Chapter 1

Introduction

This chapter presents the background and the motivation of this research work. A brief history of CO_2 as a refrigerant (R-744) and the challenges faced during its exploitation at high ambient temperature conditions are presented. It also discusses the emergence of ejector as a prominent solution for mitigating the expansion losses during the throttling process in transcritical R-744 refrigeration system, especially for warm ambient conditions.

1.1 Background and Motivation

Greater demand for cooling is being realized worldwide due to urbanization, economic growth and also due to rise in average global temperatures owing to climate change. It is estimated that the electricity consumption in refrigeration, air-conditioning and heat pump systems will rise to 33% of total electricity consumption by 2100. International energy agency has forecast that the demand of air conditioners will surge from 1.5 billion to 5.5 billion units globally while the number of domestic refrigerators would be doubled to more than 2 billion units between 2015 to 2050 (United Nations Environment Programme 2018). According to a report (ICAP 2019), nationwide cooling energy demand in India will increase 2.2 times while the same in terms of tonnage of refrigeration is expected to surge by 3.1 times by 2027 over the baseline year 2017.

In refrigeration and space cooling applications, vapor-compression systems are generally utilized to accomplish cooling by transferring thermal energy from lower temperature source to a higher 1.1) shows the aggregate cooling energy consumption and emission in various sectors of HVAC. In India, the total energy consumption for cooling is expected to rise from 59.8 MToe to 131.9 MToe while the annual carbon emission is forecast to surge from

1]). Further, within the HVAC sector, vapor compression cycle is estimated to have consumed 83.7 TWh in year 2017-18 which was 62% of the total energy consumption in HVAC sector of about 135 TWh. The consumption is projected to 444.6 TWh nationwide, which will be 76% of total space cooling energy consumption of 585 TWh in year 2037-38 (ICAP 2019). It implies that systems based on vapor compression cycle will play significant role in overall energy consumption in HVAC sector and also will have increasing share in carbon emission.

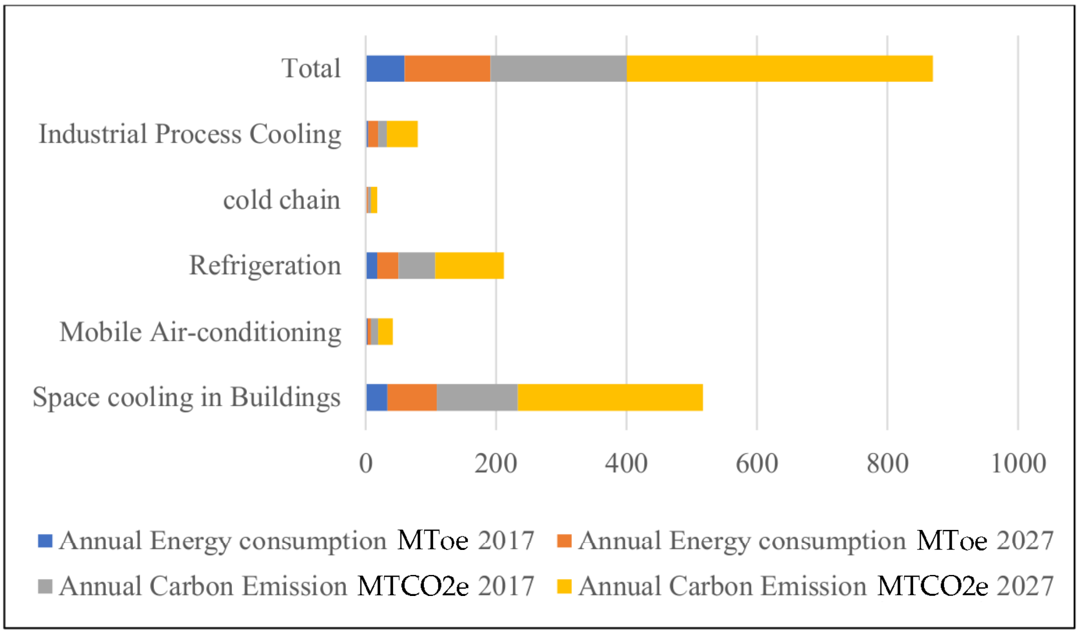


FIGURE 1.1: Annual energy consumption and annual carbon emission in 2017 and 2027 (Kumar 1]).

