Chapter 10

Conclusions and scope for future study

This thesis numerically investigated a series of efficient novel designs of solar chimney power plant (SCPP) and solar air heater (SAH), with working fluid as air. Both the devices work on the same buoyancy principle. Suitable computational fluid dynamics (CFD) models were developed and validated against the available experimental data. A combination of new concept of bell-mouth (BM) design inlet, converging collector flow channel and divergent chimney show significant power output by multiple folds. If multiple of such systems of SCPP are installed in the regions which are rich in sunshine, it can efficiently produce electricity to power almost thousands of villages. Further, this bell-mouth design was examined in conventional buoyancy-driven SAH with an objective to enhance the low hydraulic efficiency of the device. It was interesting to observe that the integration of bell-mouth design inlet significantly enhanced the mass flow rate of heated air. The high mass flow rates makes the device suitable for high flow rate applications. Apart of new designs as stated above, the convex and concave shaped flow passage of naturally-driven SAH was also developed and investigated. The energy and exergy analysis has been carried out for corrugated curved SAH. All the aforesaid new designs show significant impact in increasing the thermal and hydraulic performance of the solar-thermal devices. Lastly, a detailed aerodynamic analysis was conducted to predict the real environmental wind impact on flat and curved SAH performance. Following key conclusions drawn from the various chapters and fruitful thoughts for future work are presented in this chapter.

10.1 Conclusions

Novel designs of bell-mouth-converging collector integrated SCPP

In this chapter, innovative designs are proposed and analysed for maximising the power generation capacity of conventional solar chimney power plant that suffers from extremely low energy conversion efficiency. Apart from design changes in collector duct and chimney, for the first time, a third component in terms of bell-mouth inlet was conceptualised and integrated in the power plant. It was observed that customary horizontal inlet performs poorly. The optimised bell-mouth design oriented in downward direction boosts overall performance of the solar plant by about 33% compared to the conventional designs. However, such design of bell-mouth and its integration would require the system to be placed on an elevated foundation. The proposed design of bell-mouth is expected to reduce the ambient wind effect, dust and water entry problem, though no such analysis has been performed in this chapter. Results show that design adaption in collector and chimney is indispensable to take the advantage of bell-mouth inlet design. Numerous designs of tapered collector and divergent chimney was investigated along with the optimised bell-mouth design. Key findings of the investigation are:

- Chimney alone is optimized, increase in velocity was about 110% with conventional collector.
- When both collector and chimney are optimized, increase in velocity was 240%. However, when the optimised bell- mouth is integrated with the optimised collector and chimney, a significant increase in velocity by 270% was observed.
- Bell-mouth integration makes the static pressure recovery uniform along the chimney height thereby enhancing the chimney's capacity to handle higher volume flow rates without getting susceptible to recirculation zones formation at the outlet.

- Further investigation were carried out in 287 kW conventional power plant by uniformly scaling the optimised lab-scale model. The collector area that receives the suns' energy was kept the same in both the cases. Results thus obtained are highly encouraging. The scaled model with bell-mouth and optimised collector-chimney design produced 9981.5 kW of electrical power, which is about 35 times the conventional design.
- The proposed new designs are simple and easy to construct.
- If multiple of such designs can be installed in the regions which receives adequate sunshine, it can meet the electrical power needs of almost thousands of villages.

Designs of collector-chimney of PV integrated SCPP

In this chapter, knowledge from the previous chapter is implemented in the collector design and possibility of integrating a PV panel was investigated. A 2D axisymmetric numerical model of a hybrid solar chimney power plant integrated with a photovoltaic panel is developed. Since the conventional solar chimney possess very low thermal to electrical conversion efficiency, this chapter explored the avenues of integrating and enhancing the PV panel electrical conversion efficiency in the collector duct. Various design configurations of collector duct and solar chimney was investigated for increasing the PV panel efficiency in terms of temperature drop and turbine power output in terms of air velocity changes in the system. The hybrid system was studied for the range collector taper ratio (TR: $0.34 - 1$) and chimney outlet to inlet radius ratio (CORR: $1 - 5$). Following are the important findings of the research:

