Chapter 2

Literature Review

This chapter presents a review of the relevant literature on the ejector based transcritical R-744 refrigeration systems. The review focuses on the thermodynamic modelling of the different R-744 cycles and the various system components like compressors, evaporators, heat exchangers, expansion valves and ejectors etc. The review also considers expansion work recovery based applications, system modifications seeking performance enhancement including internal heat exchanger, inclusion of multi-compression, multi intercooling, subcooling, suction nozzle pressure drop and multi ejector systems. The review finally focuses on the computational fluid dynamics based analysis of phase change ejectors. In the end, a summary of the literature survey is presented and thesis objectives are identified.

2.1 Introduction

There is a renewed interest among the scientific community for CO_2 based refrigeration systems which have seen many ups and downs in the course of time since their first introduction, Elbel et 9]. These systems have regained attention mainly due to the high Ozone depletion potential and greenhouse effect of Chlorofluorocarbons. The main limitation of CO_2 based systems is the use of extremely high pressure values which are required for heat rejection in hot climate zones. Pressure values of the order of 90 bar are required which cause huge losses during the expansion stage if a simple throttling valve is used, causing poor cycle efficiency. Previous experimental and analytical studies have demonstrated that the use of an ejector in the refrigeration cycle recovers 10]. The ejector based expansion system recovers pressure losses by converting the kinetic energy of the high pressure motive stream into a pressure boost and also by entraining the secondary flow from the suction stream. Because of an ejector, the compressor inlet pressure becomes higher compared to that achieved with a simple expansion valve in a conventional system. This ultimately reflects in an improvement in the overall coefficient of performance (COP) of the refrigeration system. As can be imagined, the ejector is a critical component, the flow processes inside which directly affect the efficiency of the system. A detailed information on the entrainment, mixing and shearing of the fluid streams along with the effect of possible shock waves inside an ejector may help in improving its design. In the following, we review the relevant previous works based on thermodynamic modeling of R-744 refrigeration systems.

2.2 R-744 Transcritical Refrigeration Systems

A transcritical R-744 cycle is a promising option for the refrigeration & air conditioning appli- 11]. However, its prominent drawback is the relatively low COP due to higher operating pressure under high ambient temperature conditions. For the conventional cycle, condensing temperature is chosen on the basis of coolant temperature in the condenser and corresponding saturation pressure is taken as the condensing pressure. As there is no saturation state for supercritical heat rejection, the gas cooler pressure is independent of the refrigerant temperature at the gas cooler exit. The gas cooler pressure has noticeable impact on the specific enthalpy due to the S-shape of the isotherm in supercritical region. The COP of the transcritical R-744 system is significantly influenced by the gas cooler pressure.

A thorough review on the modifications of the transcritical R-744 refrigeration and heat pump 12]. Various important cycle modifications, such as the use of multi-staging, internal heat exchanger, expansion turbine, ejector and vortex tube etc. have been reviewed. A comprehensive review on the R-744 based low temperature cascade type refrigeration 13]. This review reveals that the R-744 based cascade system perform 60% better compared to the conventional single stage systems based on R-404A for 14] presented a detailed review on the internal and external methods of subcooling for R-744 at the exit of the gascooler / condenser. Subcooling of R-744 is found to enhance the COP of the conventional system by up to 40%. A detailed review on development in R-744 refrigeration systems and its applications in various industries 15]. The study suggested the replacement of conventionally used expansion device with work recovery expanders or ejectors to recover large exergy losses associated with the isenthalpic expansion process. It also concluded that the most effective way to improve the system performance is to reduce the number of hours a system operates in supercritical state in warmer and relatively dry climatic conditions.

2.3 Use of Ejectors for Expansion Work Recovery

8] as an alternative expansion device in place of conventional throttling device as the same has no moving parts and also produces lesser irreversibility 16]. In this model, he divided the ejector into four parts: driving nozzle, suction nozzle, mixing section, and diffuser. Flow-through both the nozzle parts were calculated iteratively using total energy balance, assuming the outlet pressure equal for both nozzles. Further, the losses within the nozzles were estimated using nozzle efficiencies. The mixing section was considered isentropic. They also incorporated some efficiency parameters for the diffuser to account for losses.

17] conducted several studies on the R-744 air conditioning system equipped with a two-phase ejector. In 2004, they proposed an ejector expansion transcritical R-744 refrigeration cycle. Based on the constant pressure flow assumption, they concluded that the system equipped with an ejector had 16% higher COP than that of a conventional system. Further, they developed 18]. They also studied the effect of various ejector geometries and a range of operating conditions for R-744 ejector performance and showed that the motive nozzle efficiency decreases with a decrease in the ejector throat area. The suction nozzle efficiency was also affected by the outdoor temperature and ejector throat area. Besides, the distance from the motive nozzle exit to the mixing section constant area entry affected the suction nozzle efficiency and the mixing section efficiency. In 2012 Liu et al. 19] published a study on the effects of three parameters, namely ejector geometries, operating conditions, and compressor frequency on the performance of an ejector expansion. Experimental results showed conclusively that the COP of an R-744 transcritical air conditioning system could be enhanced by using an ejector expansion device. This enhancement became more significant as the outdoor air temperature increased. There is also enhancement of efficiency with a decrease in compressor frequency in the 50 to 30 Hz range and also with decrease in nozzle throat diameter. They performed another experiment with a 3 ton controllable ejector expansion transcritical R-744 air conditioner setup. The effect of a various physical parameters on the ejector efficiency 20 21] presented a two-phase ejector model. The ejector model was used to determine the isentropic efficiencies of the motive and suction nozzles, and the efficiency of the mixing section of the nozzle independently.

