CHAPTER 1

Introduction

With the rising price and burden on conventional sources of energy due to limited resources, it is necessary to improve the energy conversion efficiency of solar energy-based appliances by investigating and incorporating suitable design configurations. In the present thesis, a series of strategically incorporated new designs of solar air heaters (SAH) working on the force convection principle is put forward and investigated for thermal and hydraulic performance by developing experimentally validated numerical models. Besides, various correlations are proposed as a function of flow (Dean number and Reynold number) and geometrical parameters to forecast the performance of SAHs. In this chapter, the first section presents an assessment of renewable energy and its significance. The second section describes solar energy utilization in conventional design of solar thermal collector. In addition, discussions are focused on its working principle, application and operational limitations. The third section presents a brief overview of novel efficient designs of single-pass curved corrugated solar air heater, parallel curved double pass solar air heater (semicircular ribs attached upper and below at central location of absorber), counter curved DPSAH (semicircular ribs and arched baffles attached upper and below at central location of the absorber and insulating wall of lower channel respectively) and single-pass solar air heater (elliptical cross-section with sinusoidal wavy absorber). Detailed investigations and findings on these designs are presented in different chapters of the thesis. The fourth section discusses the objective of the thesis. In the last section, the layout of the thesis is presented.

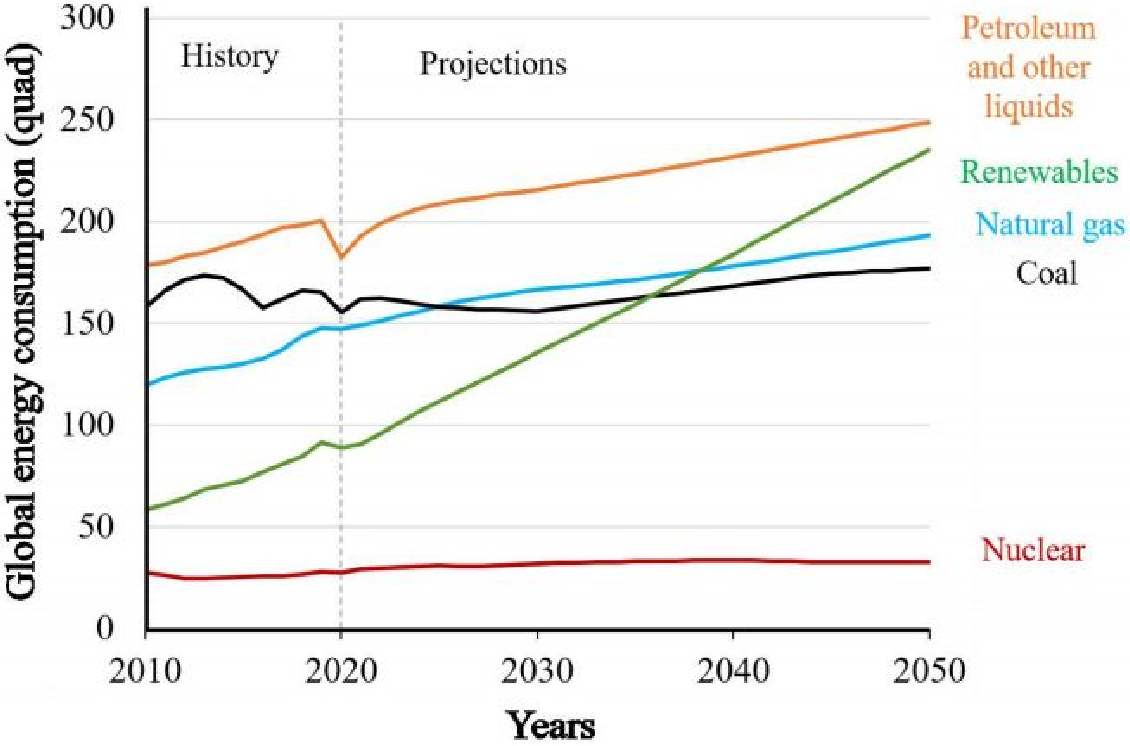

Figure 1.1: Projections of global primary energy consumption for 2020 to 2050.

1.1 Assessment of energy resources

Economic development of any nation depend on energy availability. The rate of global energy utilization has increased significantly as the word's population increased from 7.3 billion in 2015 to 9.2 billion in 2040 [14]. With the massive demand for energy and rapid depletion of conventional energy sources, there must be alternative energy sources to meet all the future global energy needs, but what will that energy be ?

