CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

With the phaseout of R-22, existing air-conditioning appliances will have to be replaced with new appliances or retrofitted with alternative refrigerants. Current research focuses on the development of new refrigerants to retrofit the existing R-22 systems. Various alternative refrigerants are available to retrofit the conventional systems, but each one has its own merits and demerits. Previous researchers have studied the performance of various alternative refrigerants and their mixtures both experimentally and theoretically. In this chapter a comprehensive survey of the previous study on the performance of alternative refrigerants and their mixtures in refrigeration and air conditioning system is presented. The need for and the scope of this research work have been outlined at the end of the chapter.

2.2 ALTERNATIVE REFRIGERANTS AND THEIR PERFORMANCE

Since this study has been focussed on retrofitting of existing R-22 systems with alternative refrigerants, a detailed literature survey related to the performance of HFCs, HCs and their mixtures in refrigeration and air conditioning systems has been made.
Fischer and Sand (1993) have analysed for chlorine free alternative refrigerants to replace R-22 in air-conditioning applications and found that nine ternary blends containing E-125 and eleven ternary blends that exclude E-125 have promising results. It was observed that the ternary blend of R-32/R-125/R-134a had 4% higher COP and 20% higher capacity than R-22 and the ternary blend of R-32/E-125/R-134a have 6% to 8% higher COP and 30% higher capacity than R-22.

Donald et al (1994) conducted an experiment to study the performance of R-407C as a drop in substitute for R-22 for air conditioners and heat pumps. It has been reported that R-407C was a close match to R-22 in capacity and energy efficiency. Additional performance improvements were also possible through optimisation of the expansion device and other system components, including the use of liquid line/suction line heat exchange and counter flow evaporators and condenser. Energy efficiency values were found to be 6% to 7% higher than those of R-22.

Kim et al (1994) conducted a test on heat pump with two azeotropic refrigerant mixtures of R-134a/HC290 and R-134a/R-600a. Their experiments indicated that the COP of R-290/R-134a was lower than that of R-22 and R-290. However, R-134a/R-600a showed higher COP than that of CFC12 and R-134a. The discharge temperature of R-290/R-134a was found to be lower than that of R-22 and slightly higher than that of R-290. For R-134a/ R-600a mixture, the discharge temperature was lower than that of R-12.

Vince et al (1995) based on an experimental study on the performance of R-407C against R-22 have reported that the cooling capacity of
ternary mixture of R-32 (30%)/R-125 (10%)/R-134a (60%) was 7.7% less than that of R-22 at 35 °C ambient for baseline operation. For liquid overfeeding operation, the cooling capacity of this mixture was only 1.1% less than that of R-22. It has also been reported that the above mixture has slightly higher compressor discharge pressure, a lower compressor discharge temperature, slightly lower compressor power consumption, and a higher compressor pressure ratio.

Yunho et al (1997) have observed that there was no pure non-flammable substitute refrigerant for R-22. It has been also reported that R-407C and the ternary mixtures composed of R-32, R-123, R-134a performed closer to R-22, but with minor hardware changes.

Sami et al (1997) have conducted an energy efficiency analysis of a new ternary blend composed of R-23/R-32/R-125 against CFC502 and R-22 in an experimental heat pump set up with a 3 kW rotary compressor. The results showed that the ternary HC blend R-23/R-32/ R-125 had superior performance compared to other refrigerants.

Macline and Leonardi (1997) measured the performance of HFC and HC based refrigerants in air-conditioning appliances and reported that the energy consumption could be reduced by zeotropic blends.

Yunho and Reinhard (1998) have presented the performance potential of the most probable HFCs (R-407C, R-410A and R-32). It has been reported that R-407C and R-410A have similar steady state capacity and COP to R-22 within 6% variation whereas, R-32 has similar COP, but higher steady
state capacity by 12-14%. It was also reported that R-407C has lower seasonal performance factors (Ratio of the total amount of cooling provided during a season divided by the total amount of electrical energy consumed during that season) by 6% to 7%; R-410A has similar seasonal performance factor within 4% variation and R-32 had better seasonal performance factors by 2% to 5% as compared to R-22.

Purkayastha and Bansal (1998) in their experimental study on HC290 and LPG mix as replacements for R-22 reported that the hydrocarbon refrigerants performed better than R-22 but with small loss of condenser capacity. The mass flow rate and compressor discharge temperatures were found to be significantly lower than R-22. Their study revealed that LPG could be an excellent refrigerant in heat pump and refrigeration applications.

Vince et al (1998) have conducted an experimental study of drop-in test for R-407C on an Off-the-shelf air conditioner using a counter and parallel cross flow Evaporator was examined under ARI-rated indoor and outdoor conditions. It has been reported that the results showed a 8% higher cooling capacity and 3.8% higher COP for counter-cross flow evaporator than that of the parallel-cross flow evaporator.