22] presented a procedure of using library functions. These library functions can be used to simulate ejector refrigeration cycles in applications like Modelica, Matlab, LabVIEW, 23] investigated variation of gas cooler pressure, gas cooler outlet temperatures, ejector efficiency, entrainment ratio, and pressure recovery in a cycle having ejector as an expansion device for R-744 transcritical cycle. COP improvements of 17% could be reached. In 2013, they presented a numerical investigation of the R-744 ejector cycle based on

24]. Correlations tracked the ejector efficiency and the mass flow rates within an error margin of 10% and 5%, respectively.

25], presented theoretical investigations for a hybrid ejector and R-744 vapor compression (VC) system for road transport cooling. They proposed to utilize the waste heat from the exhaust gas and the VC sub-system to drive the ejector system, whose cooling effect will be employed to sub-cool the VC sub-system. Preliminary experimental studies were carried out on a single ejector cycle using steam, with boiler temperatures between 115°C and 130°C, and evaporator temperatures between 5°C and 10°C. The results indicated that, for a given boiler temperature, an increase in evaporator temperature improves system performance and produces a higher critical condenser pressure. The nozzle exit position only had a small influence on the system performance. The utilization of exhaust heat from a vehicle engine combined with the heat from the VC sub-system in the hybrid system was demonstrated to reduce the VC

26] presented a review on the recent development in ejectors, applications of ejector refrigeration systems, and system performance enhancement. Subsequently, a novel ejector cascade refrigeration cycle was introduced by Yari

27], which utilized waste heat from the gas cooler to drive a supercritical R-744 power cycle.

9]. Ejector refrigeration systems that utilize low-grade energy source to produce cooling effect were summarized and modifications of R-744 transcritical refrigeration system were discussed. A thorough review about two-phase ejector used in vapor compression refrigeration and heat pump system was

28]. Ejector performance characteristics for subcritical and transcrtical

25] presented a detailed review on background and operating principles of ejector. The review paper covered various topics including selection of refrigerants used, mathematical and numerical simulation modelling,

29] reviewed various efficiency associated with ejector in various ejector systems, like solar driven ejector system and vapor compression systems. It was reported that ejector cycle efficiency is very much sensitive to the ejector efficiency. The effects of operating conditions, geometrical parameters and refrigerant characteristics on ejector efficiency were discussed.

2.4 Works on Ejector Geometry and Performance

An ejector expansion device consists of four parts namely motive nozzle, mixing chamber, constant area throat section, and a diffuser section. An ejector is considered as a promising expansion device, as it can be easily retrofitted, cost-effective, and also have no moving part. A compressible flow model based on control volume approach for a constant area ejector was

30]. Study revealed that increment in diffuser exit area increase both ejector and refrigeration efficiencies. System efficiency can also be improved by increasing the boiler or evaporator temperature or lowering the condenser temperature. A simulation based study of a LiBr-H2O based combined refrigeration cycle having an ejector and an absorption 31]. Constant pressure mixing ejector was integrated in absorption cycle to increase the refrigerant flow rate from the evaporator to increase the cooling effect. later, a solar powered combined ejector-vapor compression cycle was also proposed for 32]. The ejector cycle was operated with water while the vapor-compression cycle operated with R-134a. It was was observed that the combined cycle shows 50% higher efficiency than the conventional solar powered refrigeration system. An experimental study of controllable steam-ejector having movable primary nozzle of a 33] revealed that controllable ejector provides a more flexible operation than the fixed one. Further, an optimum primary nozzle position is limited to particular operating condition. It was reported that with the help of moving primary nozzle the COP and cooling capacity of the system can be varied as much as 100%. Use of ejector to enhance the concentration process by increasing the heat input and the flow of leaving vapor was suggested for single effect lithium bromide based absorption-recompression refrigeration 34].

35] reported experiments done on rectangular section convergent-divergent nozzle for the supersonic flow of R-744 with various divergence angles (0.076°, 0.153°, 0.306°, 0.612°). For a nozzle with a divergence angle greater than 0.306°, it was shown that the decompression curve above 35°C approached the curve predicted by the isentropic homogeneous equilibrium theory. For divergence angle smaller than 0.306°, the slope of the decompression 36] studied the effects of various pressure parameters on the entrainment ratio of an ejector used in the R-744 heat pump water heating system of 12 kW heating capacity. The theoretical study was based on a constant pressure model (described later) and the ejector was modeled using the gas dynamic approach. The model predictions for ejector operation were compared with experimental results. It was shown that an increase in the entrained flow pressure increases the entrainment ratio at constant primary flow. A decrease in the back pressure induces a corresponding improvement of the entrainment ratio up to a critical point. The primary flow pressure has a great effect on the entrainment ratio, further the entrainment ratio increases as primary flow pressure increases.

