Development of a solar thermal energy harnessing system for engineering applications

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P. D. C. Kumara

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Abstract

This research study reports the development process of the first parabolic trough solar thermal power plant in Sri Lanka. The power plant consists of a parabolic trough concentrator (PTC) module with parabolic reflectors (with dimensions 4.5 m × 4.8 m) constructed with 3M 1100 reflective solar mirror films pasted on stainless steel sheets and mounted on unplasticised polyvinyl chloride (UPVC) profiles clamped onto a galvanised iron structure. The module is mounted on a horizontal steel axel at a height of 3 m. The effective aperture area of the PTC is 20.3 m^2, and it is capable of capturing 18.2 kW of solar thermal energy, under the solar irradiation level of 900 W/m^2. The harnessed energy is transferred to the power block through a heat transfer fluid (Mobil Therm-605). The power block was designed to be compatible with various other solar thermal applications with feasibility tested for distillation of water.

During the designing phase of the mechanical structure for PTC, the wind load effects were analysed and optimized to achieve maximum stability and precision-focusing. In the proposed site for install from where the maximum daytime wind speed is around 8.3 ms^{-1}, the calculated maximum wind load and torque were found to be 3.2 kN and 3.6 kN m respectively for a gust factor of 1.53. The structural design was optimised using a computer simulation to bring the maximum stress below the yield point. For the critical stress of 23.7 MPa, the total deformation was found to be 1.12 mm, which does not affect the focusing of the reflector significantly. The solar energy concentration ratio measured for the PTC module was 1:66, while experimental focusing efficiency was 79%, which is on par with the values available for commercial plants. The thermal efficiency of the selective paint-coated stainless steel (SS) receiver tube with 70 mm diameter was 37%. However, it was noted that this efficiency could be increased up to 65% to 70% by using an evacuated glass receiver tube. When the receiver is a non-evacuated glass tube with a still-air gap, the efficiency could be 10% lower than the evacuated glass receiver tube. The preliminary investigations towards the development of a thermal storage (heat battery) revealed that a heat battery capacity 17.7 MJ helped to get rid of power output fluctuations due to wind and cloud.

The system was utilised for water distillation by coupling the power block to a steam generator. The reusable thermal capacity of the thermal storage was 7.4 MJ for this application. The steam generator consumed 86% of the harnessed energy from the solar power plant, and the thermal storage can supply thermal energy up to an efficiency of 40%. SS tubes of diameter 13.7 mm (¼ inch) were employed to construct the tube bundle of the steam generator, which was both

economical, and yielded better results from flow analysis. A cost analysis revealed that the surface condenser (cooling water flows inside the tube and steam at the shell) had an 82% cost saving compared to a traditional condenser (steam flows inside the tube and cooling water at the shell) due to high heat transfer efficiency. The minimum cooling water flow rate for the surface condenser was 8.5 l min^{-1}. However, in the case of traditional condenser, it was not possible to find an optimum or a safe running cooling water flow rate up to 60 l min^{-1} due to creation of sudden vacuumed pressure pulses. These vacuumed pressure pulses with a magnitude of approximately 85 Hgmm occurred due to sudden ejection of pressurised steam from the blocked condensate layer in the tubes. The traditional condenser was modified later by inclining it by 5° to the horizontal and dipping the condensate outlet in a water bath. The optimum flow rate was 30 l min^{-1} with the above modification. The distilled water production rate of the surface condenser at optimum running conditions was 0.026 l min^{-1} kW^{-1} while that was 0.025 l min^{-1} kW^{-1} for the modified traditional condenser. In addition to the better distilled water production rate, the surface condenser surpasses the traditional condenser by saving the material cost by 82% and reducing the cooling water consumption by 72%. The surface condenser had to be supplemented with a condensation sump, and it was revealed that the condensation level in the sump should be maintained in between ¼ to ¾ from the total height of the sump for optimum performance.

An efficiency of 30% was obtained for the solar thermal harnessing system and is equivalent to a power plant having a thermal capacity of 5 kW. The efficiency of the water distillation system in the power block was 80%. After accounting for losses due to coupling, the overall efficiency of the water distillation system powered by the PTC plant was estimated as 25%, with a condensate production rate of 1.3 l h^{-1} kW^{-1}.