Chapter 7

Conclusions based on this thesis work

This chapter summarizes the important findings from the work performed in this thesis. First we summarize the conclusions from the thermodynamic modeling of various ejector based transcritical R-744 cycles. Afterwards, we present the conclusions from the CFD based work. Finally, we present the unresolved issues and the scope for future work.

7.1 Main conclusions from the thermodynamic modeling work

The main conclusions from the thermodynamic modeling work are as follows:

- The performance of the MCEETRC with supercritical R-744 power cycle is found better than other cycles for all evaporator temperatures. In comparison to MCMIEETRC, it is found favorable for lower evaporator temperature. With an increase in evaporator temperature, COP for all cycle configurations increase but gas cooler outlet temperature has an opposite effect on COP irrespective of cycle configuration.
- The pressure recovery is higher in cycle configurations without IHX compared with cycle configurations having IHX. The pressure recovery is also found to be maximum at lower gas cooler pressure irrespective of the evaporator temperature. The entrainment ratio decreases while the vapor quality increases with an increase in gas cooler outlet temperature.
- The highest exergy output is found for the MCEETRC with supercritical CO2 power cycle. The total exergy destruction rate is found highest for the EETRC+IHX. Second law

efficiency is also found highest for the MCEETRC with supercritical CO2 power cycle and the same is found lowest for the EETRC+IHX.

- The importance of SNPD is identified towards the enhancement of system performance in terms of parameters like COP and pressure recovery. The system performance is found to be very sensitive to SNPD at lower gas cooler outlet temperature. A significant variation of ejector efficiency is observed with SNPD; the ejector efficiency is higher at higher gas cooler outlet pressure. Changes in pressure recovery and ejector efficiency are found insignificant with variation in gas cooler exit pressure and SNPD for a wide range of evaporator temperatures. For stated operating conditions, optimized SNPD is determined to be 0.18 MPa, potentially resulting in an increment in COP by about 4.95%. COP of EETRC+IHX is found to be very sensitive to the degree of sub-cooling at lower gas cooler pressure. With an increase in the degree of sub-cooling, pressure recovery and ejector exit vapor quality are found to decrease whereas entrainment ratio and ejector efficiency are found to increase. EETRC+IHX shows almost 50% less component exergy destruction compared to CTRC+IHX. The slope of the exergy destruction line is less steep in EETRC+IHX implying less exergy destruction at higher gas cooler exit pressure.

- For year-round operation in subcritical mode (below 24° C ambient), the heat rejection pressure is found substantially lower. EETRC configuration using the suggested control strategy is found comparable with other studied configurations. In transcritical mode, the requisite overall system mass flow rate for a constant cooling load is found lowest for MCEETRC+IHX. While the same is found comparable for other proposed configurations EETRC and EETRC+IHX. In transcritical operational mode, the configuration MCEETRC+IHX shows significantly lower energy consumption followed by MCMIEETRC, EETRC, and EETRC+IHX configurations. In terms of optimum operating pressure, EETRC+IHX configuration has the lowest operating pressure for the entire range of operation.

- MCEETRC+IHX shows the highest COP among all the ejector systems for operation up to 40° C. While for operation at ambient greater than 40°C, the relative advantage of MCEETRC+IHX is somewhat lost and the performance is found comparable to MCMIEETRC. For overall year-round operation, MCMIEETRC and EETRC+IHX configurations are found comparable for the weather condition of arid and semi-arid regions. While for weather conditions of tropical wet, tropical wet and dry, and humid subtropical regions, all three configurations (MCMIEETRC and EETRC+IHX and EETRC) are found to have comparable performance. By analyzing the various ejector systems based on energy and environmental point of view, it is concluded that the MCEETRC+IHX system consumes the lowest energy annually followed by EETRC, MCMIEETRC, and EETRC+IHX. In terms of environmental consideration, the MCEETRC+IHX system is found to have the lowest TEWI followed by EETRC, MCMIEETRC, and MCEETRC+IHX. Among the selected cities, the annual energy consumption and TEWI are one of the highest for the weather condition of the tropical wet region followed by tropical wet and dry region, while the same is found lowest for the humid tropical region.

- Modified dual ejector R-744 refrigeration system has 4.7% to 7.6% higher COP in comparison to conventional dual ejector R-744 refrigeration system. The pressure recovery ratio decreases whereas the entrainment ratio increases with an increase in both gas cooler exit pressure and evaporator temperature for both MDERC and DERC. The WRE in MDERC has 85% lesser exergy destruction in comparison to Exp 2 used in DERC. The exergy efficiency of MDERC is about 3.9% to 5.2% higher than DERC.