37], studied the effects of entrainment ratio of an ejector, heat rejection pressure, outlet gas cooler outlet temperature and evaporating temperature on the COP and exergy loss. They reported that the use of an ejector in place of the throttling valve; can reduce exergy loss by about 25% and increases COP by about 30%. The critical entrainment ratio of the ejector, optimal heat rejection pressure, and critical outlet temperature of the gas cooler 38],

investigated a two-phase ejector for R-744 air conditioning system. The ejector was designed and developed considering the non-equilibrium state for evaluating the sonic velocity and the critical mass flux. The experiments were performed concerning the variation of ejector geometry such as the motive nozzle throat diameter, mixing section diameter, and the distance between the motive nozzle and diffuser. They determined optimum design parameters in each test. It was demonstrated that the COP of the system using an ejector was about 15% higher than
39] studied the effects of various outdoor temperatures and inverter frequencies. The COPs of the system using an ejector and conventional system were computed and compared. The result showed that at the beginning of the compressor frequency increases, the recovered work also increases but then it starts decreasing after it reaches a particular frequency. Further when the gas cooler secondary fluid inlet temperature increases, for a range of 30°C to 40°C, the net COP decreases but it makes gas cooler pressure and work recovery to be higher.

2.5 Ejector Expansion Cycle Performance Enhancement

In this section, we briefly review how published literature has discussed about the ways in which the performance of a R-744 system can be enhanced with the help of extra components like multiple compressors, internal heat exchangers, multiple ejectors and using techniques like suction nozzle pressure drop.

2.5.1 Using multi compression system

A new configuration of the ejector expansion transcritical cycle having multi-stage compression
40]. Based on a simulation study, they reported that the new configuration has the potential to improve COP by up to 21% for certain operating condition. Further improvement was reported by introducing a multi intercooling system after the first stage
41]. The intercooler at the exit of first stage compression was supported with external coolant (air or water) while the second intercooler at the exit of the second stage compressor used system refrigerant for cooling. COP improvement reported was about 19.6% over ejector expansion R-744 transcritical refrigeration cycle (EETRC) with internal heat exchanger (IHX) and 15.3% over EETRC for a range of operating conditions. We call this configuration as the multi compressor multi-intercooler ejector expansion R-744 transcritical
42] investigated the impacts of cycle operational parameters such as gas cooler temperature, evaporator temperature, and gas cooler pressure, on the performance of a modified two-stage trans-critical R-744 refrigeration cycle, which contains internal heat exchanger, intercooler, ejector, and separator. Results showed that
43]

they introduced a second internal heat exchanger for multi inter-cooling. Results showed that the use of an internal heat exchanger increased both specific cooling capacity and specific work. They reintroduced a two-stage compression ejector cycle with multiple intercooling arrangements. They claimed that this arrangement further improves the efficiency of low-pressure compression systems.

2.5.2 Using internal heat exchangers

Several means to improve the performance have been explored from time to time. The use of internal heat exchanger (IHX) for sub-cooling and superheating is one other popular option 44 45 46 47] modeled an R-744 transcritical ejector refrigeration system along with an IHX. They also demonstrated that the use of an ejector with IHX significantly enhances the performance. They simulated the ejector system at various ejector mixing pressure and also obtained conditions for maximizing COP. In 48] reported experimental validation of their model. The prototype ejector was able to recover up to 14.5% of the throttling pressure losses for the test condition. The reported improvement in cooling capacity and COP were 8% and 7%, respectively. 49] simulated a two-stage compression ejector cycle. They claimed that the new cycle configuration gives 55.5% higher COP at particular operating condition (P_{gco}=9.5 MPa, T_{gco}=40°C, T_{evap}=10°C) compared to conventional transcritical refrigeration cycle (CTRC). 50] published a comprehensive report on the effect of mixing length on the performance of a two-phase ejector with and without IHX. They demonstrated that the use of IHX in the ejector expansion cycle has a net positive effect on system performance. COP improvement of up to 26% over the conventional system was claimed. They also showed that improper sizing of mixing length can lower the COP by as much as 10%. In another experiment, 51], a comparative study of performance for various lengths of IHX (0 to 60 cm) was reported. They concluded that efficiency improves with an increase in the length of IHX. 52] studied the effects of internal heat exchanger (IHX) on the entrainment ratio, pressure recovery, and ejector efficiency for the ejector expansion transcritical R-744 refrigeration cycles. They demonstrated that the addition of IHX in the R-744 ejector refrigeration cycle increases the ejector entrainment ratio and the ejector efficiency, and decreases pressure recovery under the same gas cooler pressures.

2.5.3 Using multi ejector systems

To fulfill the need for various refrigeration applications a system needs to be operated at multiple evaporation temperatures. Nowadays, multi evaporator systems are gaining interest as the same can support multiple evaporator temperature applications, for example, in supermarket operation.

To maintain different evaporator temperatures, the system needs to be operated at multiple 53] reported a simulation-based study on two novel multi evaporator transcritical refrigeration systems. The study shows that the system performance is highly dependent on the allocation of evaporator cooling capacities. The two proposed system configurations provide improvement in COP by 21.4% to 38.1% at optimum conditions for the studied range of operation.

54], proposed a novel transcritical R-744 refrigeration cycle with two ejectors that were able to recover more expansion loss, thus improving the system performance. Further simulated results showed that with the increase of entrainment ratio of the second ejector and decrease of entrainment ratio of the first ejector, the cooling capacity increases while COP decreases. For a wide range of evaporation temperature and gas cooler outlet temperature, the COP of the double-ejector cycle was reported to be higher than that of the basic R-744 cycle.