On Earth, two types of energy resources are available; Non-renewable and Renewable. With an increase in population and modernisation of the world, the consumption of primary energy resources (Non-renewable and Renewable) is continuously growing, as shown in Fig 1.1[52]. Non-renewable energy sources are in finite reserves, while renewable energy sources are infinitely available but mostly untapped.The primary non-renewable/ fossil fuels, such as coal, natural gas, crude oil, uranium, synthetic oil, etc., are suitable for consumption because energy is available in a concentrated form. Burning of these fuels pollutes our environment, enhances global warming, and consequently, leading to adverse climatic changes. Besides the negative environmental impact of fossil fuels, the hike in price ended up the affordability; consequently, consumers are looking towards renewable energy resources such as solar, geothermal, wind, ocean and many other to meet industrial, transportation and residential sectors needs. Fig 1.2 shows the global installation of renewable energy from 2000 to 2020 [53]. From this figure, it

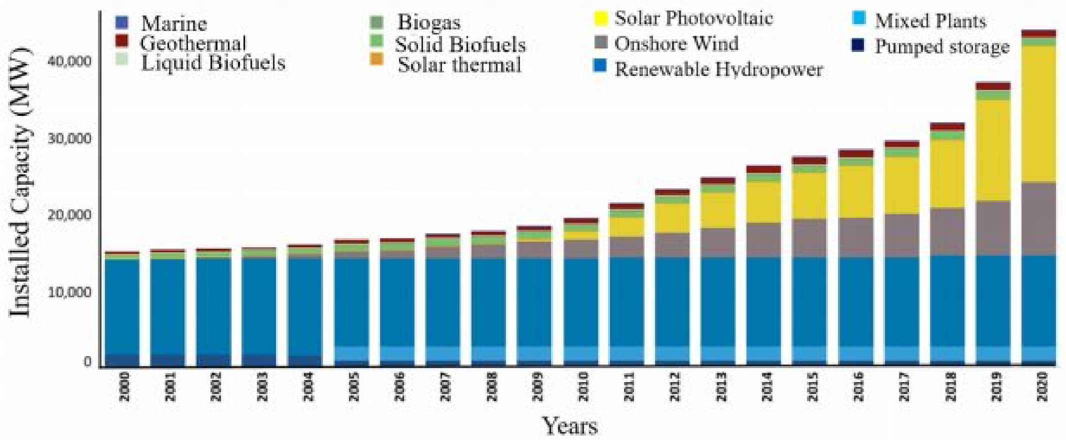

Figure 1.2: Trends in renewable energy from 2000 to 2020.

is clear that utilisation of solar energy (Solar Thermal + Solar Photovoltaic) is exponentially increasing more as compared to other forms of renewable energy. This is because solar energy has two crucial features that make it the right choice for future development among renewable energy resources. One, it is clean and hence environmentally friendly, and second, it is available in abundance. Quantum of solar energy availability can be gauged from the fact that 30 days of sunlight that falls on the Earth is equivalent to the energy all the planet's fossil fuels, both used and unused [136]. Thus, the sun's energy would power most of the devices in the future and can save millions of tons of carbon dioxide from being released by burning fossil fuels. Solar energy can not be utilized effectively unless efficient designs of the solar-thermal system are developed, which is a big challenge for the research community. They can reduce our dependency on non-renewable sources. Since 1990, renewable energy sources use have grown at an average annual rate of 2.1%, which is marginally higher than the world's total energy supply growth rate of 1.8% [51]. Interestingly, Solar Pv and Solar thermal contribute 36.0% and 10.5%, respectively, alone in renewable energy's average annual growth rate[51].These data show that the scientific community has been contributing to upgrade solar thermal devices to achieve a higher energy conversion rate and get maximum benefits from this energy sources.

1.2 Conventional solar air heater: An outlook

All around the world, solar energy is being utilized in many fields, such as power generation, the distillation of water, cooking of food, greenhouses, water heating, air heating, crop drying, and many other industrial and domestic applications [28, 136]. Thermal and photovoltaic technics are employed for the conversion of solar energy into useful energy. To utilize solar energy in cost-effective way, the thermal route is mainly preferred. In this route solar insolation passes through the top transparent cover and absorbed by black surfaces (also called collector plate) (see 1.3). Based on the target application, fluid (air/water) flows between the transparent