1.2) presents a simple vapor compression system and its corresponding temperature-entropy diagram. The vapor-compression systems utilize Evan-Perkins cycle which is also called as a reverse-Rankine cycle, that comprises of four thermodynamic processes: isentropic compression; isobaric heat rejection; isenthalpic expansion and isobaric heat addition process. The work input is given to the system during process 1-2, the work is lost during process 3-4. Due to the irreversible nature of the isenthalpic expansion process, the cyclic work input is more than that in the reversed Carnot cycle. The difference is highlighted as area A_2 in the $T-s$ 1.2). In the $T-s$ diagram, area A_2 represents the lost work due to the expansion process. Commonly, expansion valves and capillary tubes are used as expansion devices in the vapor compression systems as they are low-cost, easy to retrofit and do not have moving parts. Ideal operation of these devices are isenthalpic. However, if the expansion process undergoes in a device that operate isentropically, area A_2 1.2) would be recovered leading to an improvement in the performance and a reduction in the exergy losses . Work recovery expanders have been used to improve the performance of vapor compression systems. In such expanders, refrigerant from the higher pressure level expands in a turbine kind of arrangement

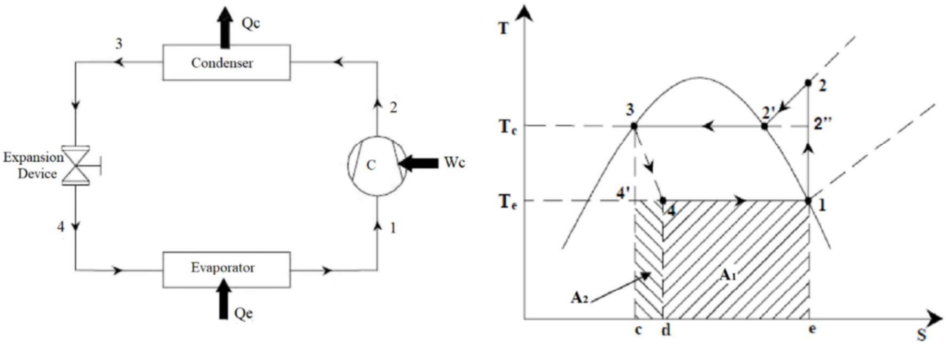


FIGURE 1.2: Schematic of vapor compression cycle and respective T-S diagram in comparison to Carnot cycle.

and the mechanical work produced reduces the net work input to the system. Additionally, by extracting the refrigerant enthalpy, lower enthalpy fluid is available at the expander exit to improve the cooling capacity of the evaporator contributing to the overall system COP. However, due to presence of rotating parts, expanders are complex in construction, expensive, prone to frequent maintenance and noisy during operation. Further, a proper utilization of the extracted work is challenging.

An ejector is static device which utilizes the kinetic energy of the expanding, high pressure fluid to obtain a drop in temperature instead of extracting the mechanical work. The kinetic energy is used to partially compress a saturated secondary fluid leaving from the evaporator, leading to enhanced enthalpy and reduced compressor load. Ejectors are emerging as an acceptable solution as these have simple construction, are easy to retrofit, have no moving parts and the flow is controllable. Ejector also creates a suction effect on the secondary fluid which helps the evaporator to have a higher refrigerant mass flow rate. Exploration of the use of ejectors in place of conventional expansion devices at higher ambient temperatures is the motivation of this thesis.

1.2 Basic R-744 refrigeration cycle

1.3). The processes in the cycle occur in the following sequence: The refrigerant evaporation (4-1) takes place in the evaporator at sub-critical pressures like conventional vapor compression refrigeration cycles. The saturated vapour then undergoes compression (1-2) in compressor. Owing to the low critical temperature of CO_2 of 31.3° C, heat rejection must take place at supercritical pressures (2-3) when the ambient temperature is high. Thus, in high ambient operation, the cycle operates partly sub-critical (low pressure side) and partly super-critical (high pressure side). In super-critical heat rejection, no saturation point exists, consequently, the gas cooler pressure is independent of the refrigerant temperature at the gas cooler exit (state 3). The throttling valve inlet condition determines the specific refrigeration effect, as the refrigerant expands from super-critical pressure to sub-critical pressure during expansion process (3-4).