Yang et al (1999) have investigated the performance on varying working conditions of some new refrigerant mixtures R-32/ R-125/ R-152a, R-125/ R-290, R-32/ R-290, R-32/R-125/ R-290 as the replacements for R-22. It has been found that performance of the substitute R- 32/R-125/R-152a mixture was close to that of R-22 over the entire range of operating conditions. It has been also inferred that the compositions of the mixture should be
optimised according to the range of operating conditions of the unit applications.

Motoshi (1999) has investigated the performance of different lubricants for use with hydrofluorocarbons (HFCs) in order to obtain satisfactory lubrication performance in compressors. It has been reported that R-22 is well soluble with mineral oil (MO56) at low temperature and low pressure and reduces the viscosity but it is also well soluble and reduces the viscosity even at high temperature and high pressure. R-407C is soluble in POE oil and reduces the viscosity at low temperature and low pressure, but it is less soluble at high temperature and high pressure and maintains the viscosity. It was also reported that the viscosity of POE became very similar to that of currently used mineral oils.

Samuel and Daniel (2000) have conducted a performance analysis of new refrigerants like R-410A, R-507, R-407C, R-408A and R-404A as substitutes for R-22. It has been reported that as an interim replacement, R-404A blend has a superior performance among the proposed blends. It has been also reported that R-410A has the highest discharge pressure among the blends whereas R-407C has similar discharge pressure and temperature as that of R-22 and R-407C has the lowest power consumption compared to other blends.

Lee et al (2002 a) have carried out a drop in test for R-407C in a commercial screw chiller with shell and tube heat exchangers originally designed for R-22. It has been reported that a severe performance reduction was observed. The heat transfer degradation in the evaporator was found to be larger
which affected the chiller performance and also indicated that the performance reduction caused by the evaporator was approximately two times compared with that of the condenser.

Aprea and Greco (2003) have evaluated the performance of R-407C and R-22 in a vapor compression plant with a reciprocating compressor. The experimental results revealed that the performance of R-22 was better than R-407C by 8% to 14%, which was mainly because of better compression process due to a number of factors such as better isentropic and volumetric efficiencies of R-22.

Adriano et al (2003) have conducted an experimental investigation to study the performance of R-407C as an alternative to R-22 in a vapor compression plant. It has been reported that COP of R-407C was 5% to 17% lower than R-22. For the same refrigeration load, R-407C required higher compressor power. The operational behaviour of R-407C was found to be improving with higher condenser and evaporator temperatures. It has been concluded that R-407C was a better substitute in all applications requiring high evaporation temperatures such as air-conditioning plants.

Aprea et al (2004) have conducted an experimental analysis of the refrigeration capacity by means of a variable speed compressor for refrigerants like R-22, R-507, R-417A and R-407C. The results show that the energy consumption for R-407C was 12% lower than R-22 when working at nominal frequency (50 Hz). Furthermore, R-407C had superior performance when compared with other refrigerants. R-22 exhibited the highest performance of all the refrigerants.
Karagoz et al (2004) have investigated the possibilities of using R-134a and binary mixture of R-134a and R-22 as working fluids to replace R-22 for vapor compression heat pump applications. The performance of the system was characterized by mixture ratio, COP and evaporator inlet air temperature. Experimental results showed that the mixture ratio affects the COP significantly, and the COP could be improved by using pure R-134a or an appropriate mixture of R-134a/R-22 instead of pure R-22. It has been also observed that the maximum COP occurred at a mixture ratio of around 50%/50% of R-134a/R-22.

In the above papers from open literature it is quite evident that identifying a suitable alternative for R-22 has been attempted from various quarters at different angles viz. improvement in refrigeration capacity, environment friendliness and reduction in compressor work. From the literature it has been observed that R-407C could be a drop in substitute in R-22 systems, but it needs POE oil instead of mineral oil as the compressor lubricant. Such POE oil used for R-407C refrigerant is highly polar and hygroscopic in nature and hence replacing of POE oil is quite important. Thus it is needless to say that R-22 phase out demands a better alternative refrigerant. In this context R-407C/HC mixture can be considered as a drop in substitute for R-22.

### 2.3 MISCELLIBILITY ASPECTS OF HFCs/HCs WITH MINERAL OIL

The use of R-407C and polyol ester lubricants for retrofitting small hermetic R-22 systems has some drawbacks due to the requirement of a rather complicated procedure for charging the refrigerant and lubricant. The addition of a small quantity of hydrocarbon, which is well soluble in mineral oil, could
reduce the viscosity of the lubricant accumulated in the evaporator sufficiently to guarantee the lubricant’s return to the compressor. In addition, this concept could also reduce the flammability issues in HC refrigerants.

Kim et al (1994) have reported that in refrigeration systems the lack of mineral oil solubility with chlorine free refrigerants was a matter of concern in the context of ODS phase out.

Janssen and Engels (1995) have reported that the addition of 5% isobutane could take care of the return of mineral oil from evaporator into compressor. Experiments conducted in domestic appliances with 8% isobutane as an additive with R-134a have shown an improvement in the performance of the appliance.

