experimental values

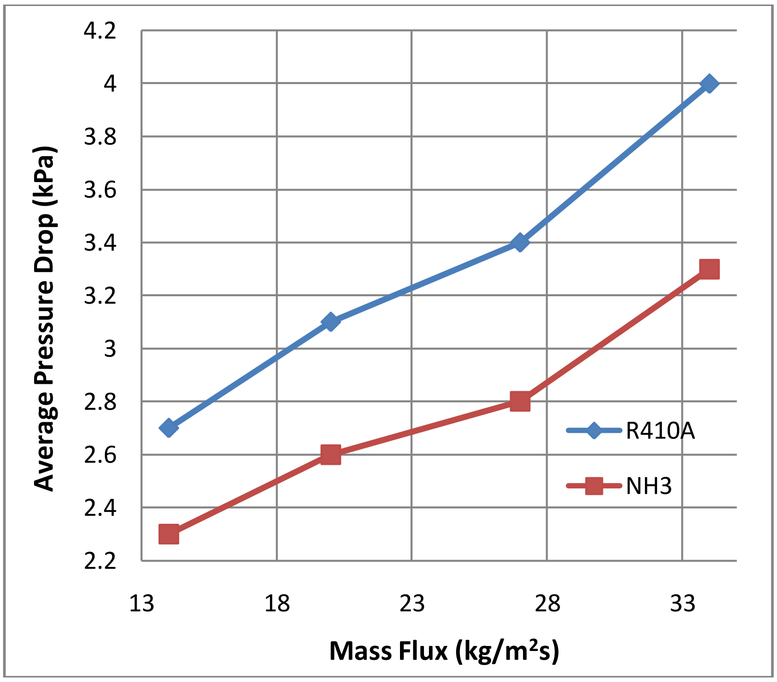


Figure 8. Average Pressure Drop Vs. Mass Flux of NH_3 and R410A – CFD values

A graph is drawn using the values of mass flux and heat transfer rate. From the figure 9 and figure 10, it can be observed that for refrigerant R410A heat transfer rate is high with respect to mass flux. This expedites the cooling process and the process is carried in relatively shorter duration.

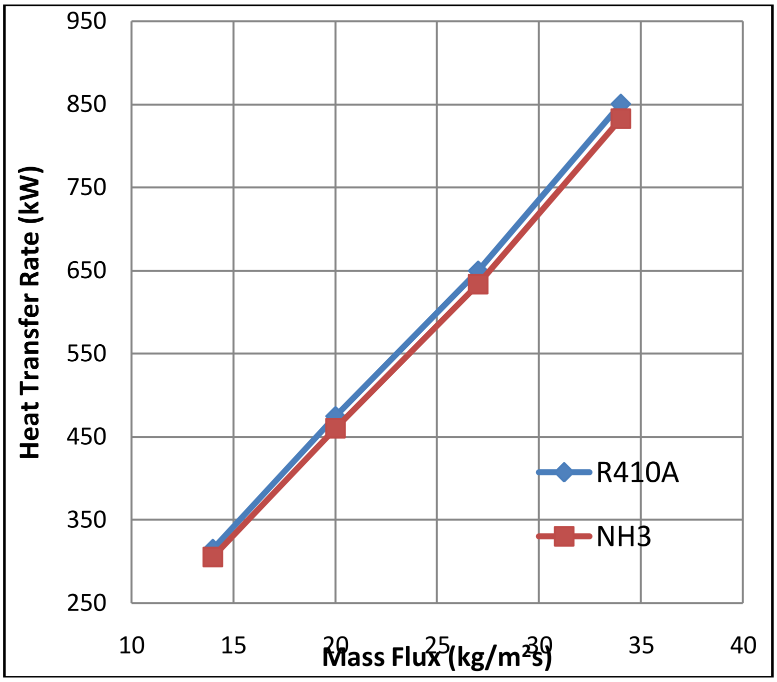


Figure 9. Heat Transfer Rate Vs. Mass Flux of NH_3 and R410A – Experimental values