55 56] proposed a modified dual evaporator R-744 transcritical refrigeration cycle having a two-stage ejector. The simulation-based study successfully exhibited that the two-stage ejectors can improve system performance in terms of COP and exergy efficiency. Later they introduced another modification in the dual temperature R-744 transcritical refrigeration cycle by the addition of one internal heat exchanger upstream of the medium temperature evaporator. Energetic and exergetic investigations were carried out for the dual ejector cycle. It was reported that the cascade ejector cycle has higher COP and system exergy efficiency compared to the basic throttling device and basic ejector refrigeration cycle. The proposed system showed an overall improvement of 5.26 to 25.5% in COP, 9.0-28.7% in exergy efficiency, and 6.0-12.2% in pressure lift ratio compared to a single ejector refrigeration system. A two ejector system, as an expansion device for a two-stage transcritical R-744 heat 57]. The ejectors were placed at low and high-pressure stages to recover available expansion work. Through the simulation-based study, they reported higher heating COP and volumetric heating capacity of two ejector systems over the basic two-stage cycle.

2.5.4 Suction nozzle pressure drop

Suction nozzle pressure drop (SNPD) aids the flow of refrigerant from the evaporator exit to the ejector mixing chamber and is an important and sensitive parameter. However, very few reports are available dealing with the effect of SNPD variation on cycle performance. The majority of the 17] first took note of the effect of SNPD on cycle performance and reported performance variation at SNPDs 0.01 MPa, 0.03 MPa, and 0.05 MPa for an ejector expansion transcritical refrigeration cycle (EETRC). They concluded that the performance of an EETRC significantly improves with an increase in SNPD. In subsequent

58] reported that at certain operating conditions for an EETRC, SNPD of 0.347 MPa can achieve up to 30% higher COP over conventional R-744 transcritical refrigeration cycle (CTRC). They concluded that with an increase in pressure drop, the ejector 59] suggested an approach of computing total pressure drop resulting from friction, acceleration, and gravitational causes in the ejector. For a particular operating condition (T_{gco}=40°C, P_{gco}=10 MPa, T_{evap}=5°C) they assumed a high value of 0.1 MPa as the suction nozzle pressure drop. 10 60], suggested a lower value of 61] reported effects of pressure drop within range 0.019 MPa to 2.32 MPa on a constant area mixing model of EETRC. They concluded that the optimum value of SNPD that ensures a higher overall COP increase with an increase in both T_{gco} and T_{evap} for a fixed gas cooler pressure and nozzle efficiency. Zhang 62] investigated the effects of SNPD for EETRC. Through a simulation-based study, they reported that both COP and pressure recovery are sensitive to SNPD and concluded that the value of the optimum SNPD mainly depends on the efficiencies of the motive nozzle and the suction nozzle. SNPD is independent of evaporating temperature and gas cooler outlet temperature. The optimized SNPD reported by them was 0.3 MPa for the stated operating conditions. They also reported that SNPD doesn't influence the entrainment ratio much.

2.6 Computational Fluid Dynamics Based Investigations

A significant amount of simulation based work has been performed on ejectors which are used in CO_2 based supercritical refrigeration systems for work recovery. Here we divide the CFD based works according to the flow aspect considered by the work like single phase flow modeling, turbulence modeling, phase change modeling, accuracy of the equation of state used etc.

2.6.1 CFD based studies on single phase flow through ejectors

Various simulations based works have been performed on the prediction of shock train structure, mixing and entrainment processes inside the different sections of an ejector. Here we briefly 63] concluded that an increase in the diameter of the constant area mixing section increases the performance of the ejector only when a shock wave exists in the diffuser section. In order to maximize the entrainment, they suggested that the motive to outlet pressure ratio should be such that the secondary flow remains choked and the shock in the diffuser section disappears. Using the real fluid properties for R142b from the REFPROP database, 64] simulated a supersonic ejector for refrigeration applications. They showed that the fluid entrainment mainly occurs in the converging secondary nozzle followed by a re-compression in the mixing section. They also observed that the presence of strong shocks at the secondary nozzle exit suppresses the mixing between the fluid streams and leads to flow 65] studied the single phase flow of an ideal gas inside an ejector with axisymmetric and full three dimensional geometries. They observed similar flow patterns with the axisymmetric and 3D simulations and concluded 66] investigated the effect of the motive nozzle outlet shape on the mixing process occurring inside a steam ejector. They observed that the nozzle shape decides the strength of the spanwise and the streamwise vortices and interaction between these governs the ejector's entrainment ratio and 67] observed that in the subcritical operating regime, the ejector's primary nozzle is over-expanded causing a slender train of oblique shocks inside the mixing section. The distance between the shocks increased with increasing primary nozzle pressure value. Under critical conditions, the primary nozzle flow became under-expanded with a thick shock train which gets reflected from the mixing section walls causing boundary layer separation and secondary flow choking. Sierra-Pallares 68] identified the fluctuating viscous dissipation as the main mechanism for entropy generation inside the mixing chamber of a R134a ejector. They also concluded that the physical nature of compression process inside the ejector due to a shock train is similar to that occurring 69] found that two parameters are most important for maximizing the ejector performance, namely, the distance of the motive nozzle from the mixing section and the diameter of the mixing section. The motive nozzle distance decides the location of the shock wave which in turn governs the entrainment ratio while the mixing section diameter decides the amount of pressure boost achieved.