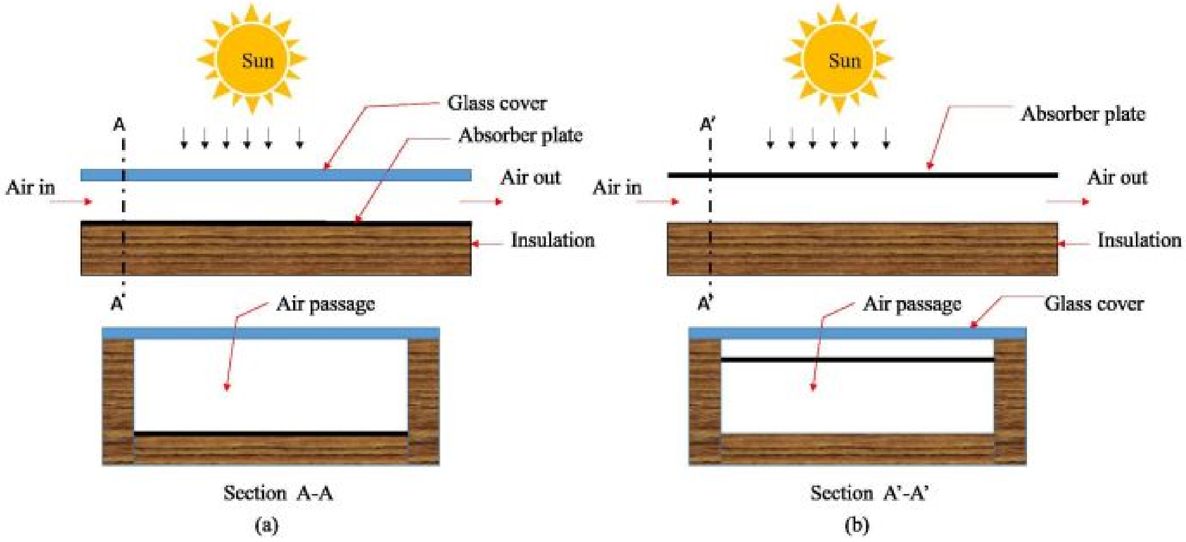

Figure 1.3: Schematic diagram of conventional solar air heater.

cover/insulation, and the absorber plate gains heat during the contact with the absorber plate. This heated fluid is collected at a delivery section of solar collector. Solar collectors for heating of air and water are typically named solar air heaters(SAH) and solar water heaters (SWH), respectively. SAH has many advantages and disadvantages over SWH, such as overheating of water, corrosion, free from freezing, leak, etc., and poor thermophysical properties of air compared to water [37, 77]. There are two types of SAH based on its operation: (i) active SAH and (ii) passive SAH. In active SAH, air flows through the channel with the help of additional devices such as a pump or blower for fast extraction of heat from the absorber plate. On the other hand, passive SAH does not need any external device for its operation as it is self-driven under buoyancy force.

Conventional SAH is also known as a flat plate collector (see in Fig.1.3). It consists of a rectangular cross-sectional shape flow channel, top transparent cover, an absorber plate, insulation at the bottom and sides. The whole assembly is encapsulated in a sheet metal container. The working fluid (air) flows between the absorber and glass (Fig.1.3a) or absorber and insulation (see Fig.1.3b). The solar radiation that falls on the absorber surface heats the plate, and consequently, the airflow gets heated during interaction with the hot absorber surface. Solar air heater with force convection mode achieves high thermal efficiency at the expense of high hydraulic losses [74, 122].

SAH is the cheapest, simplest and more favorable device used to convert solar power into heat. It has several advantages, including simplicity in design, inexpensive in operating, manufacturing and maintenance costs, smooth and noiseless operation and environment sustainability. SAHs are generally used for low and moderate temperature application like space heating, desalination, crop drying, textile, marine products, etc [68, 113, 136]. However, conventional SAH has low efficiency due to the formation of a viscous sublayer over the absorber surface, which offers the resistance to extract the heat from the absorber plate . Therefore, researchers have been investigating more in-depth to enhance the performance by making the changes in the design and construction, using heat transfer enhancement devices such as vortex generator, including roughness on the absorber surface, use of phase change material and nanocoating etc [30, 35, 61, 69]. Another major disadvantage of SAH is that the air has poor thermophysical properties; consequently, a large volume of fluid is required to be handled, which consumes more electric power to blow the air through the system.

Issues related to conventional solar air heater:

- Low thermal efficiency
- Poor thermophysical properties of working fluid (air)
- Low conversion efficiency
- High hydraulic losses
- Hybridization is a challenge
- Low convective heat transfer coefficient between the absorber and working fluid
- High thermal losses
- Low heat storage by absorber plate
- Larger response time for heating & drying application.
- Low collection area

1.3 Literature review on design modification of SAHs

As mentioned above, air flowing inside conventional SAH forms a viscous laminar sublayer over the absorber plate, resisting the energy extraction between the hot plate and nearby contact fluid. As a result, the heat transfer coefficient (convection heat transfer) between the absorber plate and the air decreases and causes poor efficiency of SAHs even though they receive a good amount of solar insolation. These factors motivate the researcher to deploy heat enhancement methods to improve the thermohydraulic performance of SAHs.