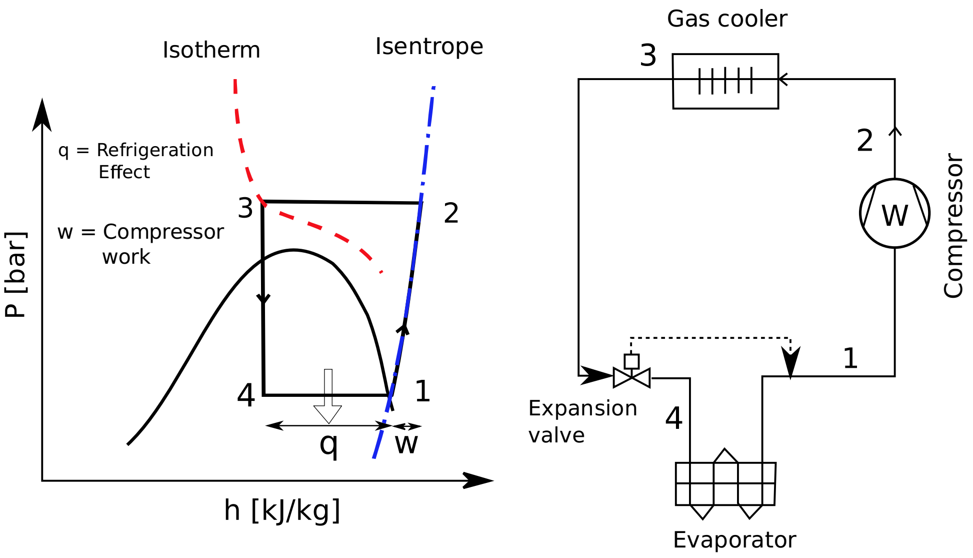


Figure 1.3: $P - h$ chart representation and schematic of the basic R-744 refrigeration cycle.

1.3 History of refrigerants and emergence of CO_2 as a refrigerant

Refrigerants used in vapor compression systems are broadly classified into natural and synthetic fluids. At the advent of refrigeration systems, people used commonly occurring natural substances like air, water, CO_2, NH_3, hydrocarbons as refrigerants. Synthetic refrigerants were introduced later and they contain man-made chemicals which include chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), Hydrofluorocarbons (HFCs) and Hydrofluorolefins (HFOs). The synthetic refrigerants thrived and pushed the natural refrigerants to almost extinction due to their superior thermal properties, higher performance, better stability and wider range of applicability. Synthetic refrigerants were also actively promoted by business houses for interests in profit making. Later, synthetic refrigerants were found to have serious adverse effect on the environment as many of them contribute to depletion of the ozone layer. Another set of synthetic refrigerants were found to contribute highly to the global warming and were soon regulated. CFCs were banned under the Montreal Protocol (1987) while HCFs were scheduled to be phase out by 2020-2030 and HFCs by 2025-2040 under the Kyoto Protocol (1997). Awareness about ozone depletion, global warming, water and soil contamination potential of the synthetic refrigerants forced the scientific community to favor natural refrigerants. A brief 1.4) Carbon dioxide as a refrigerant has been used quite extensively in the past, a British patent was filed

