CHAPTER 7

Conclusions and Recommendations

This thesis presents the numerical studies of a series of new design solar air heaters (SAHs) working on the forced convection principle. Appropriate computational fluid dynamics models (CFD) were developed and validated with available experimental results. New designs of SAHs are investigated in a large range of flow and design parameters. Starting from the new curved design to placing symmetric and asymmetric semicircular turbulators on the absorber plate, to investigating various cross-sectional channel designs, these investigations reveal that thermal performance can be enhanced if suitable design strategies are adopted. Conclusions are organised as per chapter-wise findings along the major contributions from the thesis. Following are the important conclusions and suggestions for future work.

7.1 Conclusions

Efficient Design of Curved Solar Air Heater Integrated with Semi-down Turbulators

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. $\frac{(T_0-T_i)}{I}/f$, 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: $Nu = B_0 Re^{0.78} \ln(e_r/H)^{6.85} \exp\left[(0.82).\{\ln(e_r/H)\}^3 + 4.12.\{\ln(e_r/H)\}^2\right]$, 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.

Efficient Designs of Double-pass Curved Solar Air Heaters

In this chapter, thermo-hydraulic performance characteristics of a parallel curved design double pass solar air heater (DPSAH) was investigated numerically under various ranges of Reynolds number, relative roughness ratio (d/H), and position of absorber plate (y/H). Following are the critical observations from the study:

- Asymmetric semi-circular extended surfaces or ribs show better thermal and hydraulic performance than symmetric circular ribs. High energetic vortices reattach with the heated absorber plate frequently and thus show higher thermal performance with semi-circular ribs.

- Thermal effectiveness of curved DPSAH equipped with semicircular ribs shows by about 37% enhancement when compared to smooth flow passage at $Re = 5000$. This substantial increase is due to secondary flow vortex formation, which gets further enhanced due to the curved nature of the SAH design.

- For best thermal performance, the maximum roughness height of the extended surfaces can be 25% of the duct height, i.e., for $d/H = 0.25$, enhanced heat transfer was observed with lower hydraulic losses.

- Placing the absorber plate at mid of the insulating wall and transparent glass cover shows higher thermal performance, i.e., about 5°C higher outlet temperature was observed compared to other positions.

- Two independent correlations were developed for Nusselt number and friction factor variations with Dean numbers and relative roughness height. The nature of variation is exponential, and it has the form: $Nu = k_1 D_n^{k_2} \left({}^{d}/_{H}\right)^{k_3} exp\left[k_4\{ln\left({}^{d}/_{H}\right)\}^2\right]$.

- The predicted Nusselt number and friction factor from the developed correlations agrees reasonably well with the data with a maximum deviation of 3.42% and 0.87%, respectively.

Performance Characteristics of a New Curved Double-pass Counter Flow Solar Air Heater

In this chapter, concept proposed in the previous chapter was implemented in a new design of a counter curved DPSAH, and its thermohydraulic performance was compared with new designs of parallel curved DPSAH under various flow and geometric parameters. The results show that with suitable heat transfer enhancement strategies such as curvature design passes, arrangement of fluid flow with strategically placed turbulators can play a significant role in overall performance improvement. Based on the results, main conclusions are given as follows:

- In curved design SAHs, counter DPSAH show better thermal performance than parallel DPSAH and smooth SPSAH. This is due to the counter-flow design having higher turbulence, longer duct length, and minimum top losses than other investigated SAHs. A counter design with curved double pass SAH shows almost double thermal efficiency than curved SPSAH

- The maximum increase of about 37 in thermal effectiveness was observed in roughened curved counter over parallel flow designs at Re and d/H values of 10000 and 0.25, respectively at P/H=0.75.

- Rounded asymmetrically placed ribs reduces the system losses. The value of friction factor in descending order were observed as: roughened counter curved DPSAH > roughened parallel curved DPSAH > smooth counter curved DPSAH > smooth parallel curved DPSAH > smooth curved SPSAH.

- Based on the performance data, two new correlations of Nu and f were developed in terms of flow parameter (Re) and non-dimensional geometric ratio d/H. The correlation has the form: $Nu = k_1 Re^a \left({}^{d}/_{H}\right)^b exp\left(k_2\left(ln\left({}^{d}/_{H}\right)^2\right)\right)$ where k_1, k_2, a and b are constants. A similar form was observed in friction factor variation with a negative exponent value of the constant a. The predicted Nu and f from the established correlations match reasonably well with the data with a maximum deviation of 1.8 and 0.52, respectively.