The thermohydraulic performance of solar air heaters depends on various operating and geometrical parameters such as solar intensity, the design of flow passes duct and absorber plate, heat transfer coefficient between air and absorber, the residence time of air inside the SAHs etc. This is why many investigators have focused on various aspects as mentioned above and according to modified design to improve the performance. The performance enhancement technique employed by various researchers in the design of SAHs has shown in Fig 1.4[9, 80, 101].

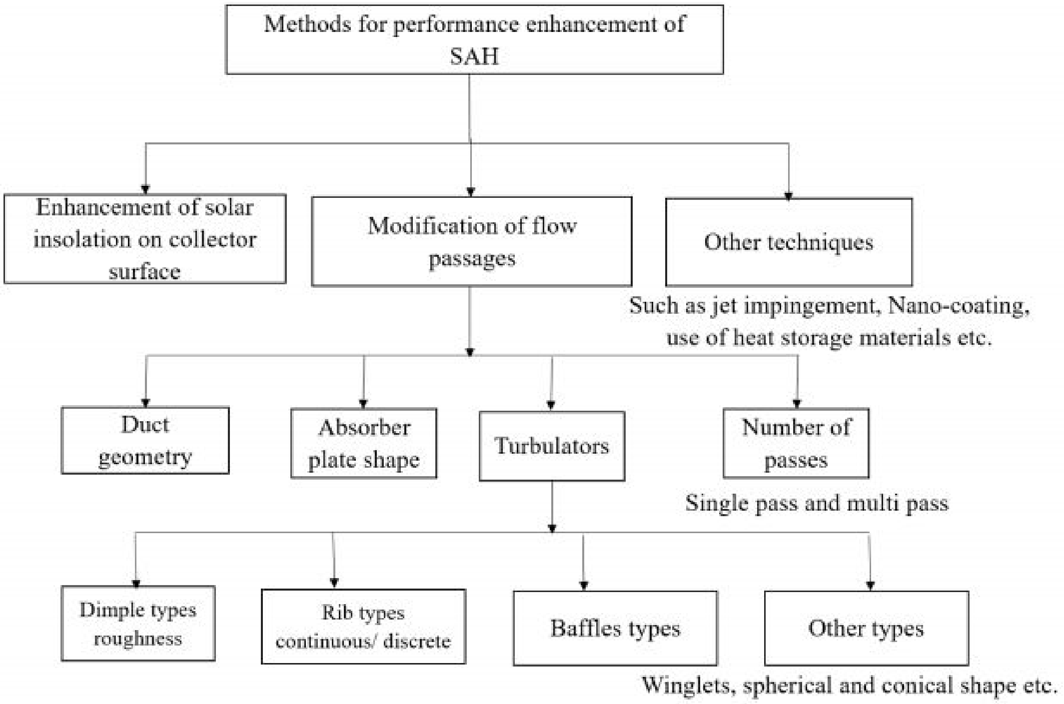

Figure 1.4: Physical representation of the performance improvement methods in the solar air heater.

Prasad and Sah [109] performed an experiment using a booster mirror to enhance the intensity of solar radiation on the absorber plate. They found that booster mirrors increase solar radiation by 40%, leading to the performance enhancement of 90% in SAH. A theoretical investigation of a reflective fin SAH has been conducted by Issacci et al [54]. It is found that lowering thermal conductivity and surface emissivity of fins increases the efficiency of SAHs. This method improves the performance of SAHs from the absorption point of view. Moreover, to augment the heat transfer from the hot plate to the air passing through the duct, it is required to focus on design modification of the flow passes area. This design modification mainly consists of: (1) Arrangement of airflow inside the duct (Single-pass or Double-pass). (2) Geometrical transformation of the flow channel or cross-sectional area of Duct. (3) Turbulator attached to the absorber plate for rupturing the boundary layer formation. (4) Absorber plate modification for better airflow characteristics to enhance the heat transfer. In the present thesis, design modification of the flow passes method has been implemented for proposing the novel design of SAHs.