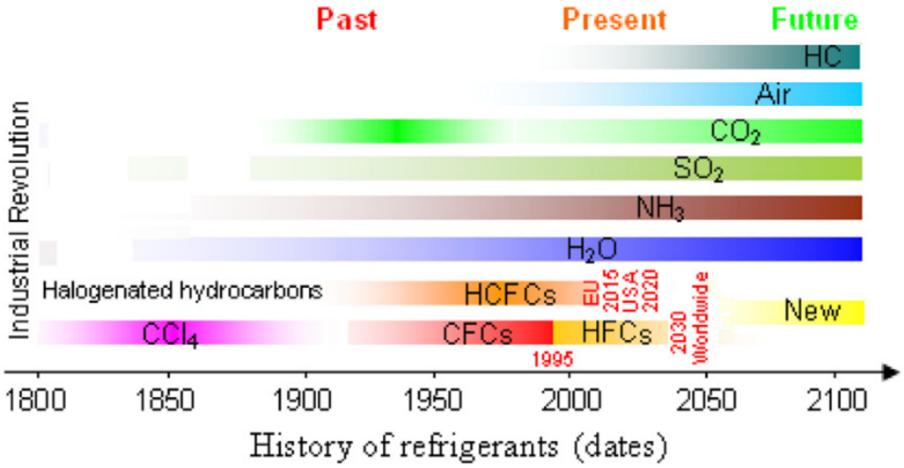
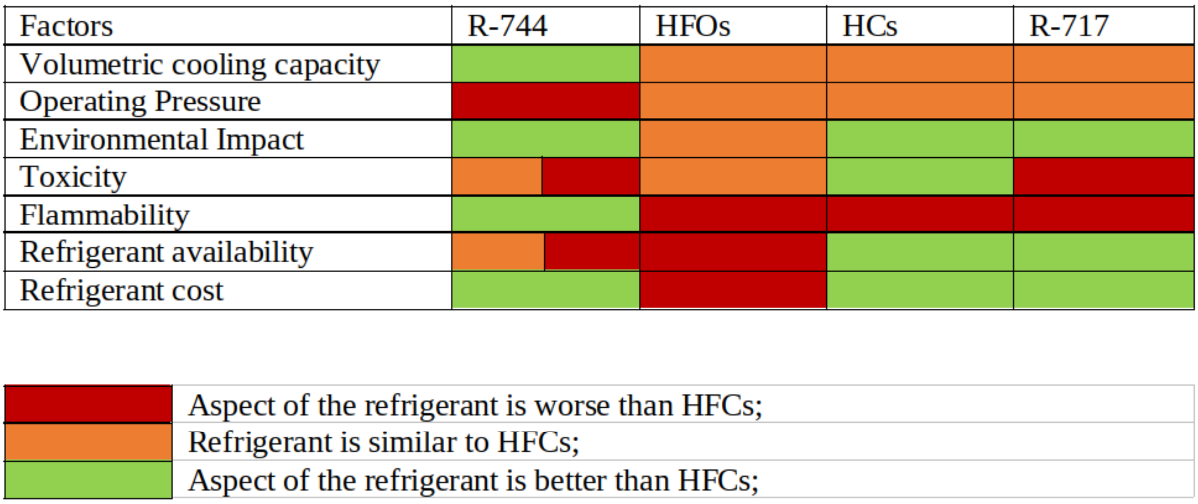


FIGURE 1.4: 2]).

by Alexander Twining in 1850 (Padalkar and Kadam 2010). CO_2 gained so much popularity during 1930s that around 80% of all the refrigeration applications at that time were CO_2 based. 3], CO_2 is an ideal refrigerant as it is completely benevolent to the environment, inexpensive, safe and hold excellent heat transfer characteristics. By using the special properties of CO_2, the transcritical operation makes it possible to adapt to the increasing heating, air conditioning and refrigeration demand. Presently, mobile air conditioning, heating, and cooling in food / dairy processing industries and supermarket refrigeration are the prominent application of CO_2 1.5) presents a comparison of the various properties of CO_2 with those of other commercially available refrigerants. CO_2 based systems have relatively higher volumetric capacity; CO_2 is cheaper, environment-friendly, non-toxic, and non-flammable. However, the refrigerant has a lower value of latent heat and the main limitation of CO_2 based refrigeration systems is the extremely high operating pressures required for high ambient temperature operation. Few points of interest and drawbacks of CO_2 as a refrigerant



Factors	R-744	HFOs	HCs	R-717
Volumetric cooling capacity	🟩	🟧	🟧	🟧
Operating Pressure	🟥	🟧	🟧	🟧
Environmental Impact	🟩	🟧	🟩	🟩
Toxicity	🟧🟥	🟧	🟩	🟥
Flammability	🟩	🟥	🟥	🟥
Refrigerant availability	🟧🟥	🟥	🟩	🟩
Refrigerant cost	🟩	🟥	🟩	🟩