Camporese et al (1997) have reported that the addition of R-290 with R-134a resulted in an increase in the refrigerating capacity, which was roughly proportional to the mass fraction of R-290. At the lower evaporating temperature, the COP was unaffected by the mass fraction of R-290 but at the higher evaporating temperature, the COP was slightly decreasing with the increase in mass fraction of HC. It was also observed that the miscibility of the mineral oil has increased considerably by even small mass fraction of hydrocarbon.

Herbe and Lundqvist (1997) have investigated the level of acid, moisture and residual mineral oil in a retrofitted refrigeration system and heat pumps. It has been observed that if the percentage of the moisture content and residual mineral oil were kept below the stipulated levels, the system could run
without any problem. It has also been indicated that copper plating was not significant in those places where proper evacuation had been carried out before charging.

Colbourne and Ritter (1998) have reported that the replacement of conventional refrigerants by hydrocarbon refrigerants could lead to a small increase in risk but that increase was negligible as compared to the background levels. Alok and Agarwal (1998) have studied the performance of R-134a/R-600a mixture as a possible drop in substitute for R-12 in a horizontal bottle cooler. It has been reported that the COP of the system was 8% less than that of R-12.

Masato et al (1999) have reported that even 5% residual mineral oil concentration could make the POE oil to be immiscible. It has also been recommended that the oil tank and pipelines in refrigeration systems should be adequately flushed during retrofitting.

Tashtoush et al (2002) have experimentally studied the performance of a 320-litre R-12 domestic refrigerator charged with mixtures of HC and HFC refrigerants. The results showed that the R-600/R-290/R-134a mixture could provide excellent performance parameters such as coefficient of performance, compressor power, volumetric efficiency, condenser duty, compressor discharge pressure and temperature as compared to R-12.

Joseph et al (2003) have studied the performance of R-134a/HC blend refrigerant mixture as a possible drop in substitute for R-12 in a domestic refrigerator. It has been reported that the addition of 9% of HC blend (R-290/
R-600a) with R-134a could solve the miscibility problem and also improves the performance of the system.

Based on the above observations it has been recognized that the addition of HC with R-407C could solve the oil miscibility issues of R-407C also with mineral oil and is expected to improve the system performance. The need for research to identify a suitable HC and its composition with R-407C to retrofit the R-22 systems is realised.

2.4 INFLUENCE OF OPTIMUM REFRIGERANT CHARGE ON THE SYSTEM PERFORMANCE

The refrigerant charge used in the hermetic cycle systems is an important parameter that influences the thermodynamic behaviour of the system. Dennis and Mohsen (1990) have studied the effect of improper refrigerant charge using R-22 on the performance of an air conditioner with capillary tube as an expansion device. A 10.6 kW split system air conditioner was used for the study. The degradation in performance of the system was generally greater for undercharging than for overcharging. Results indicated that undercharging by as little as 5% can cause as much as 6.1% drops in seasonal COP.

Mohsen and Dennis (1991) have studied the influence of the refrigerant charge using R-22 on the steady state and cyclic operation of a residential split-system air conditioner. The charge was varied to determine the effect on capacity, flow rate, evaporator superheat, power consumption and seasonal energy efficiency ratio (SEER). It has been reported that a larger
degradation in capacity was realised with undercharged systems than with over charged systems at a given temperature due to the variation of flow rate. It has also been reported that the measure of SEER dropped from 9.44% to 7.50 for 20% undercharging whereas it dropped to 8.47% only for 20% overcharging.

Radermacher and Kim (1996) have arrived at the conclusion that the optimisation of the capillary length and charge quantity was more important in selecting the new refrigerants R-134a and HCs for refrigeration systems.

Agarwal (1998) has investigated the performance of domestic refrigerators and commercial appliance using R-600a and R-290/ R-600a blend and observed that the energy consumption was influenced by the quantity of charge. The results showed that proper optimisation of charge and capillary length could improve the performance of the systems.

Choi and Kim (2002) have studied the effects of off-design refrigerant charge on the performance of a water-to-water heat pump by varying refrigerant charge (R-22) amount from – 20% to +20% of full charge at steady state with the capillary tube and electrostatic expansion valve. It has been reported that the capillary tube system was relatively sensitive to refrigerant charge and outdoor load conditions. It has also been reported that the degradation of the performance was higher at undercharged conditions due to the reduction of refrigerant flow rate and indicated that the Electrostatic expansion valve system showed much higher system performance as compared with the capillary tube. For overcharged conditions, power consumption of the heat pump increased due to a rise of refrigerant flow rate and compression ratio.
The survey of above papers confirms that proper refrigerant charge is an important prerequisite to study the system performance.

2.5 BEHAVIOUR OF ZEOTROPIC REFRIGERANT MIXTURE

Since this study has been focussed on zeotropic mixtures, knowledge of their behaviour is essential to study their performance. A detailed literature survey has been done to highlight the possible avenues composition shift and methods to circumvent such issues in refrigeration systems.