Single flow and double flow channel SAH are also known as single-pass solar air heater (SPSAH) and double-pass solar air heater (DPSAH), respectively. In a SPSAH, air flows between the glass and absorber plate or absorber and bottom plate while in DPSAH, air flows in two channels, i.e., above and below the absorber plate. Based on the previous investigations, DPSAHs are found to be thermally better than SPSAHs because of the high heat extraction rate from the absorber plate, top minimum losses, and increased flow interaction due to double heat transfer area [27, 149]. It has been reported that the thermal efficiency of a DPSAH is $10-15\%$ higher as compared to SPSAHs for different range operating conditions[118, 142] Further, it has also been reported that in double-pass ducts, efficiency is higher (nearly 20%) when air flows over the absorber plate in a counter or return type duct design compared to parallel flow duct [26]. This is because the residence time of working fluid in counter DPSAH is higher than parallel DPSAH. Consequently, a low heat transfer rate between air and absorber surface in parallel design leads to the higher temperature of the absorber plate, which manifests into higher radiation losses to the environment than counter design [42].

In addition to airflow arrangement inside the duct, the design modification in the cross-sectional area or flow channel path of SAHs also plays a significant role in thermohydraulic performance improvement. Rajneesh et al.[81] changed the cross-section of duct from conventional rectangular into triangular and rounded corner triangular and investigated their performance by numerical and experimental. They found that rounded corner triangular duct SAH has higher thermohydraulic performance than all tested conditions. The rectangular duct produces more eddies at sharp corners. These eddies can be reduced by giving into other shapes of crossectional duct (trapezoidal, semi-ellipse etc.) and triangular duct with rounded corners. Moreover, it has seen most of the previous studies on SAH performance have been conducted in a straight flow channel [4, 85]. However, few recent investigations [87, 123] have shown that curved flow channel performs better compared to flat channel design. Due to centrifugal forces, secondary flow vortices in the curved channel were observed as a result of forcing the mean flow velocity near the absorber plate. This enhanced the heat transfer rate. Further, some researchers also modified the flow path into spiral type [59], serpentine type [5], Z-shaped path [107], etc. and found pressure drop is higher, causing more pumping cost. A trade-off between pressure drop and heat transfer is essential for this modification to optimise the pumping cost. Therefore, the current thesis, curve flow channel modification, is adopted, which has a slightly higher pumping cost than a straight flow channel.

In the scientific endeavor to improve the heat transfer rate from the heated absorber plate, various innovative design concepts of the duct have been investigated previously. The most prominent method has been to add artificial flow modification devices even termed as turbulators [7, 35] and fin [10]on the absorber plate to break the thin boundary layer. In other words, the heated fluid near the plate should interact with the cold fluid above it to enhance the overall heat transfer rate. Based on the geometrical shape, turbulators are broadly classified as small dimple protrusion type, baffle type, rib type, and others like winglets, diamond shape roughness, spherical etc. Saini et al. [117] conducted an experimental study to investigate dimple-shaped protrusions' effect on the flat absorbing plate for thermohydraulic performance. They found that maximum heat transfer has been seen at the reattachment region of flow. Ho et al. [46] reported a theoretical and experimental investigation of baffled counter double-pass duct with external recycle and attached internal fins. The study revealed that baffles created more turbulence and increased heat transfer area, and reduced the boundary layer growth. Menni et al. [95] investigated the effect of diamond configuration baffle attached with the hot lower wall for thermohydraulic performance. They found that the heat transfer and skin friction factor improvement in duct with diamond baffle were 3.962 and 29.82 times higher, respectively than duct without baffle. Ribs types turbulator create flow separation and reattachment regions on both sides of roughness geometry when attached to the absorber surface. As a result, heat transfer coefficient and turbulence intensity increase inside the duct. Ribs geometries, including their shapes, size, orientations, pitch etc., are more influencing parameters for the performance of the air heater like absorber plate temperature, Nu, thermo-hydraulic enhancement factor etc. Prasad and Saini [110] conducted a theoretical analysis to investigate the influence of artificial roughness height and pitch on heat transfer and fluid flow inside SAHs. They found that for optimum thermohydraulic performance, rib height should equal laminar sublayer height, and roughness pitch should be such that flow reattaches before reaching the next rib. Hans et al. [40] experimented with investigating the effect of multiple v-rib roughnesses on friction factor and heat transfer coefficient in an artificially roughened solar air heater duct. They found that the reattachment point and the angle of attack of the flow influence secondary flow generation. In order to investigate the shape of discrete rib roughness on thermohydraulic performance characteristics, Boulemtafes et al. [13], Yadav and Bhagoria [144], Gawande et al. [35], Yadav and Bhagoria [146], used rectangular, circular, chamfered and semicircular respectively in their studies. They found that the ribs' thermo-hydraulic performance was in the ascending order of chamfered, rectangular, circular, and semicircular rib, respectively.