🟥	Aspect of the refrigerant is worse than HFCs;
🟧	Refrigerant is similar to HFCs;
🟩	Aspect of the refrigerant is better than HFCs;

FIGURE 1.5: Comparison of CO_2 4].

are listed below:

- CO_2 being a natural substance, have zero ODP and unit GWP. It is non-combustible and non-poisonous. However, high concentration accumulation at a place can give rise to asphyxiation for any life form.
- CO_2 has higher cooling capacity which leads to higher refrigerating capacity.
- It has higher heat transfer coefficient.
- It is noncorrosive with most of the metallic structural materials leading to a longer operational life.
- Due to the performance degradation at high ambient temperature conditions, its usage is restricted in tropical regions.

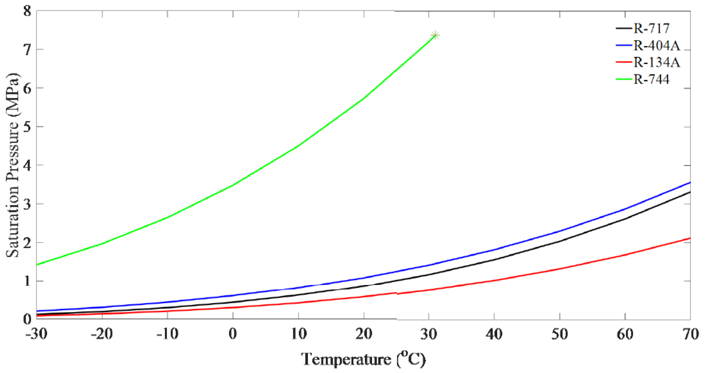
In the following, we refer CO_2 with its technical name which is R-744.

1.4 Challenges in R-744 at high ambient

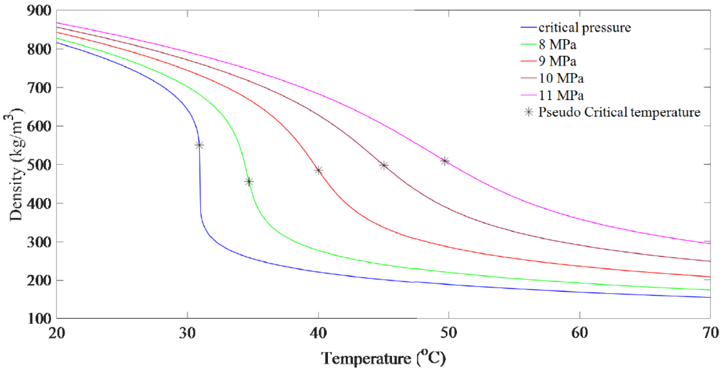
Operating pressure in R-744 systems is considerably higher than that in other refrigeration 1.6A). The behavior of important thermophysical properties like density, thermal conductivity, dynamic viscosity, and Prandtl number for a temperature range 1.6B 1.7 5]). It can be observed that thermophysical properties have a rapidly changing nature near the pseudo critical temperature. It can be seen from the R-744 property charts that at higher ambient temperature conditions, the R-744 properties like density, dynamic viscosity, thermal conductivity and Prandtl number have rapidly decreasing nature. In order to have higher heat transfer, R-744 needs to be operated above the critical pressure under higher temperature conditions. Generally, isenthalpic process based throttling devices such as expansion valves, capillary tubes are used to bring down the refrigerant from higher side pressure to the lower side pressure. Isenthalpic expansion process in the R-744 system implies higher work consumption by the compression device and lower cooling capacity of the evaporator. It makes the role of R-744 as a refrigerant significantly challenging under high ambient temperature conditions.