- Initially, increasing the chimney outlet radius enhances the HSCPP performance for CORR $1.5 - 3$. However, further increase in outlet radius deteriorates performance in CORR range $3.5 - 5$. Static pressure recovery was highest for $CORR = 3$. At this value, the flow velocity was considerably enhanced by 121% , and hence the turbine power output by 363% . The PV panel efficiency increased by about 4%.
- No significant gain in turbine power output was observed by only tapering the collector flow passage. However, PV panel electrical output increased by maximum 4.5% for collector taper ratio 0.34.
- Results show that neither the divergent chimney nor a tapered collector duct designs alone are sufficient to enhance the system performance when integrated with the PV panel. The combination of suitable design changes in both collector and chimney seems the best design strategy for hybridization of solar chimney system. High electrical efficiency of PV panel was observed (by about 7%) with taper ratio 0.34 and $CORR = 3$.
- About 80% of the collector area near the chimney is the most influential region for cooling of the PV panel, where consistent temperature drop of $10 - 12°C$ was observed. This manifested an increase in the PV panel electrical output efficiency by about 7%.
- Design categorization of the solar chimney was presented in terms of percentage gain in PV panel efficiency. To achieve higher efficiency gain beyond 10%, further innovative design changes in the inlet design of collector in combination with other cooling mechanisms such as phase change materials can be investigated.

Convex and concave collector designs of self-driven SAH

In the previous two chapter (chapter 2 and 3), it was observed that collector design plays a significant role in thermal performance of the solar device. In this chapter, the new designs of curved collector of naturally-driven SAH were developed and numerically. The two promising designs were studied: concave and convex for different range of curvature angle. The main purpose of the study was to enhance the thermal performance without significantly compromising on the hydraulic performance. The proposed concept designs are novel for SAH in natural convection scenario combined with chimney effect. Based on the outcomes of the investigations, some important conclusions have been drawn as mentioned below:

- Thermo-hydraulic performance of the conventional flat plate solar air heater can be increased without incorporating any extended surfaces if flat parallel plate is transformed into concave and convex designs.

- The convex and concave designs are 43% and 31%, respectively, thermally more effective than conventional flat natural convection SAH.
- Nusselt number per unit pressure drop (Nu/P) was found to maximum for convex design. The averag8e Nu/P values for convex and concave designs are respectively 7% and 6% higher than conventional flat parallel plate design for a constant heat flux condition.
- Two new correlations were developed for Nusselt number as a function of Rayleigh numbers and curvature angle. These correlations were found to be in good agreement with the values of Nusselt number obtained numerically. The mean percentage error associated with concave designs were found to be 1.37%, respectively, while it is 2.95% in case of convex design of SAH.

Bell-mouth integrated SAH for high flow rates

Low adoption of natural convection solar air heaters for wide applications has been mostly due to its low air mass flow rates. The novel concept of bell-mouth inlet design examined in SCPP (chapter 2) was further investigated in SAH with an aim of improving thermo-hydraulic performance. In this chapter, investigations have been performed for new designs of SAH with an aim to increase the mass flow rates without considerably altering the basic design of SAH. Integration of various designs of bell-shaped inlet and chimney at the outlet with the conventional SAH shows considerable enhancement in thermo-hydraulic performance. The range of parametric ratio h/R of bell-mouth design investigated was $0.1 \leq h/R \leq 0.6$ for solar insolation range 500 – 1100 W/m^2. Following major conclusions are drawn from the study:

- Integration of bell-mouth at the inlet of conventional naturally driven flat SAH always increases the mass flow rates of heated air.
- The thermo-hydraulic performance is significantly enhanced by increasing h/R ratio when integrated with chimney. Higher h/R ratio indicates large inlet opening. Higher h/R ratio gives better thermo-hydraulic performance at higher solar insolation.
- Due to enhance mass flow rate, significant drop in pressure coefficient of about 22% was observed with bell-mouth and chimney in comparison to conventional flat SAH.
- In the range of parameters investigated, the highest mass flow rate of 111% was observed for bell-mouth design of $h/R = 0.3,\ R = 100mm$ when integrated with chimney.
- Integration of bell-shaped inlet minimizes the entry losses by reducing the formation of recirculating vortices in the SAH duct and, thereby resulting in significant drop in hydraulic losses and hence, enhances the mass flow rate.
- The pertinent question on energy conversion efficiency of SAH that has not been investigated before is: which is better – a low-flow high-temperature system or high-flow low-temperature system. In this chapter, we have shown that when the SAH is integrated with application such as space heating, the later system with high-flow low-temperature shows better solar energy conversion with significant saving in sun-shine hours. It was also observed that a high-flow low-temperature solar air system is better suited for cold climatic conditions where ambient temperature is low.
- An independent correlation for Nusselt number variation as a function of Rayleigh numbers and bell-mouth ratio h/R. It varies as $ln\, Nu \sim [ln\,(Racos\theta)]^m\ \left[\ln\left(\frac{h}{R}\right)\right]^n$ where m and n are constants. The relation showed excellent agreement with the numerical results with mean percentage deviation of 2.1% with respect to numerical data.