Different geometrical shapes of turbulator, such as rectangular, triangular, square, etc., are equipped with absorber plates that create eddies that get entrapped in upstream and downstream corners, leading to local hotspots' formation diminishing the heat transfer rate. Further, pressure drop increases due to eddies formation in the separated region. Consequently, pumping power increases. These effects can be overcome by modifying the design of the absorber plate itself into a hyperbolic [138], sine wave [91] and groove [57]which is also an innovative method.

1.4 New efficient designs of SAH

Conventional design of solar air heater exhibit dropping performance characteristics. The thesis consists of various novel designs to augment the thermal and hydraulic performance of these conventional SAHs systems. A brief discussion on different novel designs of solar air heaters is discussed here. SAH is highly versatile equipment and has great potential for thermal application if designed efficiently. For this, the above-discussed design modification of the flow passes area strategies are adopted in the thesis as follow: (see 1.5, 1.6, 1.7, 1.8 and 1.9): (i) Straight passage to curved passage (ii) Roughness on the absorber surface (iii) Arrangement of airflow into channels (Parallel or counter) (iv) dislocation of absorber plate (v) Attaching deflector in lower channel to alter the flow toward absorber surface (vi) Rectangular cross-sectional flow passages into the non-rectangular cross-section.The efficiency of solar air heating device largely depends on the design of absorber plate and flow passage duct [25, 50]. Recently, the investigation revealed that curve SAH show higher thermo-hydraulic performance than flat SAH design [87]. Secondary flows near the curved surfaces enhance heat transfer[123]. The other aspect of SAH design is the absorber plate over which ribs or turbulators are integrated to improve thermal performance. Depending on the configuration of SAH, the absorber plate is either placed on the top i.e. down-configuration [71] or bottom i.e. up-configuration [137] of the flat duct. The investigations show that though the interaction of cold fluid with heated flat absorber plate increases with addition of turbulators in either position, down-configuration of ribs shows the higher mean temperature of air as compared to ribs in the up arrangement [72]. Figure.1.5 shows a new design of corrugated curved SAH integrated with different shapes of semi-down turbulators. Integrating down-configuration of ribs in curved SAHs is the first of its kind design investigation (Chapter 2). The curve channel and integration of ribs enhance the mixing between cold and hot fluid due to the formation of secondary vortices and rupturing the boundary layer. Moreover, energy and exergy analyses are performed to investigate the best design of turbulators. The exergy recovery show maximum for trapezoidal and circular shape ribs, and it was about 35% more than the smooth flat SAH. Figure.1.6 depicts a new design of a parallel curved double pass solar air heater (DPSAH) with asymmetrical attached semicircular ribs on both sides of the absorber plate. Integrating curve passage with double flow arrangement and asymmetrical attached semicircular ribs on both sides of an absorber plate is a new design concept(chapter 3). Due to the curved passage design, centrifugal force pushes the mean flow velocity near the absorber plate; and as a result, secondary flow vortices are observed in the curved channel. In addition, double-flow arrangement and asymmetrically attached semicircular ribs on both sides of the absorber plate diminishes the top losses and enhances the convective heat transfer coefficient between the absorber and working fluid. 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. Besides, new counter curved DPSAHs have been proposed, as shown in Fig.1.7 (chapter 4). This unique design has a longer residence time, double heat transfer area and lower top losses with slightly higher hydraulic losses than parallel curved DPSAH. Consequently, a maximum increase of about 37% in thermal effectiveness was observed in roughened curved counter over parallel flow designs. Further modification has been implemented in counter curved DPSAH by incorporating backwards arched baffles in the lower channel, as shown in Fig. 1.8 (chapter 5). The integration of arched baffles deflects the fluid returns after the upper channel to the lower channel toward the absorber to extract more heat from the absorber plate. In addition, its design parameters are