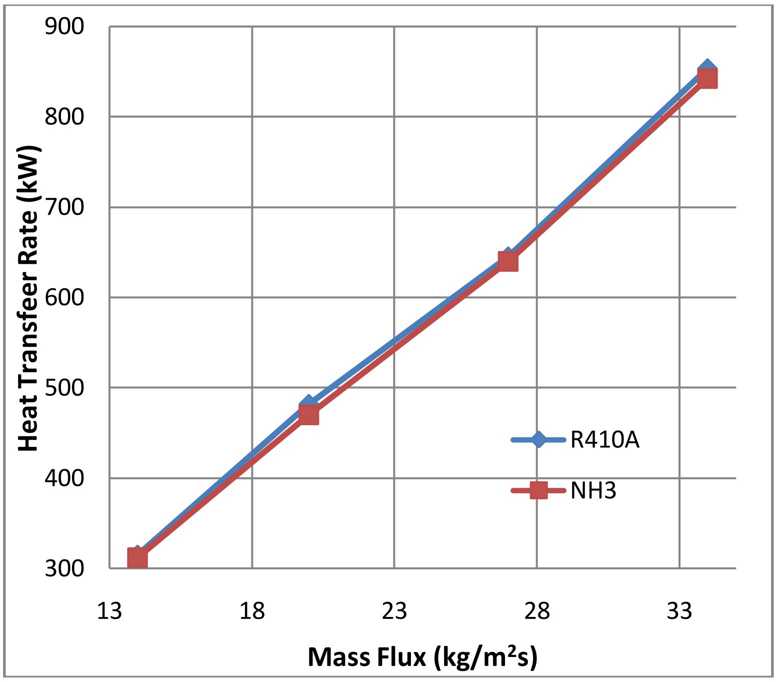


Figure 10. Heat Transfer Rate Vs. Mass Flux of NH_3 and R410A – CFD values

LMTD obtained for R410A is also relatively higher. The rate of increase of effectiveness with respect to mass flux for R410A compared to that of NH_3 is high. This is shown in the figure 11 and figure 12.

