## ABSTRACT

To safeguard the environment, it would be prudent to use technologies that are eco-friendly and energy efficient. Ozone layer depletion and global warming phenomena caused by synthetic refrigerants have brought about an increasing interest in technologies based on ecologically safe natural refrigerants instead of continuing search for new chemicals. Carbon dioxide is one such natural refrigerant that, although is old and was abandoned earlier due to the invention and vigorous promotion of synthetic refrigerants, has been revived recently as a potential candidate due to its environmental and personal safety features. This has led to subsequent development of transcritical carbon dioxide cycles where the condenser gets replaced by a gas cooler. Use of a gas cooler, with heat rejection taking place over an unusually large temperature glide, offers several unique possibilities such as simultaneous refrigeration and heating, heat pump drying, etc. Along with eco-friendliness, $CO_2$ based vapor compression systems have various advantages over conventional systems such as, compatibility with normal lubricants and common machine construction materials, non-flammability and non-toxicity, greatly reduced compression ratio, easy availability, high volumetric refrigerant capacity, and excellent heat transfer properties. Unique possibility in simultaneous cooling and heating applications along with various advantages are the main motivating factors behind the present research work.

The main objective of this research work was to carry out theoretical and experimental studies on $CO_2$ heat pumps for simultaneous cooling and heating applications. A high precision property code was developed initially based on recently reported correlations. The transcritical $CO_2$ cycle has been analyzed to optimize the performance. Analyses of the optimum condition indicate that a system meant for low or moderate temperature heating is more economical not only due to high COP but due to lower optimum discharge pressure (low operating pressure ratio) as well. Expressions for optimum cycle parameters have been developed and these correlations offer useful guidelines for optimal system design. Effects of several cycle modifications such as

internal heat exchange, multi-staging, use of expansion turbine and ejector-expander device on optimum condition, have been studied. Results show that multi-staging has more significant effect than other modifications. The simulation code of $CO_2$ heat pump for simultaneous water cooling and heating applications including heat transfer and fluid flow effects in each component has been developed and the energetic and exergetic performances with different operating parameters at optimum discharge pressure have been obtained. Gas cooler to evaporator heat transfer area ratio has been optimized as well. A nomogram suitable for optimum design has been presented. Exergy flow diagram has been presented and techniques to reduce the irreversibility for various components, which yield improved system exergetic efficiency, have been suggested. The expansion valve contributes a significant amount of exergy loss here whereas it is negligible for a conventional system. Replacement of expansion valve with a turbine will increase the COP as well as the exergetic efficiency significantly, but it will also raise issues related to cost, design and dynamic balancing of the system. Detailed exergetic analyses of the gas cooler and evaporator of $CO_2$ heat pumps have been studied to obtain optimum sets of diameter, length and tube passes for given operating conditions and capacity, to get minimum total irreversibility associated with operational (thermal, pressure drop), material and manufacturing stages. Although the effect of pressure drop on the irreversibility can be neglected for higher diameter, it is quite significant for smaller diameter tubes. Such exergetic optimization exercise is expected to help design the optimal heat exchanger for a given capacity and the operating parameters.

The thermodynamic comparison of R744 with R134a and R22 has been carried out for heat pump drying applications, which showed that R744 exhibits better performance than R134a whereas it performs poorer compared to R22. Then a simulation model of $CO_2$ heat pump dryer including heat and mass transfer, and pressure drop in each component has been developed and validated with experimental data available in the literature and shown fairly good agreement. Finally, effects of different operating parameters such as bypass air ratio (BAR), ambient temperature and relative humidity, dryer efficiency (DE), recirculation air ratio (RAR) and air mass flow rate on COP, MER and SMER have been investigated. Results show that unlike BAR and ambient relative humidity, the effects of DE, RAR, ambient temperature and air mass flow rate are significant on system behavior.

A fully instrumented prototype of $CO_2$ heat pump for simultaneous water cooling and heating has been developed and tested. The gas cooler pressure has been successfully controlled by simultaneously controlling the total mass of the system and degree of opening of expansion device. Uncertainty analyses show that the test data is fairly good. Results of transient analysis and performance with different operating conditions (water mass flow rates and inlet temperatures, pressures, valve opening, etc.) have been presented. The valve opening has significant effect near the valve closing condition. Effect of water mass flow rates is not significant for both evaporator and gas cooler, whereas the effect of water inlet temperature to gas cooler on the system performance is significant. Compressor performance results have been presented as well. Recently available correlations for heat transfer and pressure drop, used in the theoretical analyses, have been validated by test data obtained from the experiments and showed reasonable agreement for both gas cooler and evaporator. Comparison between test results and simulation model prediction has been presented as well and shows reasonable agreement and the trends are fairly similar. Finally based on the theoretical and experimental work, several conclusions have been drawn and recommendations have been made for future studies.