Venkataratnam et al (1996) have reported that the pinch point would occur only in the condensation or evaporation region of the heat exchangers for zeotropic mixtures. It has also been found that the perfect glide matching might not be possible when two phase enthalpy varies non-linearly with temperature, and if the variation was significant, temperature pinches occur somewhere within the ends of the condenser and evaporator depending on the nature of the enthalpy curve. Equations to find the pinch conditions of 300 zeotropes have also been reported.

David et al (1997) have developed a computer model to simulate the handling of zeotropic mixture in a refrigeration system. It has been identified that the ratio of distribution tank volume to the bulk tank volume, temperature of the charging process and the composition of the refrigerator in the factory prior to subsequent charging were the important factors that affect the concentration shift of zeotropes. It has also been recommended to limit the upper and lower composition limits of each component within 2%. 

Donald et al (1997) have investigated the performance of Zeotropic mixture (R-32/R-125/R-134a) in systems with accumulators or flooded evaporators. It has been found that the different liquid and vapour composition could increase the mass transfer resistance during evaporation and condensation leading to the degradation of heat transfer co-efficient as compared with single compounds and azeotropes.

Horst and Florian (1997) have reported that the concentration shift in non-azeotropic mixtures was due to the factors such as leakage of refrigerant mixture, thermodynamic behaviour of refrigerant mixtures in two-phase regions, and differential solubility of the components of refrigerant mixtures in lubricant oil. It has also been reported that the overall average concentration in the heat exchangers with two-phase regions was different from that of the concentration at charging.

Yunho et al (1997) have investigated the effect of temperature glide of azeotropic refrigerant mixtures and reported that, when the system was running, a greater fraction of the less volatile component was stored in the liquid phase of the refrigerant. Due to the above fact, the low vapour pressure component in a mixture has a lower circulation concentration than the changed one. It has also been observed that the zeotropic mixture that has a temperature glide does not cause any changes in system operation except temperature profiles in the exchanger. The study also indicates that the temperature drops in the condensation process and temperature gains in evaporation process depend on the temperature glide.
Frank and Dennis (1997) have reported that the composition shift was very small by 1% or less when liquid blend was filled from a storage tank. It has been found that the fractionation effect was increased exponentially as the liquid level drops below 10% of the total volume of the tank. The following observations have also been made regarding the fractionation of zeotropic blends.

- Fractionation of a non-azeotropic blend in a system would only occur when there is potential for significant liquid hold-up or storage.

- Leaks could alter the composition of the Refrigerant blend and were most significant when they occur in the vapour side while the systems are off.

- Recharging the system after a leak with a blend of the original composition would bring the blend closer to the original system composition.

- Charging at nominal room temperatures at any reasonable rate would not produce major composition changes.

Per (1998) has investigated the possible causes of composition changes of zeotropic mixture retrofitted in an existing system. It has been reported that, the change in composition due to the improper charging decrease the cooling capacity, condenser heat transfer (UA), COP, volumetric efficiency, super heat and compressor isentropic efficiency and increase the condenser temperature, UA of evaporator, evaporator temperature and sub cooling. It has
been also reported that the oil solubility (or) dissolving capacity of refrigerant with oil also considerably influences the above said properties.

The studies carried out on the behaviour of zeotropic blends in the above papers show that the handlings of the above blends are very critical. Hence when these refrigerants are used for testing, care must be exercised to avoid concentration shifts. The necessary procedure to prepare and charge the zeotropic refrigerant has also been understood from these literatures, which were highly useful for this study.

2.6 MODELLING OF REFRIGERATION AND AIR-CONDITIONING SYSTEMS / COMPONENTS

With the advent of computers, the study of various components of a domestic air conditioning system under a range of operating conditions has become possible through mathematical modelling, saving thus a huge amount of time and money. Subsequently, simulation of an air conditioning system demands a thorough knowledge on simulation techniques. Hence an elaborate literature survey has been conducted and it is presented in this section.

Chi and Didion (1982) have developed a computer program to analyse the transient behaviour of the heat pump. They used a first order differential equation in both time and space domain. The compressor, heat exchanger, expansion devices and also the accessories in the system were modelled using lumped parameter modelling. The results were also compared with experimental values. Since complexities in the two-phase region were not considered, the result was not accurate.
William and Doyle (1988) have developed an analytical model for compressor. The compressor shell was divided into three sections namely top, sides and bottom. Forced as well as free convection heat transfer coefficients were applied. A constant volumetric efficiency (53.3%) was assumed for compressor. The results obtained from the computer program were comparable with the experimental values. The heat transfer in suction, discharge plenum and the compression process were not included in the simulation.

Wang and Touber (1991) have modelled the evaporator using distributed parameter model. It has been suggested that the distributed model could be useful only for short-term simulation i.e. only for an hour and not for days or years. It has also been recommended that for long-term simulation, a combination of a steady-state refrigeration machine model with a dynamic refrigerated room model could be feasible.

