Abstract

Thesis Title: Investigation on Direct Steam Generation in Parabolic Trough Solar Collector

A parabolic trough solar collector (PTSC) used for direct steam generation (DSG) has the potential to bring down the levelized cost of electricity (LCOE) by performance improvement and reduction in capital cost. However, the application of DSG in PTSC for solar thermal power generation is in the nascent stage and needs improvement in the components of PTSC and process control mechanisms. The DSG process comprises preheating, evaporation, and superheating of steam in the solar collectors. The DSG using PTSC is facing thermal-hydraulic instability and controllability issues in its commercialization. The modeling and simulation of DSG are challenging because of the complexities associated with the boiling phase change in the evaporation section. In view of this, an attempt has been made for the thermal-hydraulic investigation of DSG in PTSC. Further, the structural stability analysis of the absorber tube of PTSC has been performed for DSG.

The Eulerian two-fluid modeling approach, coupled with the mass transfer and critical heat flux boiling models, has been used to model the DSG process in a three-dimensional (3-D) computational domain. Interfacial interactions, such as mass, momentum, and energy exchanges between liquid and vapor, have been modeled using appropriate empirical correlations.

The thermal-hydraulic study has been performed for DSG in a 12 m long single module of PTSC. The analysis has been performed for both uniform and non-uniform concentrating solar flux profiles around the absorber surface at solar noontime with direct normal irradiance (DNI) of 750 W/m^2. Further, the effect of inlet mass flow rates (0.3 kg/s to 0.6 kg/s) and operating pressures (30 bar to 100 bar) have been investigated. It has been observed that the vapor volume

fraction at the outlet varies between 0.3 to 0.6, and the flow pattern is stratified flow under the subjected boundary conditions. The vapor volume fraction at the outlet decreases with an increase in the operating pressure. The absorber's outer surface temperature varies in the range of 517 K to 639 K under uniform heat flux conditions and 511 K to 603 K under non-uniform heat flux conditions. The maximum circumferential temperature difference in the absorber is 77 K under uniform heat flux conditions and 16 K under non-uniform heat flux conditions. The circumferential temperature difference and pressure loss decrease with an increase in the operating pressure.

The characteristics of the concentrating solar flux profile on the absorber tube continuously vary from morning to evening because of the apparent motion of the sun and tracking of the solar collector. It results in the shifting of a non-uniform flux profile on the absorber surface that induces a high-temperature gradient in the absorber. The study has been performed to investigate the impact of concentrating solar flux profiles corresponding to various solar times of the day. It has been observed that absorber wall temperature varies between 550 K to 638 K from morning to evening for a DNI of 750 W/m^2. If the DNI increases to 1000 W/m^2, absorber wall temperature varies between 550 K to 656 K. The maximum circumferential temperature differences at DNI of 750 W/m^2 are 60 K and 51 K, respectively, at 60 bar and 100 bar operating pressures. Similarly, when DNI increases to 1000 W/m^2, the maximum circumferential temperature differences are 79 K and 69 K, respectively, at 60 bar and 100 bar operating pressures.

The modeling of all three zones of PTSC row privileges identifying the critical process conditions leading to thermal-hydraulic instabilities in the DSG solar field and is beneficial for the engineering design of components forming the DSG solar field. In view of this, a study has been performed for thermal-hydraulic investigation of DSG in a 500 m long row of PTSC. It has been observed that the maximum absorber temperature is reduced by 27% at 60 bar and

20% at 100 bar operating pressure when the inlet mass flow rate increases from 0.4 kg/s to 0.6 kg/s. Similarly, the maximum circumferential temperature difference reduces by 12% and 14%, respectively. Moreover, the fluid temperature, steam quality, absorber temperature distributions, fluid velocity, and pressure loss have been summarized.

The conventional absorber tubes (inner surface is smooth) suffer from thermal instability due to a high non-uniform temperature gradient. The absorber's configuration affects the capability of collection and extraction of heat from the receiver. The absorber's thermal performance could be improved by introducing circumferential grooves etched at the inner surface. In view of this, a thermal-hydraulic investigation of a grooved absorber has been performed and compared with the conventional absorber. It has been observed that the maximum absorber temperature is reduced by up to 6 K with the grooved absorber. Simultaneously, the circumferential temperature difference is reduced by 2 to 3 K. Further, the pressure loss in the grooved absorber is increased by up to 8 times as compared to the conventional smooth absorber.

The absorber tube is a key component of a PTSC, and the bending of the absorber has an important role in receiver failures. The detailed survey of existing commercial PTSC power plants reveals that 55% of failures happened due to the rupture of glass envelope and 29% due to the loss in annulus vacuum. In view of this, coupled thermal-hydraulic and structural stability analyses have been performed to understand the thermo-structural performance of absorber tubes. The deflection in the absorber is maximum in the superheating section, followed by preheating section and evaporation section. The maximum deflection in the absorber at 60 bar and 100 bar operating pressures are 17.1 mm and 16.3 mm, respectively, which are at an inlet mass flow rate of 0.4 kg/s. Simultaneously, there may be a thermal expansion of up to 23.22 mm and 25.37 mm at 60 bar and 100 bar operating pressure, respectively.

In summary, the study presents a detailed thermal-hydraulic investigation of DSG in parabolic trough solar collectors using the Eulerian two-fluid modeling approach because it offers more accurate results as compared to the homogeneous equilibrium modeling approach. The thermal-hydraulic impacts of several influencing parameters, such as mass flow rate, operating pressure, DNI, absorber configuration, and concentrating solar flux profiles, have been investigated. The deep insight observations of the thermal-hydraulic behavior of the DSG process are presented under realistic operating conditions and are useful for the configuration of the DSG solar field for optimum performance. Further, the obtained results could be employed for the engineering design of the receiver of PTSC and the development of the DSG technology.