Bell-mouth with tapered collector for high temperature applications

In this chapter, the knowledge of high flow SAH was further studied for high temperature building applications. Hence, the new designs of bell-mouth equipped SAH with converging collector channel identical to one in SCPP of chapter 2 was further examined with SAH device to improve thermal performance. Enhancing the thermo-hydraulic performance of a naturally driven solar air heater is a big challenge as both thermal and hydraulic performances comes at the expense of each other. Lower mass flow rates limit the device usage in the applications where high mass flow rate and medium temperature range are the major priority such as building heating, crop drying etc. In the present study new designs of tapered SAH and the effect of integrating bell-mouth shape at the inlet in augmentation of thermal and hydraulic characteristics were discussed in detail. Following key findings are drawn from this chapter:

- Redesigning the conventional flat parallel flow channel design of SAH into tapered designs has a significant impact on enhancing the thermal performance of the device. Tapering resulted in better interaction of cold fluid with the thermal boundary layer near the absorber plate.
- Tapered flow passage slightly hinders the upcoming heated fluid due to boundary layer interaction, and hence lowers the mass flow rate. The decrease in mass flow rate was compensated and further increased by incorporating the bell-mouth opening at the SAH inlet section.
- Tapered flow passage increases the thermal effectiveness of the device by about 70% and enhances Nu per unit pressure drop i.e. NuP by about 6% compared to conventional SAH design.
- The maximum increase of about 313% in mass flow rate was achieved by the integration of bell-mouth opening in tapered SAH having $t_c = 100\,mm$ for the design parameters $H_2/H_1 = 0.89$ and $h/R = 0.3$.
- An individual relationship of Nusselt number as a function of Rayleigh number and taper ratio was obtained and it has the form $Nu = C_o\,(Ra\,cos\theta)^a \left(\frac{H_2}{H_1}\right)^b$, where a and b are constants. The obtained correlation was in good following with the numerical data with an average percentage deviance of 2.41%.

Curved vs. flat collector designs: A comparative analysis

A comparative study between curved and flat SAH designs to figure-out the performance variation was studied in this chapter. The numerical simulations have been carried out for different geometries of curved absorber plate to study the dynamic thermal performance of smooth (single and double pass mode) and effect of different relative height and pitch ratios of semicircular groove and V-groove corrugation of the absorber plate of curved solar air heater. The effect of various designs of absorber plate on heat transfer characteristics i.e. Nusselt number, air outlet temperature and thermal efficiency were obtained. Correlations for the Nusselt number and friction factor are derived. The key aspects drawn from the results obtained in the present study are mentioned below:

- Curved geometry of the smooth flow convex rectangular passage of the curved solar air heater proved to be more efficient than the flat plate solar air heater. Considerable increase in the air outlet temperature and thermal efficiency have been seen for curved plate smooth single pass and double pass solar air heater compare to the flat plate smooth single and double pass solar air heater, respectively.
- Increase in the relative height and pitch ratios of the corrugation of the absorber plate of curved solar air heater enhances the formation of secondary vortices which imparts more turbulence in air, results in intense mixing of air near to wall of the absorber plate. It provides scope of transferring more heat to the flowing air at larger values of mass flow rates compare to curved plate smooth solar air heater without corrugated absorber plate.
- Maximum thermal efficiency of 91.93% has been seen for the solar air heater with curved plate V-corrugated single pass having P/e_v=0.834 and 32.05% percentage increase in the air outlet temperature with respect to curved plate smooth single pass solar air heater.
- Pressure drop in case of absorber plate with corrugation has slightly more than the absorber plate without corrugation, as air flow obstructed by the corrugation of the absorber plate. Considerable increase in the thermal efficiency due to excess mixing of air which diminishes the drawback of slight increase in the pressure drop of curved solar air heater with corrugated absorber plate with respect to solar air heater without corrugated absorber plate.