Investigations for Efficient Design of a New Counter Flow Double-pass Curved Solar Air Heate

In this chapter, with the knowledge from the previous chapters (chapters 1 and 2), a new curved counter flow double-pass solar air heater (CDPSAH) with arched baffles was develoved. Focus of design optimization was the second duct, where thermal performance was observed to be low due to the curve nature of the solar air heater. Arch baffles were introduced, and their design parameters are optimized for higher thermal performance. Following were the observations:

- Large secondary vortices are observed in the second duct on downstream of the arched baffles.
- Due to high acceleration and more reattachment zones, higher heat transfer coefficient was observed in the second channel, thereby increasing the overall performance of the system.
- The maximum thermal and hydraulic performance has been achieved at the configuration at relative pitch ratio $P/d = 6$, relative baffle angle $\alpha/90 = 0.5$.
- Two new correlations are developed to predict the thermal (in terms of Nusselt number) and hydraulic performance (in terms of friction factor) of the curved DPSAH.
- The developed formula agrees well the numerical data with an error of ± 1.6% and ± 7.6% in Nu and f respectively.

Effect of Channel Designs and Its Optimization for Enhanced Thermo-hydraulic Performance of Solar Air Heater

In this chapter, a new concept was introduced for enhancing the thermal and hydraulic performance of the conventional solar air heater. The conventional SAH has low performance due to low interaction of working fluid with absorber surface due to formation of viscous sublayer over the absorber plate. Therefore, flow interaction of the heated fluid in the flow channel of the SAH affects both its hydraulic and thermal performance. To enhance the thermal performance of this device, a systematic investigation has been performed numerically for a large range of flow and geometric parameters. In the first stage, conventional rectangular channel design performance was compared with the non-rectangular designs and results are discussed in terms of temperature factor $\left(\frac{T_0-T_i}{I}\right)$, thermal effectiveness (ε), Nusselt number (Nu), Nusselt number per unit friction factor (Nu/f) and friction factor (f). In the second stage, best configuration channel design was further investigated to enhance its performance by introducing sinusoidal wavy absorber with relative roughness wavelength (λ/D_h) and relative roughness amplitude (A/D_h). In addition, two new correlations were proposed to predict the thermal and hydraulic characteristics of the device. Following are some of the important observations:

- The maximum percentage increase of 10% in temperature factor has been found for SAH duct having semi-ellipse cross-section compared to conventional SAH (rectangular cross-section), while the next maximum was 5% increase for the trapezoidal cross-section. For unit pressure drop or losses, semi-ellipse cross-section design is the best choice considering the compromise between thermal and hydraulic performance.

- The value of Nu/Nu_s and f/f_s have been observed maximum at wavy roughness parameters, i.e.,$A/D_h$and λ/D_h of 0.12 and 0.8, respectively for the $11000-19000$ range of Reynolds number.
- The value of Nu/f flattens at higher Reynolds number and decreases with increase in relative roughness amplitude.
- Two empirical correlation have been developed for Nu and f for best cross-section with sinusoidal wavy absorber SAH. The predictions from these relationships agree well with numerical data and have absolute average percentage deviation of 3.68 and 9.84 for Nu and f, respectively.

The designs and data presented in the chapter would help the scientific community in developing thermally efficient designs of solar air heaters to harness the solar energy.

7.2 Major contributions of thesis

A series of novel designs of solar air heaters based on force convection mode have been reported and investigated in the present thesis. Conventional solar air heaters convert solar energy into useful energy in a less efficient manner. Therefore, new ideas include: (a) straight passage to curved passage (b) roughness on the absorber surface (c) arrangement of airflow into suitable channels (parallel or counter) (d) reposition of absorber plate (e) Utilizing deflectors and (f) changing rectangular to non-rectangular channel designs have been introduced in SAH for enhancing thermal performance. Few important contributions are highlighted below:

- The concept of increasing the mixing rate between hot and cold air in solar air heater for maximum heat extraction from the absorber, curved solar air heaters integrated with semi-down turbulators are reported. Energy and exergy analyses are performed to determine the effective geometrical shape of the turbulator. Quarter-circle turbulator offer 10–12% higher thermohydraulic performance i.e. $\left(\frac{T_0-T_i}{I}\right)$ and Nusselt number per unit pressure drop ($Nu/\Delta P$) in comparison to half trapezoidal turbulators. 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.
- A new design of parallel curved DPSAHs is proposed, which is more efficient than the conventional SAH design. It is found that higher outlet air temperature by about 5°C was observed when the DPSAH absorber plate is located at the mid of the insulating wall and

transparent glass cover. Furthermore, putting asymmetric semi-circular roughened surfaces shows better performance than symmetric circular shapes as the reattachment of vortices with the absorber plate is more frequent in the former. However, such designs vis-a-vis forced convection solar air heaters have not been documented in the scientific community. Authors hope that these new designs will assist the scientific community in further developing efficient designs for harnessing solar energy efficiently.

- An investigation was carried out in a new counter curved DPSAHs under various flow and geometric parameters. Its performance is compared with new parallel curved DPSAHs. With suitable heat transfer enhancement strategies such as reducing the top loss, increasing the duct passes length and deflecting the fluid toward absorber, it is found that in curved design SAHs, counter DPSAH show better thermal performance than parallel DPSAH and smooth SPSAH. The proposed new designs are simples and easy to construct. If these efficient new designs are integrated with building and grain drying systems, huge amount of electricity cost can be saved.