- Effect of evaporator temperature and gas cooler exit temperature on parameters like COP, pressure recovery ratio, and entrainment ratio is found to have a similar trend for both R-744 and R-744A systems. R-744A systems show better performance in terms of system COP and lower discharge pressure. For the selected operating conditions, R-744A systems hold an advantage of 6.08% to 16.6% in COP compared to its counterpart R-744 system configurations. R-744 based both single and multi-ejector systems show better cycle performance at higher gas cooler exit pressure while the systems based on R-744A have better cycle performance at lower gas cooler exit pressure. R-744 based systems have higher volumetric cooling capacity compared to its similar R-744A system configurations. Further, R-744 based systems have an overall higher-pressure recovery ratio while the entrainment ratios are observed to attain lower values than R-744A systems for the full range of gas cooler exit pressure and evaporator temperature. Lastly, exergy output for both single ejector and multi ejector configurations of R-744A are found 2.51% to 6.56% higher than R-744 system configurations.

7.2 Main conclusions from the CFD modeling work

The main conclusions from the CFD modeling work are as follows:

- The equilibrium solver is robust and behaves well with the Refprop based thermophysical data for R-744 in tabular form and gives more accurate results with respect to prediction of pressure distribution in the nozzles. The results with the Span-Wagner equation of state are observed to be better than those obtained with the Redlich-Kwong equation of state.

- The droplets based non-equilibrium solver faces convergence issues with real gas property (RGP) data generated based on NIST Refprop even with time steps as low as 10^{-9} second. The solver behaves well with cubic equations of state like the Redlich Kwong equation of state already available in CFX. The extreme values of thermophysical properties near the critical point are responsible for the convergence problem.

- The solver needs thermodynamic data from the metastable states for simulating non-equilibrium conditions which prevail during high speed flows. The non-equilibrium solver also requires fine tuning of several 'expert parameters' for obtaining correct results.
- Converged results could easily be obtained for the flow of R-744 through the Claudio Lettieri nozzle and the Gyarmathy nozzle. Convergence was not obtained for the flow of supercritical R-744 through the Berana nozzle. The reasons could be the nozzle geometry which is very narrow and just one millimeter thick. There is a pressure difference of 55 bar across the nozzle length which is around 35 mm. Most importantly, the inlet state is supercritical (90 bar, 318 K) for the nozzle, the critical state occurs somewhere near the throat and extreme variation of thermophysical properties of R-744 near the critical point do not allow convergence.
- Based on the CFD based investigations, we observe that a very high nucleation rate ($\sim 10^{33}$ nucleation per m^3 per second) is concentrated in a narrow portion of the nozzle just before the throat region. Droplets nucleated in this region are advected downstream in the nozzle / ejector by the vapor where these grow in size. A droplet size of 10^{-8} m and droplet number density of 10^{23} droplets per m^3 prevail in the motive, mixing and diffuser sections of the ejector. A maximum liquid mass fraction of around 0.24 inside the motive nozzle is predicted by the solvers. A maximum supercooling level of 1.1 K is observed inside the ejector.
- Overall, we conclude that Ansys CFX is capable of simulating compressible, high speed phase change problems with acceptable accuracy which depends on several factors, among which, the use of real gas property database is the most important one.

7.3 Future scope of the work

The ejector has been applied to large-scale R-744 refrigeration and air-conditioning applications such as in the field of the supermarket because of the complex nature of its operation. Further, in a large-scale application, high-pressure operation of R-744 can be handled by providing appropriate material strength. In small scale applications (such as vending machines, domestic refrigerators) the role of ejector will be challenging. A more simplified control strategy is needed to gain practical advantages in small scale real applications. Additionally, the investigation of low-pressure refrigerants in a lower temperature cycle in a multi ejector system is needed to exploit better ejector efficiencies. It will be interesting to identify the ejector performance for different profiles of motive nozzle tip. Further investigations on the optimum motive tip location with different nozzle cross-sectional area can be carried out. Lastly, new and innovative multi-ejector R-744 systems are desirable for mobile applications to preserve various perishable commodities in warm weather conditions.

The following CFD related points need further investigation. The most important parameter for the phase change process under non-equilibrium conditions is the droplet critical radius. Only droplets having size greater than the critical radius can grow in size, others will evaporate back to vapor. It simultaneously governs both the maximum supercooling in the domain as well as the amount of liquid phase condensed from the vapor. The role played by this parameter in Ansys CFX needs further investigation. The cases where thermodynamic state inside the nozzle / ejector lies near the critical point are difficult to converge. This is due to the spike in the thermophysical properties of R-744 at the critical point. The spike in properties also governs the time step taken by the solver for stable computations. A systematic study needs to be conducted on the effect of maximum allowed value of a thermophysical property at the critical point on the time step required for stable computations and accuracy of the simulation based results. The compressible phase change simulations are computationally expensive. Ansys CFX takes time steps of the order of 10^{-9} second during the phase change process. Other solvers, like the Eulerian-Eulerian model available in Ansys Fluent, can be tested and used if found better in terms of accuracy and performance. An in-house compressible flow code can also be developed for further insight into the process. Finally, an optimization based study can be performed for finding the most efficient ejector geometry.