- Nusselt number for curved solar air heater varies as $Nu \sim C_o\ Re^a\ \ (P/e)^b\,(e/H)^c$ where a = 0.8102, b = 0.1733 and c = -0.64 in the range of parameters used. Data of Nusselt number and friction factor obtained by correlations under various conditions for different geometries of solar air heater were in good agreement with the data obtained by CFD.

Energy and exergy analysis of curved SAH with semi-down turbulators

Based on the performance analysis between curved and flat SAH, new active SAH designs were proposed to harness maximum heat from the collector has been investigated in this chapter. The present study has been performed to determine effective geometrical shape of ribs in down-configuration in a curved SAH device to augment thermo-hydraulic performance. The heat transfer characteristics were obtained for different range of Reynolds number under constant solar insolation condition. The comparisons were made between flat and curved flow passage, respectively for smooth and roughened flow channels of SAH. The following important observations are made:

- The down-configuration half-trapezoidal and quarter-circle ribs curved SAH show higher thermal performance. The maximum percentage increase in temperature factor was observed for trapezoidal ribs and it was about 17% higher than the conventional flat SAH.
- The down-configuration quarter-circle ribs offer 10-12% higher thermohydraulic performance i.e. $\frac{(T_o-T_i)}{I}/f$, and Nusselt number per unit pressure drop ($Nu/\Delta P$) in comparison to half trapezoidal ribs. The maximum exergy content was associated with curved SAH integrated with down-configuration ribs of half-trapezoidal and quarter-circle shapes.
- Ribs with quarter-circle shape offer less obstruction to airflow in the flow vicinity of SAH in comparison to half-trapezoidal shape ribs. The friction factor for half trapezoidal ribs was found to be about 10% higher than the quarter-circle ribs, for the range of Reynolds number 11000-15000.
- A new correlation was developed for Nusselt number variations a function of Reynolds number and geometric parameters for the down-configuration of quarter-circle shapes. The correlation has the form: $Nu = B_o Re^{0.78} \ln\left(\frac{e_r}{H}\right)^{6.85} \exp$, where $B_0 = 1.2$.

The findings of this investigation would be beneficial to researchers in industry and academia in developing effective designs of curved solar air heater that offers higher thermal performance and lower hydrodynamic losses in a wide range of flow parameters and turbulator designs.

Curved vs. Flat SAH analysis under diverse ambient conditions

In this chapter, we have reported the performance of an optimized curved solar air heater and systematically compared its various characteristics such as thermal performance, environmental heat loss and aerodynamic characteristics with the conventional flat plat SAH. The analysis were performed in a real surrounding factors to access operational performance of SAH device. The parameters range investigated are: curvature angle $(22-40°)$, tilt angle of SAH $(0-60°)$, environment heat loss characteristics for both windward and leeward (velocity range: $0-4$ m/s) and aerodynamic characteristics $(0.5-4$ m/s). In the range of parameters used, curved SAH was observed to more efficient than convectional flat SAH. We hope that the data reported in the paper would be beneficial to the scientific community in design and development of better solar air heaters for harnessing sun's energy in efficient ways. Some specific observations are enumerated below:

- A curved solar air heat with curvature angle of 25° shows higher thermal efficiency associate with lower pressure drop. It was observed that heat content in terms of outlet air temperature is maximum for the curved SAH with 25°.
- For a given mass flow rate at different solar inclination angle, the value of heat transfer enhancement factor, EF (ratio of $Nu_{curved,25°}$ to Nu_{flat}) was observed to always greater than unity in the range of parameters used.
- For 0°, 60° (for windward condition) and 30° (for leeward condition) during windy condition, heat loss to surrounding is less for curved SAH compared to flat SAH. For rest of the tilt angle, flat plate SAH shows less heat loss characteristics and hence, better than curved SAH.

- Under natural convection condition, environmental heat losses are higher in curved SAH in comparison to flat plate heater except for one tilt angle. Clearly, curved SAH performs poorly under natural convection. However, this higher heat losses are compensated by its better thermal performance in comparison to flat plate SAH.

- Aerodynamic performance is compared between the two SAH with same solar collector areas. In the extreme case of 60° title angle, maximum wind speed of 4 m/s, flat plate performs slightly better than curved SAH in windward condition, while in leeward condition, curved design experiences comparatively less lift forces.

10.2 Major contributions from the thesis

A series of new designs of naturally driven solar devices such solar chimney power plant and solar air heater has been proposed and investigated in this thesis. Solar energy devices have extremely low thermal conversion efficiency. For the first time, a novel design concept of integrating a bell-mouth inlet in both SCPP and SAH has been proposed for enhancing the thermal performance. Few important contributions are highlighted below.