- The possibility of enhancing the performance of conventional SAH was explored and investigated by changing flow channel designs keeping the same energy input.The results show that the SAH duct having a semi-ellipse cross-section offers the best thermo-hydraulic performance. The channel design (semi-ellipse) that gives the best performance was further investigated by incorporating a sinusoidal wavy absorber having variable wavy roughness parameter. It is observed that value of Nu/Nu_s and f/f_s have been found maximum at wavy roughness parameters, i.e., A/D_h and λ/D_h of 0.12 and 0.8, respectively. Authors hope that the finding would provide insight and a blueprint for such design strategies for enhancing the efficiency of SAH.

7.3 Assumptions and limitations of the present investigation

The proposed novel designs of SAHs have been investigated under the following assumptions: (1) Air is dry, and its density is calculated via ideal gas equations. (2) The properties of materials are assumed to be isotropic, homogeneous and constant. (3) The effect of dust or dirt deposition on the glass cover is ignored. (4) The external wind velocity is considered to be zero. (5) The optical properties of materials is independent of wavelength. (6) There are no side and bottom losses of heat. (7) The ambient temperature and solar radiation flux are assumed to be constant and doesn't vary with time. (8) There is no leakage of air from the duct of SAHs. (9) The absorption and emission of radiation in the air are negligible. (10) The flow is turbulent and incompressible. (11) Inlet air and ambient air temperature are the same.

Thus, all the above discussed SAHs have been investigated under ideal environmental conditions. They can work only during sunshine hours and doesn't operate at night. However, environmental conditions have a severe impact on the solar-thermal performance when the system has to work under actual conditions such as intermittent solar energy due to rainy and cloudy days, reduction in sunshine hours, fluctuation of ambient temperature and wind velocity, dust deposition diminish the solar energy intensity, variable heat transfer coefficient from collector to glass and imperfect insulation (i.e., side and bottom losses of heat) etc., deteriorate their performance. These factors have been not included in the present study. A separate investigation would be needed to predict the performance of these devices in real surrounding and climatic conditions. Another limitation of these devices would be constant material properties in all directions, even if significant variations in air temperature were observed near the absorber wall. Other limitation of this work is the absorbance of all solar radiation by absorber surface, but it is somewhat different in the actual scenario. However, its effect might be small, but its quantification would add a new body of knowledge in scientific literature.The primary attention was given to its simplicity of design, inexpensive manufacturing, operating, and maintenance costs, smooth and noiseless operation, and high thermo-hydraulic efficiency. These factors are the most vital aspect to justify their wide acceptability and feasibility

7.4 Recommendation for future work

The following work can be consider in the future :

- The novel designs of SAH discussed in the present thesis work efficiently only when sufficient solar radiation is available. They don't work at night. The integration of phase change material enables these SAHs to work diurnal(both day and night). Therefore it would be interesting to study these SAHs with phase change material and analyse their thermal performance during the charging and discharging period by numerical analysis.

- Analysis of proposed new SAH designs can be further extended by using response surface methodology (RSM), artificial neural network (ANN) and wavelet neural network (WNN) model.

- Air is used as a working fluid in proposed new designs of SAH but has poor thermo-physical properties. Therefore these SAHs can be investigated using high absorption fluid such as CO_2, H_2 etc., instead of air as a working fluid in a closed-loop with solar distillation for achieving their higher yield performance.

- Nano-particles have good thermophysical properties and are mixed with black paint, used for coating purposes on the absorber plate. Consequently, more thermal energy can be absorbed by the absorber plate. Moreover, Few experimental studies have been conducted on the performance enhancement of SAHs using nano-coating on absorber plates. Therefore performance enhancement using nano-coating on absorber plate of proposed new designs of SAH by the experimental study can be future work. .

- Numerical investigation of natural convection curve solar air heater with integrated bell mouth and diverging or converging chimney can be further conducted to enhance its thermal and hydraulic performance.

- Insertion of turbulators in SAH increases the absorber duct outlet temperature, simultaneous increasing the pressure drop. Hence efficiency of the turbulator is being decided by the values of thermo-hydraulic enhancement factor. It is generally seen that as Reynolds number increases thermo-hydraulic enhancement factor decreases. This is because, increase in pressure drop is considerable as compared to the increase in Nu at higher Re. Hence an efficient design that increases the thermo-hydraulic enhancement factor for higher Reynolds number remains as a challenge

- The proposed new designs of SAH provide only hot air, which is used for room heating and drying of agriculture products etc. Moreover, PV panel convert solar radiation energy into electricity. With its operation, electrical efficiency decreases due to increasing the PV panel temperature. Therefore a hybrid system of PV/T air heater can be investigated by computational fluid dynamics approach for dual purpose.

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