1.5 Mitigation of Challenge with Ejector Expansion

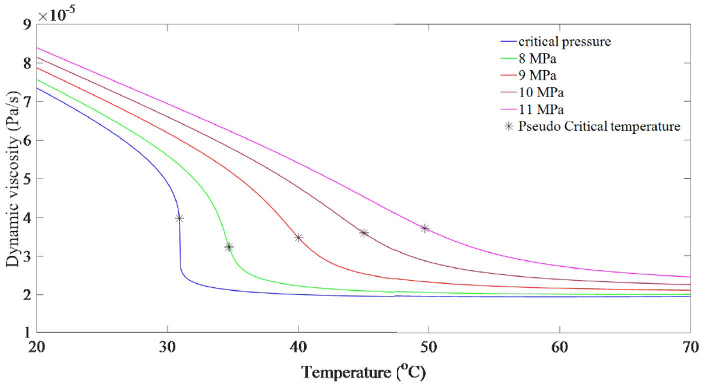
The use of R-744 for refrigeration purposes has motivated new cycle configurations as well as better component design to enhance the system performance. R-744 refrigeration systems



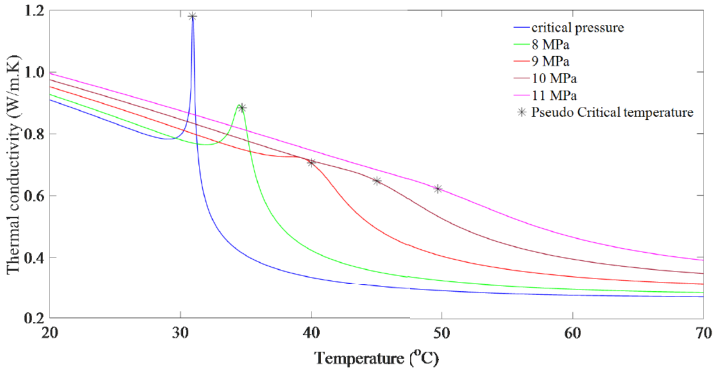
(A) Saturation pressure of R-744 and other refrigerants.



(B) Density profile.



(C) Viscosity profile.



(D) Thermal conductivity profile.

FIGURE 1.6: Variation of different thermophysical properties of R-744 in the supercritical region calculated using NIST Refprop.

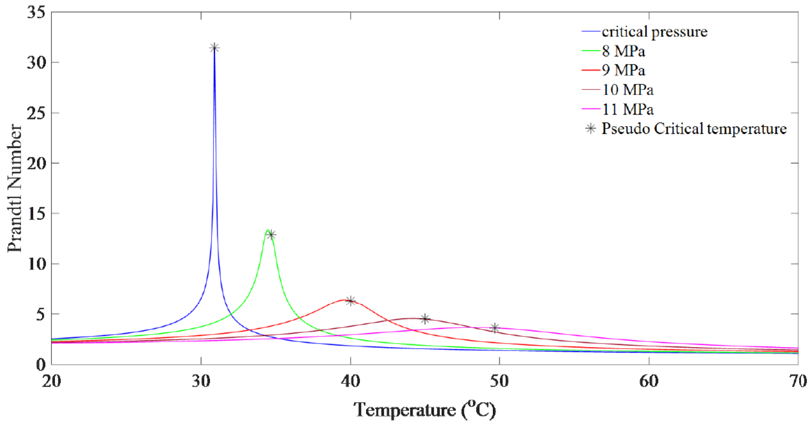


FIGURE 1.7: Prandtl number profile of R-744 in supercritical region based on NIST Refprop.

operate in the transcritical mode in warm climates which implies higher compressor work as 6]. Further, the higher irreversibility associated with the isenthalpic expansion process from the supercritical to the subcritical condition leads to poorer 7]. To reduce the large exergy loss associated with the throttling process, various two-phase, ejector expansion devices have been proposed. Ejector was first introduced in 1859 by Henry Giffard as a condensing-type injector for pumping liquid water to the reservoir of steam engine boilers. Later, a patent was filed for its use in refrigeration 8]. Since then, ejectors have been studied extensively for a 9