- The concept of enhancing air mass flow rates by bell shape designs that adds to the ram-air effect is common in high-performance engines, higher discharge efficiency in vertical intakes, improved aerodynamic performance of outdoor unit of air conditioner and many other applications. However, the effect of such designs vis-à-vis natural convection solar air heaters have not been documented in the scientific community. Enhanced mass flow rates of SAH would be a boon especially for high altitude regions on earth where air density is low due to low atmospheric pressure. Although there can be many other designs that may enhance mass flow rates, the major focus of the investigation was to keep the original design of SAH intact and explore the designs that can be easily incorporated into the original design without major modifications and cost inputs. We hope that these new designs would assist the scientific community in further developing efficient designs for harnessing solar energy efficiently.

- Investigation carried out in 50 kW conventional solar chimney power plant by uniformly scaling the optimised lab-scale model to field-level design. The collector area that receives the suns' energy was kept the same in both the cases. Results thus obtained are highly encouraging. The scaled model with bell-mouth and optimised collector-chimney design produced 1738 kW of electrical power, which is about 35 times the conventional design. First time such significant increase in power output has been reported in the literature. The proposed new designs are simple and easy to construct. If multiple of such designs can be installed in the regions which receives adequate sunshine, it can meet the electrical power needs of almost thousands of villages.

- The possibility of integrating a PV panel in a solar chimney was explored and investigated avenues for increasing its electrical efficiency by cooling the panel. Trade-off between turbine and PV panel requirements was investigated. Turbine power output and PV panel electrical output comes at each other's expense. High cooling of PV panel would reduce the buoyancy force which is against the requirement of high turbine output. Appropriate design strategy was adopted in the conventional solar chimney configurations. Since the efficiency of solar chimney is hardly 2%, authors hope that the findings would provide insights and blueprint for various design strategies for enhancing the efficiency of such important solar power plant systems.

10.3 Limitations of the present investigation

The investigations presented in the thesis has been performed under ideal environmental conditions. The objective was to achieve high thermo-hydraulic efficiency which is the most important aspect to justify its feasibility and wide acceptability. Environmental conditions has severe impact on the solar-thermal performance when the system has to work under real conditions such as rainy day, dust deposition on the collector glazing, variable heat transfer coefficient from collector glass cover, swirl formation due to ambient wind velocity at collector inlet and chimney outlet, etc. These factors deteriorate solar-thermal devices performance which has not been considered in the present research work. A separate examination would be needed for prediction of solar energy-based devices performance in real surrounding and climatic conditions. The other limitation of this work is that material property has been assumed to constant even if significant variation in air temperature was observed near the collector. Though its effect might be small, but its quantification would add new body of knowledge in scientific literature.

10.4 Suggestions for future research

Based on the thesis findings, following suggestions can be implemented for further advancement in the solar powered devices:

1. Analysis of proposed new SAH designs can be further extended using techniques such as artificial neural network and wavelet neural network model.

2. In hybrid SCPP, cooling of the PV panel by bleeding cold air near the panel or using some combinations of air along with other fluids such as water or placing phase change materials beneath the panel. A theoretical analysis followed by a experimental examination of the optimized design would be a promising work to bring significant improvement in PV panel efficiency.

3. More than 6 billion people on this earth live without adequate access to fresh drinking water. With suitable changes in solar chimney design (converging-diverging design for creating swirling, condensing and turbulent flow) along with the designs proposed in this thesis, suitable designs for solar cyclone can be developed and investigated for fresh water production from Earth's atmosphere. Since high velocity and temperature are the basic criteria for fresh water production from solar cyclone chimney, work carried out in this thesis has laid a foundation in this direction.

4. Some of the researchers have investigated the air flow in conventional SAH by applying electric field. The idea is novel and need a consistent research to mature the technology to justify its techno-economic feasibility. It would be interesting to study the effect of electric field on the designs proposed in this thesis.

5. Further, the working medium considered was air in all the investigations. Higher increase in efficiency can be achieved is a closed loop system with high radiation absorbing medium such as CO_2 gas can be investigated.

6. The SCPP and SAH devices considered in this study work efficiently only when good radiation is available for energy conversion. They don't work in night. To extend their operational efficiency even during night time, energy storage materials such phase change materials (PCM) can be integrated with these devices.