Domanski and McLinden (1992) have developed a simulation program to evaluate the performance of pure refrigerants and refrigerant mixtures. Isentropic compression and isenthalpic expansion processes were assumed. The heat exchangers were modelled by using effective temperature difference and pressure drop. For the zeotropic mixture, the heat exchanger area was divided into number of small sections and LMTD approach was applied to every section. In the compressor, polytropic compression with efficiency of 85% was used. Two volumetric efficiencies were used. In the first case, the volumetric efficiency was assumed as 100% and in the second case it was calculated from appropriate equation. The results were comparable with the experimental values referred.
Herbas et al (1993) have modelled the Compressor by assuming polytropic compression. Air-cooled condenser was modelled using a three-zone model. In expansion device, isenthalpic process was assumed. Constant overall heat transfer coefficient was assumed for the evaporator. The other assumption made were: 85% Electric motor efficiency, 3% clearance ratio, polytropic compression index 1.19, and 75% volumetric efficiency. The results showed that R-134a has greater temperature lift than R-12.

Geoffrey and Chen (1994) have introduced the pinch method to facilitate the refrigerant cycle simulation for Zeotropic refrigerants. A system with a COP of 3.5 was increased to 4.5 while the condenser pinch was 6.5°C for R-22. The power saving was also 35%, however for a pinch of 10°C the COP was increased to 3.77 with power saving of 22% for a binary mixture (R-22/R-142b).

Sami and Dahmani (1996) have proposed lumped parameter model using control volume formulation in which the whole system has been discretized into number of control volumes, nodes and links. A new correlation was developed to predict the boiling and condensing heat transfer coefficients of zeotropic mixtures.

Bensafi et al (1997) have developed a computational model for the design of plate-fin-heat exchangers for R-22, R-134a and refrigerant mixtures based on R-32, R-125 and R-134a. It has been reported that their model could handle the non-conventional coil circuits with different numbers of inlets and outlets, non-uniform air distribution at the coil inlet face using smooth, wavy and louvered fins, and smooth and internally finned tubes. The programme has been validated with the experimental results.
John and Radermacher (1997) have developed a heat exchanger model and reported that the refrigerant side heat transfer depended on the accuracy of the airside heat transfer coefficient. Since the airside heat transfer resistance was larger than the refrigerant side heat transfer resistance, the inaccuracy of the heat transfer coefficient in refrigerant side has not significantly affected the overall heat transfer coefficient. A 20% decrease in the evaporation heat transfer coefficient resulted in 2.7% decrease in the overall heat transfer coefficient.

Jameel and Syed (1999) have developed a thermodynamic model to simulate the working of actual refrigeration system. Simple cycle used for the analysis showed that the super heating has more influence on the COP of the system. Using this model, the COP and other system parameters were calculated with \( \pm 2\% \) accuracy.

Metin and Nilufer (2002) have tested the performance of heat exchangers having different geometry under dry conditions. The heat transfer coefficient’s dependency on the heat exchanger geometry and Reynolds number has been proved.

Jakob and Hogaard (2002) have modelled the condenser and evaporator using the new moving boundary model. Dynamically tracking the length of different region (single-phase and two-phase) was the basic technique used in their approach. The main advantage of this method was its speed. The disadvantage of the model was the analytical integration of conservation equation that made the model mere specific to particular configuration.
The refrigeration and air conditioning system modelling discussed in the above papers show that the performance of the air-conditioner with the new alternative refrigerant can be evaluated using a modelling program. The assumptions and considerations for simulation have been noted and are enumerated in the respective sections of chapter 4.

2.7 COMPRESSOR COMPATIBILITY FOR RETROFITTING

The compressors available in existing systems are designed for the conventional refrigerants. Hence their behaviour with alternative refrigerants have to be ascertained to ensure the energy efficiency and also life of the retrofitted systems.

Chen et al (1994) investigated the feasibility of using hydrocarbon mixtures in residential air conditioning and heat pumps. A mixture of R-290 and R-600 gave the highest COP. It has been considered to represent the best balance between COP and volumetric capacity for hydrocarbons. The disadvantage with R-290/ R-600 is its low volumetric capacity.

Riffat et al (1997) have reported that the alternative refrigerants like ammonia, hydrocarbons, carbon dioxide, water and air demand for special changes in main system components like compressor, evaporator and control devices.

Agarwal (1998) has reported that one of the important advantages of R-600a/ R-290 blend is that it was compatible with mineral oil and commonly used materials for manufacturing of refrigeration systems. It has been also
reported that it requires minimal or no changes while retrofitting R-12 refrigeration system.

Devotta et al (1998) have tested the reliability of various parts in a hermetic compressor with alternative refrigerants and reported that the hydrocarbon blend has better compatibility with hermetic compressor components.

Dongsoo et al (2000) have conducted a performance study of R-22 alternatives using 14 refrigerant mixtures composed of R-32, R-125, R-134a, R-290 and R-1270 in a heat pump in an attempt to substitute R-22. The test result showed that ternary mixtures composed of R-32, R-125, and R-134a have 4% to 5% higher COP and capacity than R-22. It has also been showed that the compressor discharge temperature with all the mixtures tested were lower than that of R-22, indicating that these mixtures would offer better system reliability, fluid stability and longer lifetime than R-22.