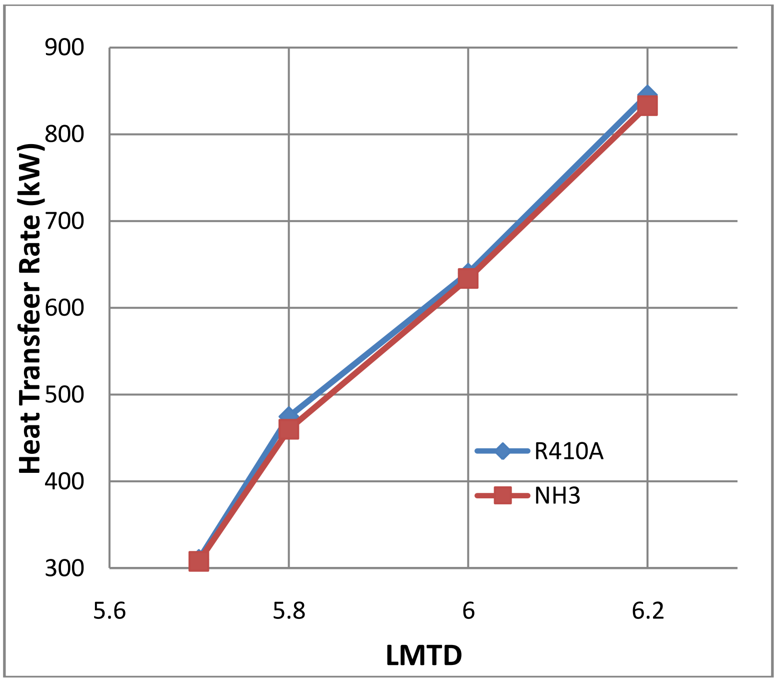


Figure 11 Heat Transfer Rate Vs. LMTD of NH_3 and R410A – Experimental values

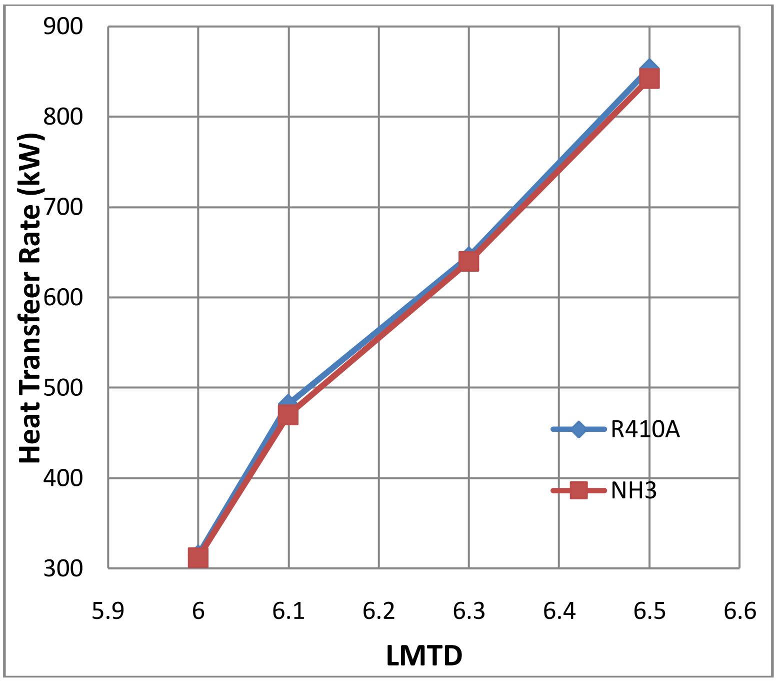


Figure 12 Heat Transfer Rate Vs. LMTD of NH_3 and R410A – CFD values

A graph is drawn using the values of mass flux and effectiveness. From the figure 13 and figure 14, it can be observed that for refrigerant R410A effectiveness is high with respect to mass flux.