2.6.2 CFD based studies on the accuracy of turbulence models

Another highly investigated topics among the numerical simulations is finding the most suitable turbulence model for accurately predicting the flow field inside the ejectors. Here we briefly 70 71] numerically analyzed the performance of various turbulence models for predicting the shock strength, position and their interaction with the boundary layers for supersonic flow inside an ejector. They observed that the RNG and $k - \Omega$ SST turbulence models perform the best for predicting the shock strength and location but none of the models predict the expansion process correctly. They attributed this under-prediction to the vapor condensation occurring inside 67] observed that the RNG $k - \epsilon$ turbulence model based mass flow rate and shock structure match better with the experimental data. Mazzelli et al. 72] investigated the accuracy of various turbulence models for supersonic flow of air through an ejector. They concluded that the various turbulence models investigated, namely the $k - \epsilon$, the $k - \epsilon$ Realizable, the $k - \Omega$ SST and the Reynolds Stress model, are equally effective for computing the mass flow rates and entrainment ratio but the $k-\Omega$ SST model performed the best. They further concluded that three dimensional computational domains must be used for accurately predicting the various physical quantities of interest under off-design conditions. 73] who found that the the $k-\Omega$ SST model performs the best for predicting the global and local flow features inside supersonic 74 75] found that the CFD simulations with $k-\Omega$ SST turbulence model and thermophysical properties from NIST REFPROP offer the most accurate results with respect to entrainment ratio for single phase flow of R134a inside an ejector. For outlet pressure values greater than a critical one, they observed that the oblique shocks dissipate most of the motive stream energy, thus reducing the entrainment ratio drastically. They further conducted an exergy analysis of the ejector which shows that almost 85% of the exergy loss is concentrated in the region next to motive nozzle.

2.6.3 CFD based studies on modeling the phase change process

76] expressed the heat conduction term in the energy equation in terms of enthalpy, which combined with the pressure was used to track the two phases under the homogeneous equilibrium approach. The need to solve an extra equation for tracking the volume fraction of the phases gets eliminated due to this. They observed a maximum discrepancy of around 20% in the computed mass flow rates through the 77] analysed the entropy generation inside a two phase CO_2 ejector based on the homogeneous equilibrium model. They concluded that the oblique shock train and flow turbulence contributed most towards the entropy generation inside the ejector's mixer and diffuser sections. The entropy generation was found to be minimum at a 78] investigated the accuracy of homogeneous equilibrium method (HEM) for two phase flow through an ejector geometry. They concluded that the HEM model gives accurate results for operating conditions near and above the fluid critical point. The accuracy of the results decreased as the non-equilibrium effects become dominant when the temperature of the motive fluid was decreased (the inlet state point became nearer to the 79] used genetic and evolutionary algorithm based techniques to optimize the efficiency of a two phase ejector used in a CO_2 based refrigeration system. The dimensions (diameter and length) of the mixing section of the ejector were varied in order to maximize the efficiency. The homogeneous equilibrium method was used for computing the two phase flow inside the ejector. It was observed that the diameter of the mixing section of the ejector strongly affects the ejector efficiency. Using the homogeneous equilibrium method, 80] compared the efficiency of fixed and variable geometry type ejectors. It was found that the fixed geometry ejector is more efficient compared to the variable geometry type over the entire range of operating conditions. The efficiency of the variable geometry ejector (needle controlled variable throat area) passed through a maxima with a decrease in the motive nozzle throat area.

81] compared the accuracy of the homogeneous equilibrium model (HEM) and homogeneous relaxation model (HRM) based phase change approaches with experimental data on mass flow rates through an ejector. It was observed that both the phase change models predicted inaccurate mass flow rates for operating conditions far from the critical point. The HEM approach was found to be more accurate for operating conditions above the critical point. For pressure and temperature values lower than those at the critical point, the accuracy gained by the use of HRM approach was found to be lower than expected, hinting that a better relaxation time formulation is required. With respect to the distribution of phases at the outlet of the motive nozzle, the HEM approach predicted lower amount of condensed phase for different 82] investigated the effect of variation in the relaxation time parameters on the distribution of pressure, velocity and vapor quality inside an ejector. It was observed that an increase in the value of the coefficient θ_0 decreased the quality and the pressure inside the diverging portion of the motive nozzle. It also strongly influenced the shock formation and the flow process inside the mixing zone. They further optimized the relaxation time parameters using genetic algorithm so that the errors in the motive and suction mass flow rates are minimized for operating conditions typical for the supermarket refrigeration systems. The computed motive nozzle mass flow rate values were most 83] modelled the one dimensional two phase flow of CO_2 through an ejector motive nozzle using homogeneous relaxation approach. They claimed that the proposed model has better consistency compared to 84] simulated the compressible two phase flow of CO_2 inside an ejector. The vapor phase was taken as the continuous phase while the liquid phase was the dispersed phase. The various thermodynamic properties of CO_2 85]. The pressure distribution within the mixing and the diffuser sections was predicted well but a larger difference between the experimental and numerical results was observed for other flow quantities.