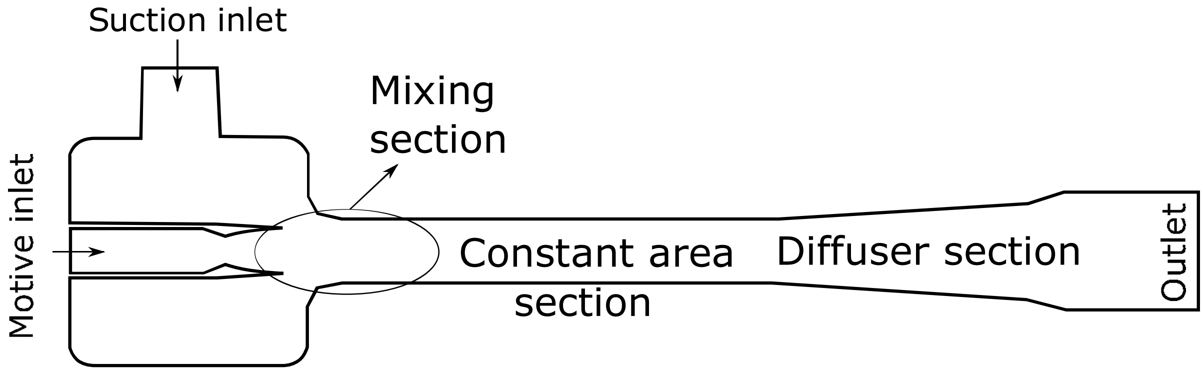


FIGURE 1.8: Schematic of an ejector expansion device.

1.8). High-pressure primary fluid expands and accelerates through the primary nozzle and is called as the motive stream. It goes out, generally at supersonic speeds, to create a very low pressure region in the mixing chamber. The high-velocity primary stream draws and entrains the secondary fluid through the secondary (suction stream) nozzle into the mixing section. The combined streams are assumed to be completely mixed at the exit of the mixing section and the flow speed may remain supersonic. A normal shock wave or an oblique shock train is produced within the constant-area section, creating a compression effect. As a result, the flow speed is reduced to subsonic. Further compression of the fluid is achieved as the combined streams flow through the subsonic diffuser section. The pressure of the mixed stream increases while passing through the diffuser. Thus, the ejector expansion system recovers kinetic energy loss by converting the kinetic energy into a pressure boost. Therefore, it results in an improvement in the overall COP of the refrigeration system. High ambient temperature operation of the R-744 refrigeration cycle at a higher pressure in the transcritical mode provides higher pressure recovery with the use of ejector, resulting in a better cycle performance. However, the ejector performance and coefficient of performance are sensitive to the various ejector operating parameters.

1.6 Structure of the Thesis

In this thesis, an attempt is made to identify the possible cycle / system modifications and optimize the ejector parameters for a particular operation. Further, Computational fluid dynamics based study of the ejector operation is performed for a better understanding of the phase change phenomenon inside the device. This thesis is organized as follows:

1 summarizes the use of ejectors for expansion work recovery in transcritical R-744 cycles. R-744 is introduced as a natural refrigerant and its properties are presented. Further, challenges associated with R-744 at high ambient temperature conditions and mitigation of these challenges with ejector expansion is explained.

2 presents a detailed review of the relevant literature on the R-744 transcritical refrigeration systems, application of ejectors in early refrigeration applications and expansion work recovery. Performance enhancement measures for the ejector expansion R-744 systems are reviewed and the research gap areas are identified. This chapter finally discusses the objectives of the current work.

3 describes the various thermodynamic models for the different R-744 ejector expansion based cycles. Modeling is done for both the single and the multi-ejector systems. Further R-744 ejector expansions are simulated for year-round operation in high ambient temperature conditions in India with suitable control strategy based on energy and environmental impact.

4 discusses the equations which govern the mass, momentum and energy conservation equations for a compressible fluid. The equations for the compressible phase change process of a vapor based on the equilibrium and non-equilibrium formulations are also identified.

5 discusses the phase change process of R-744 inside converging-diverging nozzles. The aim of the chapter is to validate the numerical setup by performing simulations of R-744 condensation inside geometries for which experimental data is available in literature.

6 discusses the phase change process of R-744 inside an ejector geometry based on the validated numerical setup. The aim of this chapter is to get an idea about the distribution of various physical quantities like the vapor Mach number, vapor supercooling, nucleation rate, droplet diameter, droplet number density and liquid mass fraction inside the ejector geometry.

7 presents the overall summary, conclusions from this thesis and the scope for the future work.