Devotta et al (2001) have investigated the alternatives to R-22 for air-conditioners and reported that R-134a offers the highest COP but its capacity is the lowest and requires much larger compressor. It has been also reported that the characteristics of R-290 are very close to that of R-22, but the compressor requires little modification.

Samuel and Daniel (2000) have reported that the R-22 alternatives like R-407C, R-410A, R-507, R-408A and R-404A are characterized by higher discharge pressure.
The performances of the compressors with alternative refrigerants discussed in the above papers show that mixtures would offer better system reliability, fluid stability than R-22 but natural refrigerants need compressor modifications which may not be viable while retrofitting the existing R-22 systems with new refrigerants.

2.8 REFRIGERANT PERFORMANCE IN HEAT EXCHANGERS

The evaporation and condensation heat transfer of alternative refrigerants in refrigeration system decides the refrigeration effect and energy efficiency of the systems. A detailed study of the heat transfer characteristics is also important to understand the behaviour of heat exchangers with alternative refrigerants.

Shah (2002) has presented a dimensional correlation for predicting condensation heat transfer coefficients for R-22, R-11, R-12, R-113, methanol, ethanol, benzene, toluene, and trichloroethylene in horizontal, vertical, and inclined pipes of diameters ranging from 7 to 40mm. The range of parameters covered includes reduced pressures from 0.002 to 0.44, saturation temperatures from 21 to 310°C, vapor velocities from 3 to 300 m/s, vapor qualities from 0 to 100%, mass flux 39000 to 758000 kg/m²h, heat flux from 158 to 1893000 W/m². It has been reported that the mean deviation for the 474 data points analysed was found to be 15.4%.

McLinden and Radermacher (1987) have used characteristic condensation and evaporation temperatures to compare the different zeotropic
mixtures. It has been found that the COP of the system could be increased due to the temperature glide of the zeotropes during phase change.

Kuijpers et al (1988) have reported that the criticality in optimising the capillary was reduced by a large condenser. It has also been mentioned that the usage of a large condenser leads to a lower condensation pressure and, intern, to a higher efficiency.

Janssen et al (1992) have reported that the cycling losses depend on the ON/OFF cycle length and the dimensions of the heat exchangers. Their results also showed that the efficiency of the systems with capacity control was 10% to 18% higher than that of an ON/OFF cycle system for the same cooling capacity.

Murata and Hashizume (1993) have observed that the heat transfer coefficient of R-123/R-134a mixture was lower than that of the individual heat transfer coefficients of the constituent components. Jung and Radermacher (1993) have reported that the heat transfer coefficients of zeotropic mixtures were reduced with an increase in temperature glide. It has also been reported that the heat transfer coefficient was more sensitive to the properties of liquid than those of vapour.

Stephan (1996) has studied the two-phase heat exchange for the refrigerants R-134a, R-152a, R-113 and their mixtures and reported that there was a decrease in saturation temperature along the flow path due to the pressure drop. Jee et al (1997) have investigated on the convective boiling heat transfer coefficient of pure refrigerants such as R-134a, R-290 and R-600a and
zeotropic mixtures of R-290 and HC600a. It has been reported that the heat transfer co-efficient of R-290 and R-600a was better than that of R-134a and R-22. The heat transfer coefficient of the mixture was found to be comparatively less than that of the constituent components.

Chung et al (1997) have conducted a test using R-407C as a drop in substitute for R-22 in a split air conditioner. The test included standard rating condition, overload condition and low temperature condition. It has been reported that to effectively reduce the condensing pressure it is necessary to improve the heat transfer performance of the heat exchangers. It has also been reported that the reduction in capillary tube length cannot effectively decrease the condensing pressure.

Dobson and Chato (1998) have investigated experimentally the condensation heat transfer coefficients for R-12, R-22, R-134a and near-azeotropic blends of R-32/R-125 in 50%/50% and 60%/40% compositions. The study focused primarily on measurement and prediction of condensing heater coefficients and the relationship between heat transfer coefficients and two-phase flow regimes. Heat transfer correlations that were developed for flow regimes predicted data from the present study and from several other sources. It has been reported that the two-phase multiplier was highest for R-134a, the lowest reduced pressure fluid. This resulted in R-134a having higher heat transfer coefficients than the other fluids at high qualities. It has also been reported that more analyses and experimental data are needed for the development of satisfactory understanding and reliable correlations for zeotropes.
Domanski (1999) has reported that the two-phase heat transfer coefficient of a zeotropic mixture was less than the heat transfer coefficient of the mixture constituents. Kedzierski (2000) has reported that larger heat transfer coefficient could be obtained for small lubricant mass fraction and high lubricant viscosity.

Aprea et al. (2000) have conducted an experimental evaluation of R-22 and R-407C evaporative heat transfer coefficients in a vapor compression plant. The experimental condition under which heat transfer coefficients were determined reflected a typical working situation for small-scale refrigeration systems. The heat flux ranged from 1.9 kW/m\(^2\) to 9.1 kW/m\(^2\) and mass flux was varied from 30 kg/m\(^2\)s to 140 kg/m\(^2\)s. The results illustrated that R-22 heat transfer coefficient was always greater than that of R-407C.