86] compared the heterogeneous and homogeneous models for the transonic, two-phase flow of CO_2 through an ejector. In the heterogeneous model, an additional governing equation for the mass fraction of the gas phase was solved along with the Rayleigh-Plesset equation for the phase change process. It was concluded that the results from the heterogeneous approach are in better agreement with the experimental data. Based on the open source CFD 87 88] simulated the condensing two phase flow of CO_2 inside an ejector. The fluid was assumed to be in a thermodynamic non-equilibrium state and a modified homogeneous relaxation method was used for the phase change process. They observed that most of the turbulent mixing occurs in the ejector's mixing section with a thermodynamically equilibrated flow in the diffuser section. They conclude that the turbulence model presents the greatest challenge for predicting the pressure recovery related data. Using Ansys Fluent, Yazdani 89] studied the phase change process inside a supersonic ejector using cavitation based (inertia controlled) and boiling based (heat transfer controlled) phase change mechanisms. It was observed that the cavitation based phase change process dominates near the wall whereas the boiling based phase change occurs in the core of the motive nozzle's diverging portion. It was further observed that a mild shock in the mixing section (just before the diffuser) improved the pressure rise in the diffuser. They further investigated the effect of mixing section diameter on the pressure, Mach number and liquid mass fraction distribution. Assuming thermodynamic and 76] studied the transonic two phase flow of R744 inside an ejector using an enthalpy based formulation. They demonstrated the robustness of the enthalpy based approach compared to the mixture models for two phase flows. They also highlighted the need for full three dimensional simulations for accurately predicting the flow field inside an ejector compared to the axisymmetric formulations used in the previous studies.

87 90] performed numerical simulations of an ejector flow which was operated with or without the suction, entraining mass flows. The phase change was modelled based on the homogeneous equilibrium approach. The numerical simulations predicted the driving mass flux within an error margin of 10% for the input data range investigated. The pressure recovery inside the ejector without a suction flow was predicted within an error bound 91] numerically studied the supersonic, two phase flow of CO_2 inside a converging-diverging nozzle using the Ansys Fluent flow solver. They focused particularly on the flow development and shock wave interactions inside and at the exit of the supersonic nozzle. The numerical setup used the real gas properties of CO_2 and incorporated a two-phase sonic velocity model along with the mass and energy transfer between the phases based on a finite-rate phase change process. They observed that the flow inside the nozzle choked downstream of the minimum throat area location because of the non-equilibrium effects and due to the delayed phase change process. The phase change was found to be maximum near the boundaries while the Mach number was observed to be maximum in the interior region. The shock-boundary layer interaction produced a 'shock train' where regions of subsonic and supersonic flow were observed adjacent to each other. Mazzelli et 92] implemented a custom wet steam model in Ansys Fluent with a modified formulation for nucleation rate and droplet growth law including non-isothermal correction. They observed up to 20% liquid fraction distribution inside the mixing section with the mixture temperature attaining values lower than the triple point hinting at the possibility of ice formation. Giacomelli 93] compared the performance of the HEM and the mixture model for predicting the flow field inside a flashing CO_2 ejector. They observed that the HEM is faster and more robust while the mixture model is more accurate for predicting mass flow rates and entrainment ratios

but prone to divergence. They also conclude that the mixture model requires fine tuning of evaporation / condensation related coefficients.

2.6.4 CFD based works on the accuracy of equation of state

94] investigated the accuracy of various equations of state and the resolution of real gas property tables for flow inside supercritical radial compressors and turbines. For near critical inlet states, they observed that the Span and Wagner equation gives the most accurate results among the different equations used such as the ideal gas, Peng Robinson, and Soave-Redlich-Kwong equations of state. They further presented the computational time duration required for obtaining steady state solutions for different sizes of real gas property

95] compared the simulation based results on flow of supercritical CO_2 through a converging–diverging nozzle with the experimental data provided by Nakagawa et

96]. The thermophysical properties of CO_2 in the metastable state were obtained using a bilinear extrapolation of the saturation state data. They observed that the flow becomes supersonic in the converging part of the nozzle just before the throat. They also highlighted the need to clip the critical radius of the nucleating droplets to around a nanometer. In absence of clipping, the critical radius achieves a maximum value of one millimeter due to the very small

97]

experimentally investigated the metastable behaviour of CO_2 during its high speed expansion inside a Laval nozzle at high pressure conditions. They obtained the Wilson line with the help of optical visualization and laser interferometry based techniques with input pressure values varying between 41 and 82 bar, including states near the critical point. It was also observed that the computational data obtained with an extrapolated Span and Wagner equation of state agree within 2% of the experimentally observed values. Further, they experimentally determined the condensation free inlet conditions to a supercritical compressor resulting in a 16% reduction

98] investigated the accuracy of numerical results on the flow of CO_2 through a centrifugal compressor for different sizes of real gas property (RGP) table. They compared the CFD based distribution of entropy and density values over a surface

99] as a function of temperature and pressure values over the same surface. They concluded that, although, the errors in the simulated results decrease as the resolution of the RGP table increases, it also induces instability in the CFD solution procedure. This was due to the high sensitivity of the flow behaviour to changes in the thermophysical properties which have a steep variation near

100] equation of state for CO_2 in REFPROP was not able to accurately predict the variation of thermophysical properties near the critical point. They also demonstrated the possibility of phase change at the leading edge of the compressor blade where the thermodynamic state lies in the sub-critical region.