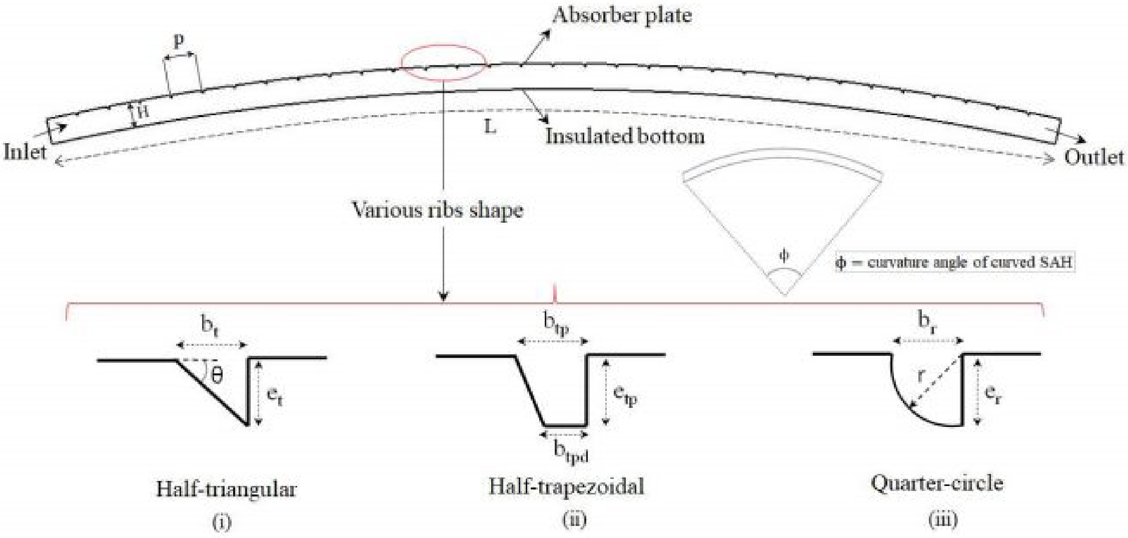

Figure 1.5: Schamatic diagram of curve SAH integrated with semi-down turbulator (i) Half-traingular, (ii) Half-trapezoidal and (iii) Qauter-circle.

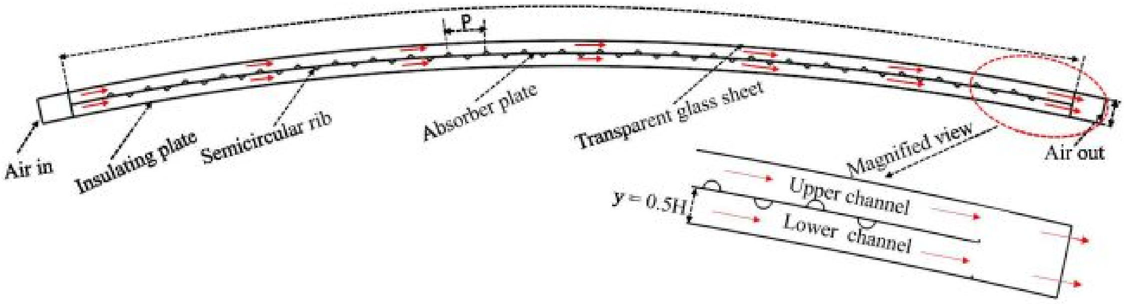

Figure 1.6: Schematic diagram of parallel curved DPSAH

also optimized for higher thermal performance. The maximum thermal and hydraulic performance has been achieved at the configuration at relative pitch ratio $P/d = 6$, relative baffle angle $\alpha/90 = 0.5$.

A flat plate SAH integrated with various channel designs are optimised by investigating thermo-hydraulic performance (chapter 6). The best configuration channel design was further investigated to enhance its performance by introducing a sinusoidal wavy absorber, as shown in Fig.1.9. A semi-ellipse cross-section design is the best choice for unit pressure drop or losses, considering the compromise between thermal and hydraulic performance. The above-discussed novel configuration of force convection SAHs would be appropriate for applications where the continuous high mass flow rate is a basic need. A detailed analysis with a description of the aforementioned solar air heaters is presented in various chapters of the thesis.

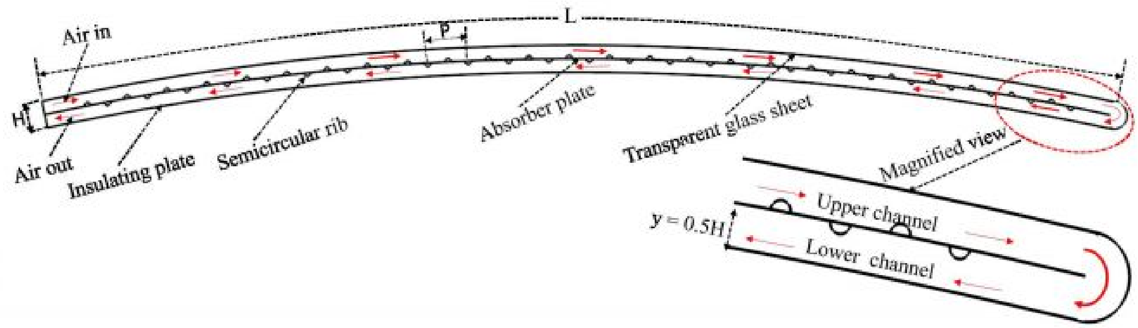

Figure 1.7: Schematic diagram of counter curved DPSAH.