Choi et al. (2000) have developed a correlation to predict the evaporative heat transfer coefficient for pure refrigerants and refrigerant mixtures such as R-32, R-134a, R-32/R-134a and R-32/R-125/R-134a. The experiments were conducted for test section average temperatures varying from –12°C to 17°C with the mass fluxes varying from 240 kg/m\(^2\)s to 1060 kg/m\(^2\)s and heat fluxes varying from 4.1 kW/m\(^2\) to 28.6 kW/m\(^2\). It has been reported that the deviation between the predicted and experimental was within 13.2%.

Boissieux et al. (2000) have conducted an experimental evaluation of Isceon59, R-407C and R-404A condensation heat transfer coefficients in a horizontal tubes and the results have been compared with existing correlation. It has been reported that the Shah correlation for condensation heat transfer coefficient was found to predict adequately the local experimental results, with
an overall standard deviation of 9.1% and the Dobson correlation gave the best prediction of the three refrigerants considered in this study, with an average deviation of 7.6%.

Radermacher and Jung (2000) in their theoretical analysis of replacement refrigerants for R-22 using binary and ternary mixtures reported that an improvement in COP by 13.7% over R-22 was observed with binary and ternary mixtures. However, significant design changes to the system will be necessary to accommodate mixtures, requiring a considerable research and development effort. Some of the design changes potentially offset the energy savings.

Lee et al (2002) have done the numerical simulation on condenser for R-22 and R-407C. A section-by-section scheme was used to find the condenser performance. Z-type and U-type path configurations were used for the analysis. It has been reported that the results predicted for R-22 were greater than experimental data by 15.9% for U-type path and 4.3% greater for the Z-type path. In the case of R-407C, the predictions were less than experimental data by 11.6% for the U-path and 9.7% for the Z-type path. It has been also reported that the simulation prediction was more accurate for Z-type configuration. It has been concluded that U-type configuration was better for R-407C and Z-type configuration was better for R-22.

Aprea et al (2003) have investigated experimentally the condensation heat transfer coefficients for R-22 and R-407C. It has been reported that the R-22 heat transfer coefficient is always greater than that of R-407C. It has been also reported that Dobson and Chato correlation when fitted with their
experimental data for both refrigerants shows a mean deviation of 12% for R-22 and 13% for R-407C between experimental data and predicted values.

From the observations made in the above literature the prediction methods have been employed in modelling and simulating the processes in the evaporator and condenser. Some are listed below.

The inputs to the condenser simulation were condensing pressure, condenser inlet refrigerant and air inlet temperature, air velocity, refrigerant flow rate, condenser tube diameter and its length. The inputs to the evaporator simulation were inlet temperature of refrigerant and air, air velocity, refrigerant pressure, vapor quality at the inlet, evaporator diameter and its length.

2.9 CAPILLARY FLOW CHARACTERISTICS WITH ALTERNATIVE REFRIGERANTS

Selection of capillary plays a key role while retrofitting the existing systems with new alternative refrigerants. Capillary tube is a simple expansion device used in window air conditioners to meter the flow of refrigerants. Therefore a detailed literature survey has been carried out and it is discussed in this section.

Chang and Ro (1996) have reported that the pressure drop of the refrigerants was increased by the increase in saturation pressure of the refrigerant. It has been also found that the pressure drop in the two-phase region was larger than that in the liquid region.
MoChung (1998) has reported that the ordinary differential equation (ODE), which is normally used to study the Fanno flows in capillary tubes, could not be used for NARMs. It has been also mentioned that an iterative procedure was required for NARMs due to their temperature glide.

Dongsoo et al (1999) have presented a model, in which pressure drop through a capillary tube is modelled in an attempt to predict the size of the capillary tubes used in residential air-conditioners and also to provide simple correlating equations for practising. Stoecker's basic model has been modified with the consideration of various effects due to subcooling, area contraction and different equations for viscosity and friction factor and finally mixture effect. McAdam's equation for the friction factor yielded the best results among the various equations. With these equations, the modified model yielded the performance data that are comparable to those in the ASHRAE handbook.

Melo et al (1999) have conducted an experimental study on capillary tubes in household refrigerators and freezers for R-12, R-134a and R-600a considering various capillary tube geometrical parameters and operating conditions. A non-dimensional correlation has also been developed to predict the mass flow rates for all refrigerants. It has been reported that the diameter affects the mass flow rates more significantly than other geometrical parameters. It has also been reported that the predictions from the developed correlations are found to be in good agreement with the measured data and other studies in the published literature.

Samuel et al (2000) have experimentally investigated the characterisation of flow inside adiabatic capillary tube. The behaviour of zeotropes inside capillary tubes in five different dimensions were
experimentally investigated and they have been presented in tables for future reference. The following are the key observations.

