ABSTRACT

Combined cooling, heating and power (CCHP) systems or trigeneration systems that run on renewable energy sources such as solar, biomass etc. find many commercial, rural and industrial applications. In the past, several systems based on a variety of system configurations have been suggested to provide all these three outputs simultaneously. Almost all the systems suggested can be viewed as integration of co-generative power and refrigeration cycles using different working fluids for power cycle and refrigeration cycle. Though these cycles offer many advantages, they are complex due to the number of sub-systems and components involved. The system complexity, and possibly the initial cost of the system itself, can be reduced considerably, if a single cycle `based on a single working fluid can be devised that can provide cooling, heating and power simultaneously using solar or other renewable heat sources.

In recent years, there is growing interest in using CO_2 directly in concentrated solar collectors due to its favourable thermo-physical properties. Solar thermal collectors based on supercritical CO_2 that can operate at very high pressures and temperatures are under development. Thus further simplification of the CCHP cycle is possible, if CO_2 can be used both as process fluid of CCHP system and thermic fluid of solar thermal system. Since solar energy is inherently unsteady, an auxiliary heat source based on other renewable energy such as biofuels can support the CCHP cycle to provide steady output. Further, at times it is also possible to produce excess power, cooling and heating and store them in appropriate form to meet peripheral requirements. Such stand-alone systems may be attractive in applications that always require cooling, heating and power simultaneously. A dairy farm is one such industry which requires cooling for milk chilling, heating for pasteurization and power to meet auxiliary requirements like lighting, fans, comfort-cooling etc.

In this thesis, two CCHP configurations (one with throttle valve and another with ejector in the refrigeration loop) relevant to dairy application are investigated based on thermodynamic cycle analysis and solar thermal heat transfer analysis. A parametric analysis using Engineering Equation Solver (EES) software is also presented for two configurations (Throttle Valve based & Ejector based) in order to understand their behaviour under various operating conditions of pressure and temperature. Expressions for COP, 2nd law efficiency, Specific Net Power Output (SNP) and

Specific Milk Flow Rate (SMF) are developed and studied parametrically to predict the CCHP system behaviour at various process conditions under certain constraints. It is observed that both the Overall COP and 2nd law efficiency of solar assisted transcritical CO_2 based CCHP systems vary predominantly with change in ambient temperature and cycle medium pressure compared to cycle maximum temperature and cycle high pressure. The cycle medium pressure should be low for higher specific net power output (SNP). Further, higher ambient temperature is detrimental in terms of overall COP and Specific Milk Flow Rate (SMF), but is beneficial in terms of Specific Net Power Output (SNP). It is also observed that cycle high pressure and cycle maximum temperature affect the COP and Specific Net Power Output (SNP) favorably. In addition, higher values of turbine inlet temperature and pressure ratio across the turbine are required if the need is electrical power. Replacing the throttle valve with an ejector results in higher net power output for the same operating conditions and milk flow rates. Based on these thermodynamic studies, it is possible to tune the solar assisted CCHP system to meet the requirements of milk processing customers, without any dependence on electrical power grid.

A suitability study of various heat transfer fluids (HTF's) for high temperature solar thermal systems is also presented in the thesis. Five HTF's namely Therminol VP1, Dowtherm Q, Hitec XL, Helium (He) and Carbon Dioxide (CO_2) are chosen for the analysis. Among the gaseous fluids, CO_2 is being considered for solar assisted cogeneration and trigeneration applications. This is because of the fact that CO_2 can function in supercritical state (s-CO_2) at temperatures near ambient temperature (t_{cric}=31.1 ^{0} C) and can be used both as process fluid and heat transfer fluid. Performance of different heat transfer fluids is compared taking supercritical CO_2 at 150 bar as the reference fluid. Suitable expressions are developed for obtaining design parameters of solar absorber tube (diameter ratio, length ratio, area ratio) and performance parameters (heat transfer coefficient ratio, heat transfer fluid inventory cost ratio, pumping power ratio, Figure of merit (FOM) ratio) in terms of fluid properties. It is observed that at higher temperatures, the pumping power required for gases is higher than liquid fluids. In terms of FOM, for CO_2 the effect of operating pressure is marginal at higher temperature ranges. In terms of fluid inventory cost, CO_2 is at least an order of magnitude smaller compared to other fluids, thereby making it a viable and eco-friendly option for large solar fields.

A detailed thermal study has also been carried out on a parabolic trough solar collector (PTSC) using s-CO_2 as the heat transfer fluid. A simulation model has been developed in EES for analysing the effect of inlet temperature and mass flow rate of s-CO_2 on thermal efficiency, heat transfer coefficient and thermal loss of solar collector. Results show that thermal efficiency, heat transfer coefficient and thermal loss are sensitive to change in temperature rather than change in pressure.

Finally, a performance study on solar assistance for the proposed throttle valve based CCHP system at two locations in India (Mumbai & Ahmedabad) on May 21 and December 21 (representing extreme weather conditions) is also carried out, taking into consideration the variation of incident angle modifier (IAM) from *9 am to 5 pm*. The solar tracking mode considered for this study is Tracking Mode 2. For this mode, focal axis is E-W and horizontal. The collector is rotated about a horizontal E-W axis and adjusted continuously so that the solar beam makes the minimum angle of incidence with the aperture plane at all times. The effect of variation in Dry bulb temperature and Direct Normal Irradiance (DNI) on useful heat gain by the solar collector field (series, parallel and combination of series and parallel) is analysed using the heat transfer model developed in EES. Solar Multiple representing ratio of maximum available solar power from the collector field to the required value by the power block, is estimated at various timings on May 21 & December 21 at both the locations. This is used to suggest additional heating requirement using auxiliary sources (such as biomass) whenever required.

Finally, a summary of all the above studies is presented along with important conclusions/contributions and recommendations for future development of solar assisted CO_2 based CCHP system.

Keywords: CCHP, Trigeneration, Parabolic Trough Solar Collector, Supercritical CO_2, Dairy Plant, Milk Pasteurization & Chilling, Heat Transfer fluid