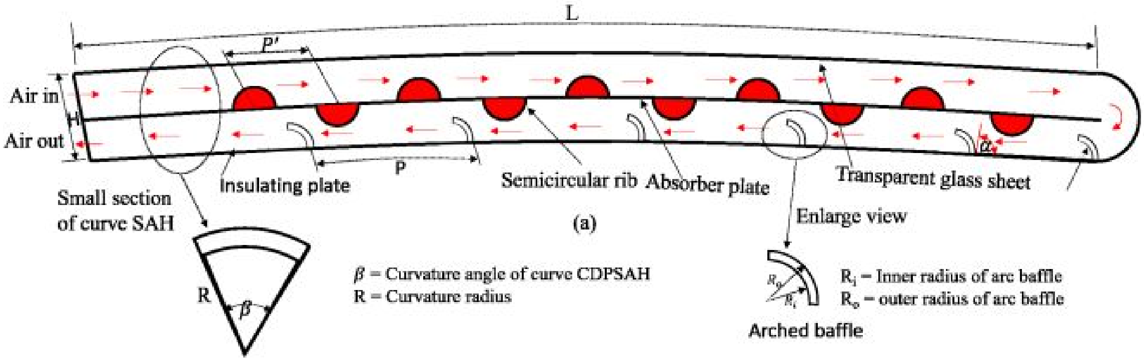

Figure 1.8: Schematic diagram of counter curved DPSAH with strategic placement of arched deflectors in lower channel.

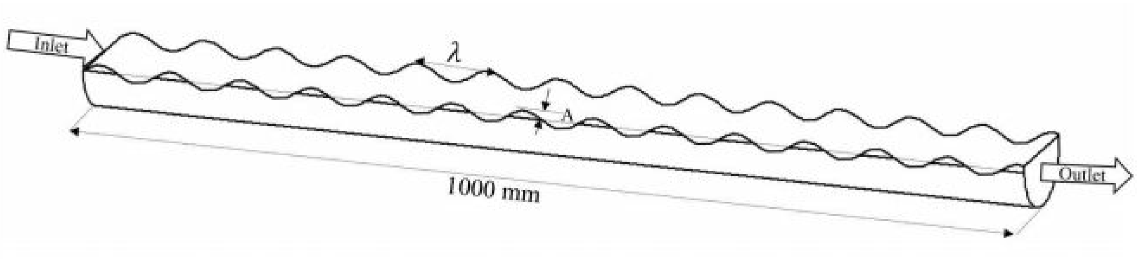

Figure 1.9: Schematic diagram of 3D view semi-ellipse cross-section with wavy absorber plate

1.5 Objective of thesis

As the efficiency of solar air heaters are considerably low, the main objective of this thesis was to investigate novel designs to enhance their efficiency to make them applicable for various application such as space heating, crop drying, industry etc.The main objective can be summarised as:

- Develop experimentally validated numerical models for novel designs.
- To find the best shape of turbulator.
- Develop new design of parallel and counter flow SAHs.
- To investigate new designs for (a) Thermal performance (b) hydraulic efficiency.
- To investigate the effect of various channel designs for the same energy input on the thermo-hydraulic performance.
- Develop the correlation for Nusselt number and friction factor as a function of flow and geometrical parameters.

1.6 Structure of thesis

This thesis comprises of various chapters. Chapters are arranged in such a manner to show the progressive operational efficiency of solar air heaters. The layout is as follows:

- In Chapter 1, introduction, motivation and objectives of the thesis are presented.
- In Chapter 2, efficient design of curved solar air heater integrated with semi-down turbulators
- In Chapter 3, efficient designs of double-pass curved solar air heaters
- In Chapter 4, performance characteristics of a new curved double-pass counter flow solar air heater.
- In Chapter 5, investigations for efficient design of a new counter flow double-pass curved solar air heater presented.
- In Chapter 6, effect of channel designs and its optimization for enhanced thermo-hydraulic performance of solar air heater
- In Chapter 7, conclusions are drawn from various chapters, and suggestions for future work are presented.
- In Appendix, publications by the author in the field of solar energy are enumerated.