2.6.5 CFD based investigations on the condensation of steam

101 102], the droplet nucleation and growth based condensation model has been widely used for studying phase change of steam inside nozzles and turbine cascades. Here we summarize only the recent simulation based works related to 103] implemented the five-equation and the seven-equation models for two phase flow in an in-house CFD code for modelling steam condensation. The homogeneous nucleation model was used for droplet nucleation and growth. The models correctly predicted the location of condensation onset but the five-equation model under predicted the droplet size 104] used the steam condensation model in Ansys Fluent to study the phase change process of steam inside the Moses and Stein nozzle. They observed a maximum vapor supercooling of around 33 K inside the nozzle. The droplet nucleation process was found to be concentrated in a very small portion of the nozzle across which the number density of the droplets increased rapidly. The maximum liquid 105] implemented a non-equilibrium wet steam model in an in-house CFD code and investigated the condensation of steam inside the Moore, Moses and Stein nozzles and inside a turbine blade cascade. A maximum discrepancy of 8% was observed in the numerical results compared to the experimental ones. 106] compared several simulation based works on steam condensation inside different nozzles and found significant scatter in the simulation data about the experimental values. They also concluded that the classical nucleation theory based simulations give the most accurate results when the non-isothermal effects are accounted for in the simulations. Dykas et 107] performed experiments on steam condensation inside a linear blade cascade followed by numerical simulations inside a similar geometry using the non-equilibrium phase change solver in Ansys CFX and an in-house CFD code. The flow field predicted by the two solvers matched satisfactorily with the experimental data, the biggest discrepancies were observed with respect 108] found that the use of vapor phase temperature for evaluating the surface tension coefficient between the two phases gives more accurate results. By default, Ansys CFX uses the liquid phase temperature for calculating the physical properties relevant to the nucleation process.

2.7 Summary and Gap Areas

2.1 2.2 that the majority of works reported in the ejector expansion trans-critical R-744 refrigeration system are at low-temperature ranges. However, a few works are also reported for temperature up to 47°C. In India, the ambient temperature goes above 40°C for some months. The experimental investigation for ejector R-744 transcritical refrigeration application for such high-temperature zones is not available. Literature survey also point out that

Table 2.1: Experimental test conditions used for ejector expander R-744 transcritical systems studied in literature

Reference	Motive Nozzle Inlet Pressure (P_m)	Motive Nozzle Inlet Temperature (T_m)	Suction Nozzle Inlet Pressure (P_s)	Suction Nozzle Inlet Temperature (T_s)
Liu and Groll 18]	12.85 MPa	50.88°C	3.748 MPa	21.63°C
19]	9.75-14.15 MPa	27.8, 35, 40°C	3.829 MPa	22.34°C
20]	10 MPa	27.8, 35, 37.8°C	3.829 MPa	22.34°C
Nakagawa et 35]	6-9 MPa	20-37°C	N.A.	N.A.
Nakagawa et 51]	9.5-10.5 MPa	41-44°C	N.A.	2,4,6,8°C
Nakagawa et 50]	9.5-10.5 MPa	42-47°C	N.A.	0°C
Banasiak et al. 109]	8.0-11.5 MPa	30°C	3.55 MPa	N.A.
38]	9.3 MPa	N.A.	4.3 MPa	0°C
Seung et al. 39]	15 MPa	30,35,45°C	4-5 MPa	N.A.
Lucas and 23]	7-11 MPa	30,35,40°C	N.A.	N.A.

performance of ejector system is sensitive to operating temperature. Further due to trans-critical nature of R-744 cycle operation at high ambient condition, the response is distinctly different 6]. Further, to explore possible COP improvement strategies, understanding of complex flow phenomenon of high pressure compressed R-744 inside ejector and beginning of condensation of two-phase flow is also required. Hence, there is requirement of in-depth study of ejector expansion R-744 trans-critical refrigeration application at higher temperatures.

2.8 Objectives of the Thesis

Refrigeration and air conditioning address fundamental human requirements in fields like food conservation, health care, and thermal comfort worldwide. Major research is currently focused on improving the cycle efficiency of natural refrigerants as they have much lower GWP and ODP. Ejector expansion R-744 transcritical cycle emerges as a promising refrigeration cycle using natural refrigerant. The pertinent literature review reported significant advances in the research on the use of ejectors in R744 transcritical systems that occurred mainly in the last decade. The literature review has also shown that the majority of works reported in the ejector

TABLE 2.2: Simulation Test Conditions used for ejector expander R-744 transcritical system in the available literature

Reference	**Ambient Temperature** (T_o)	**Motive Nozzle Inlet Pressure** (P_m)	**Motive Nozzle Inlet Temperature** (T_m)	**Suction Nozzle Inlet Pressure** (P_s)	**Suction Nozzle Inlet Temperature** (T_s)
Li and 17]	N.A.	10 MPa	40°C	N.A.	5°C
Liu and 21]	N.A.	8-14 MPa	40-60°C	2.5-5 MPa	15-26°C
Yari and Sirousazar 49]	27°C	8-14 MPa	40-50°C	N.A.	-30 to 5°C
40]	27°C	8-12 MPa	35-55°C	N.A.	-30 to 5°C
Fangtian and Yitai 37]	30°C	9 MPa	40°C	4 MPa	5°C
Hafner et al. 110]	N.A.	11 MPa	35°C	3.8 MPa	5°C
Cen et al. 54]	N.A.	10 MPa	40°C	N.A.	5°C
Lucas et al. 23]	N.A.	7.5-10.5 MPa	30-40°C	2.6, 3.4 MPa	N.A.
Lucas et al. 24]	N.A.	7-11 MPa	30-40°C	2.5, 3.5 MPa	N.A.
Ahammad 10]	N.A.	9.5-11 MPa	30-45°C	3.643-3.658 MPa	2°C
Goodarzi and Gheibi 42]	27°C	7.5-14 MPa	35-55°C	N.A.	-30 to 5°C
Goodarzi et 43]	27°C	8-12 MPa	36-44°C	N.A.	-30 to 5°C

expansion trans-critical R744 refrigeration system are at low-temperature ranges. However, a few works are also reported for temperatures up to 47° C. The ambient temperature in many highly populated cities in India goes above 45°C during summer months. The literature survey also points out that the performance of the ejector system is sensitive to the operating temperature. Further due to the transcritical nature of the R744 at high ambient temperature conditions, the system response is distinctly different from the low-temperature operation. Hence, there is a requirement of an in-depth study of the ejector expansion R-744 transcritical refrigeration application at higher temperatures.