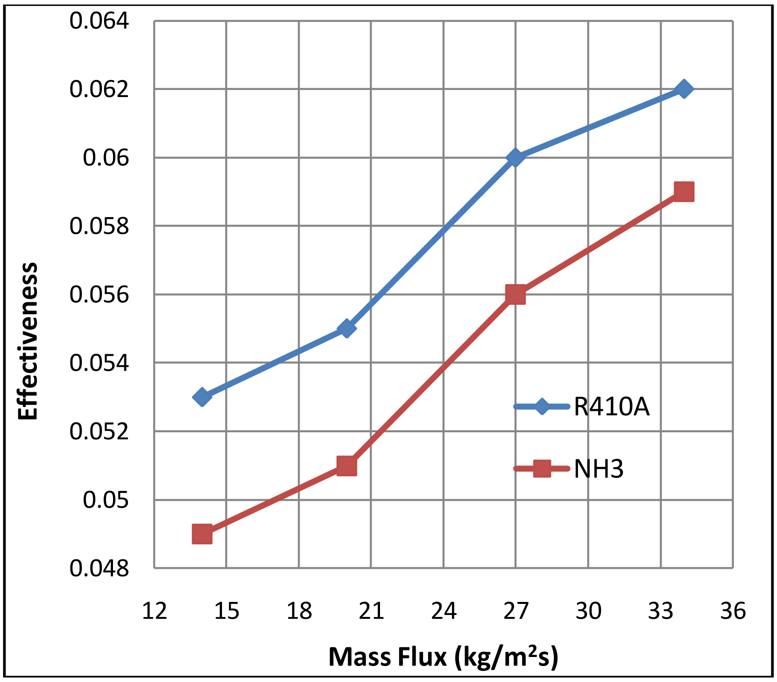


Figure 13. Effectiveness Vs. Mass Flux of NH_3 and R410A – Experimental values

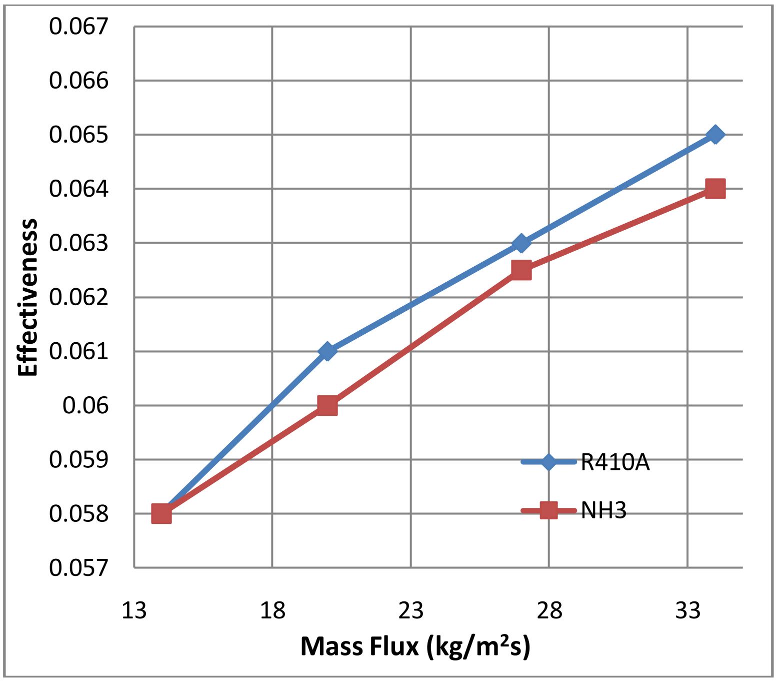


Figure 14. Effectiveness Vs. Mass Flux of NH_3 and R410A – CFD values

6. CONCLUSION

The following are the findings and the conclusion derived from this work.

- The average heat transfer coefficient of R410A is higher than NH_3. This gives better heat transfer and thus better performance. Heat transfer rate is better in R410A compared to the other one. Heat transfer coefficient increases steeply with respect to refrigerant effect in case of R410A than the other refrigerant.
- The rate of increase of average heat transfer coefficient for R410A compared to that of NH_3 is high. The rate of increase of heat transfer rate with respect to refrigerating effect for R410A compared to that of NH_3 is high. The rate of increase of heat transfer rate for R410A compared to that of NH_3 is high.
- The ratio of pressure drop for R410A is less than NH_3. Hence the ratio of pressure drop to mass flux of R410A is superior to NH_3. The rate of decrease of average pressure drop with respect to mass flux for R410A compared to that of NH_3 is less.
- From the complete CFD results, it is concluded that Effectiveness is better in the case of R410A than the other. LMTD obtained for R410A is also relatively higher. The rate of increase of effectiveness with respect to mass flux for R410A compared to that of NH_3 is high.

The above results show that R410A refrigerant outweighs NH_3 as the preferred refrigerant. Hence it is concluded and suggested that R410A could be used as an effective and safe alternate refrigerant in milk chilling system.

6.1 SCOPE FOR FUTURE WORK

This work can further be continued to study the effect of different chevron angles, different refrigerant and various condensation temperatures in plate heat exchangers. Experimental work with 20^o chevron angle may be conducted to find the effectiveness of the refrigerant R410A. Even though several different approaches of determining the performance of plate heat exchangers with different chevron angles using different refrigerants were employed in the present thesis, the work can be expanded further with a focus on different chevron angles. Also the efficiency may further be improved by reducing the area of plate heat exchanger.

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