- Experimental data for two fluids, R-407C and R-404a as a substitute for R-22 and R-502 are presented.
- The flow rate covers a range of 10 kg/h to 112 kg/h, which helps to develop a generalized non-dimensional correlation.
- Evaluating the condensing temperature for zeotropic mixture, average between bubble and due point temperatures was taken at the measured inlet pressure.

Kim et al (2002) have experimentally investigated the performance of adiabatic capillary tubes with several length and inner dia-combinations for R-22 and its alternatives, R-407C and R-410A. It has been reported that the mass flow rates of R-407C are higher by 4% and those of R-410A are higher by 23% than those of R-22. A non-dimensional correlation also has been evolved to predict the mass flow rates as a function of several non-dimensional parameters based on the Buckingham \( \pi \) theorem. It has been mentioned that the deviation of predicted results for R-22, R-407C and R-410A from experimental results lies between \(-12\%\) and \(+12\%\) for all test conditions.

BoGu et al (2003) have studied theoretically the flow behavioural of R-407C against that of R-22 in a capillary tube. It has been found that the curves were almost overlapping with each other in the single-phase region, which was attributed to the closeness of the property values. However in the two-phase region, difference was found between the two, as the viscosity of R-407C was lower than that of R-22 in that region.
Choi et al (2003) have developed a generalized correlation for refrigerant mass flow rate through adiabatic capillary tubes for R-22, R-290, and R-407C by evolving dimensionless parameters, derived from the Buckingham $\pi$ theorem, considering the effects of tube inlet conditions, capillary tube geometry, and refrigerant properties on mass flow rate. It has been reported that the generalized correlation yields good agreement with the measured data for R-22, R-290, and R-407C with average and standard deviations of 0.9% and 5.0%, respectively. Further assessments of the correlation are made by comparing the predictions with measured data for R-12, R-134a, R-152a, R-410A and R-600a from the open literature made evaluation. It has been also mentioned that the correlation predicts the data for those five refrigerants with average and standard deviations of -0.73% and 6.16%, respectively.

Choi et al (2004) have developed a generalized correlation for the flow characteristics of R-12, R-22, R-134a, R-152a, R-407C and R-410A in adiabatic capillary tubes by generating dimensionless parameters for operating conditions, capillary tube geometry, and refrigerant properties using the Buckingham $\pi$ theorem. It has been indicated that the correlation yields a mean deviation of 5.4% and a standard deviation of 6.5% from the experimental data.

From the above observations made on the flow through capillary tubes in refrigeration and air conditioning systems, it has been well understood that while searching for alternatives, determination of length and diameter of the matching capillary tube specific to appliance and refrigerant is quite significant. It has been understand that to provide an appropriate tool to design
a capillary tube, a generalised flow correlation for alternative refrigerants must be developed. The existing correlations also have not been applied to the proposed R-407C/HC refrigerant mixture and hence a new correlation will be required for predicting the flow characteristics.

2.10 SCOPE OF THE PRESENT WORK

From the review of previous studies it has been identified that R-407C refrigerant mixture offers a close match to R-22 in existing air conditioning system with respect to energy efficiency and other performance parameters such as compressor discharge pressure and temperature. Hence it could be considered as a potential drop in substitute for R-22. But retrofitting R-22 systems with R-407C needs the lubricating oil to be changed to POE oil, as R-407C is immiscible with conventional mineral oil. This POE is highly hygroscopic in nature, which leads to serious service issues with system while retrofitting. It also causes irritation if it comes in contact with our skin. From the literature, it has been found that HC addition to HFCs could solve the immiscibility problem with mineral oil. Thus, in this present study, a mixture of R-407C with HC blend is considered as a retrofit for R-22 in window air conditioners. This R-407C/HC blend mixture is expected to work with an improvement in system performance also. However these expectations are to be ascertained through experimental and theoretical investigations. Hence the total investigation was comprehensively planned and conducted through a systematic procedure as shown in Figure 2.1. Initially a preliminary cycle analysis was carried out using REFPROP software to arrive at the trial values of HC blend concentration levels. Subsequently a detailed simulation study of the entire system was carried out using MATLAB software. A detailed experimental
study was also carried out in a Room calorimeter experimental setup to optimise the concentration of HC blend in the refrigerant mixture. Further while retrofitting with a new working fluid the capillary flow characteristics are to be established. Therefore the capillary flow characteristics of the evolved optimal mixture were studied and a correlation to predict mass flow has been developed. Thus the present research work was envisaged with objectives discussed in the following section.

**Figure 2.1** Methodology of the total investigation
2.11 OBJECTIVES OF THE PRESENT WORK

The objectives of the present work are:

1. To simulate the performance of R-407C/HC blend refrigerant mixture and compare the same with that of R-22 to arrive at the optimal mixture composition.

2. To experimentally investigate the performance of R-407C/HC blend refrigerant mixture with different concentration of HC blend and to optimise the same in respect of the viability for retrofitting and energy efficiency in a window air conditioner.

3. To study the capillary flow characteristics of the optimal R-407C/HC blend refrigerant mixture in adiabatic capillary tubes and evolve a correlation for predicting its mass flow rate.