Moreover, an ejector is the most important equipment inside any transcritical R-744 cycle. The phase change process and the entrainment of secondary fluid from the motive nozzle fundamentally govern the operation of the ejector which in turn affects the overall cycle efficiency.

Numerical simulation of the phase change process of R-744 will provide further insight into ways of improving the efficiency of the ejector. The homogeneous equilibrium and the homogeneous relaxation models have been widely used by investigators for ejector study. The use of classical nucleation theory based non-equilibrium solver can provide information on the supercooling levels, droplet diameter and number density distribution inside the ejector and can further improve the design of the device.

Based on the review of the relevant literature and existing research gap, the major objectives of the present study are as follows:

- Simulate various ejector expansion R-744 transcritical refrigeration system configurations.
- Investigate of working of an ejector expansion device and suggest a suitable control strategy.
- To identify the most suitable ejector system architecture for the Indian climate condition, including the study of both economic and environmental aspects.
- Develop and validate a CFD model that can simulate the phase change process of R-744 inside nozzles and ejectors with real gas thermophysical properties from NIST Refprop.
- The CFD model should give information on the non-equilibrium effects present inside the ejector and on the droplet size and droplet number density present in the condensation fog inside the ejector.
- Identification of the section inside the ejector which contribute most to the condensation of R-744.

The objectives can be summarized with the help of the following figure:

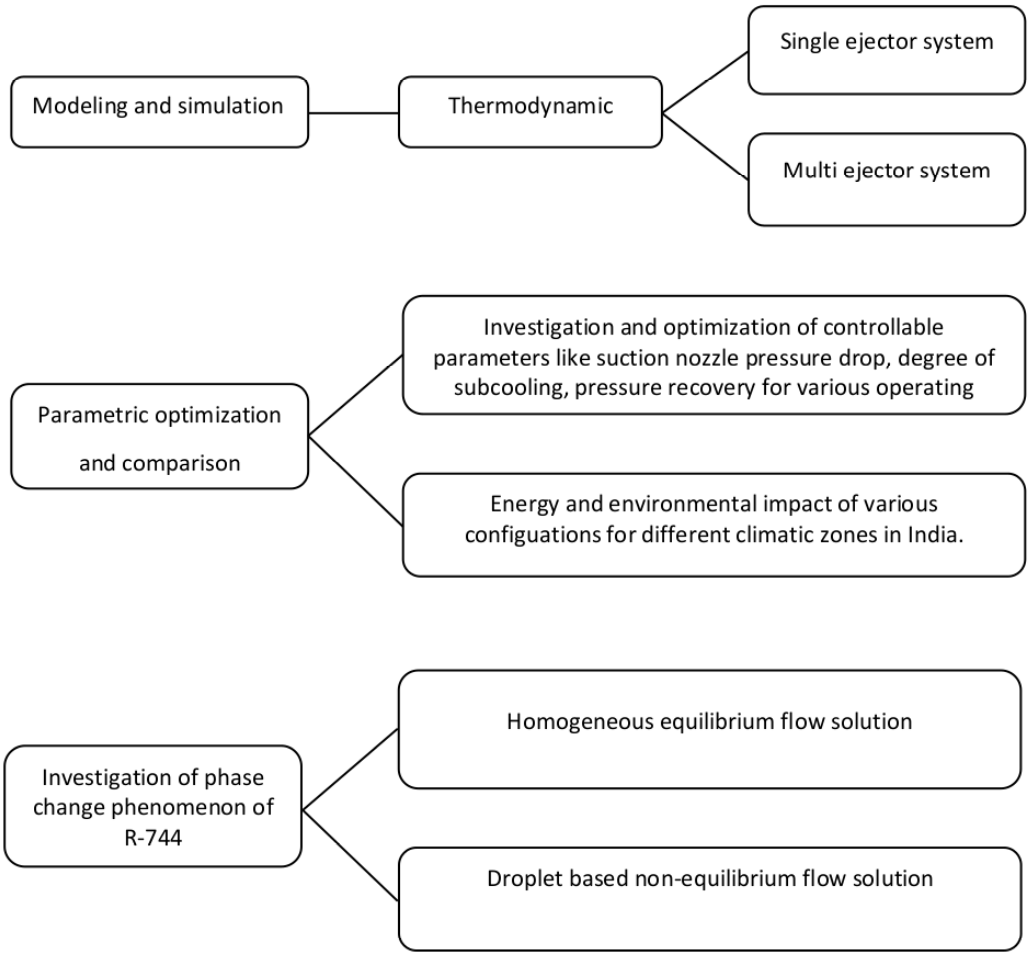

Figure 2.1: Flow chart representing the thesis objectives.