Chapter 1

Introduction

As conventional sources of energy are depleting fast, solar energy-based devices can only be mass adopted in future if suitable design innovations are conceptualized and investigated to improve their extremely low energy conversion efficiency. In this thesis, a series of new design concepts of solar thermal devices working on natural convection principle are proposed and analysed by developing experimentally validated computational fluid dynamics (CFD) models. Apart from the improvement in thermal-hydraulic performances, various correlations as a function of Rayleigh numbers, Reynolds numbers and, geometric parameters etc. are also developed to predict the device performance. The first section presents overview of renewable energy and its importance. The second section describes the solar energy powered conventional designs. Further, discussions are focused on the working principle of buoyancy-driven and forced circulation based solar-thermal devices and their operational limitations. The third section presents a brief introduction to novel efficient designs of high flow solar chimney power plant (SCPP), hybrid solar chimney power plant (HSCPP) integrated with photovoltaic panel (PV panel), and buoyancy-driven and forced circulation solar air heaters (SAH). The fourth section covers the objective of the thesis. The last section, shows the layout of the thesis. It is to be mentioned here that since each chapter (from chapter 2 onwards) of the thesis already include comprehensive literature review, I have included the essential information to lay the foundation of the thesis.

1.1 Energy resources: At a glance

Energy is the backbone of economic development of the entire world. The rate of global energy consumption swell with the rapidly increasing in the world population. With depleting sources of conventional energy, there must be some future energy source to meet all global energy requirements, but what will that energy be ?

Energy resources broadly classified into non-renewable and renewable. The one with finite reserves called as non-renewable and those which are infinitely available are termed as renewable. Major non-renewable/fossil fuels are coal, crude oil, natural gas, uranium etc. and human inventions made it suitable for consumption. A very well-known fact that the firing of non-renewable based fuels is severely polluting our environment and causing exponential increase in global warming, which is responsible for adverse climatic changes. Besides the antagonistic environmental impact of fossil fuels, the high price ends the user's affordability and consumers are forced to look over renewable energy resources such as solar, wind, geothermal, ocean and many other to meet domestic and industrial needs. Among renewable energy resources, solar energy is a vast source of heat provided by the sun in the form of solar radiation, if utilized efficiently, can save millions of tons of carbon dioxide from being released by burning of fossil fuels. This clean energy resource is environment-friendly and easily available in daylight hours. The energy received from solar radiation is not in concentrated form like fossil fuels, which is a big challenge for the research community to effectively utilize this tremendous source of heat. The effective use of solar radiation could be possible by efficient designs of the solar-thermal systems. These systems, if possess high energy conversion efficiency or faster transformation rate of solar energy into useful energy, can mitigate our reliance on non-renewable energy sources. Since 1990, renewable energy sources have grown at an average annual rate of 2%, which is marginally higher than the growth rate of the world's total energy supply of 1.8% [1]. An interesting fact that 36.5% annual growth rate has been observed alone for solar energy power [1]. The scientific groups have been putting immense efforts in upgrading solar-thermal devices to attain high energy conversion rate to avail maximum benefits from this vast reliable energy source.

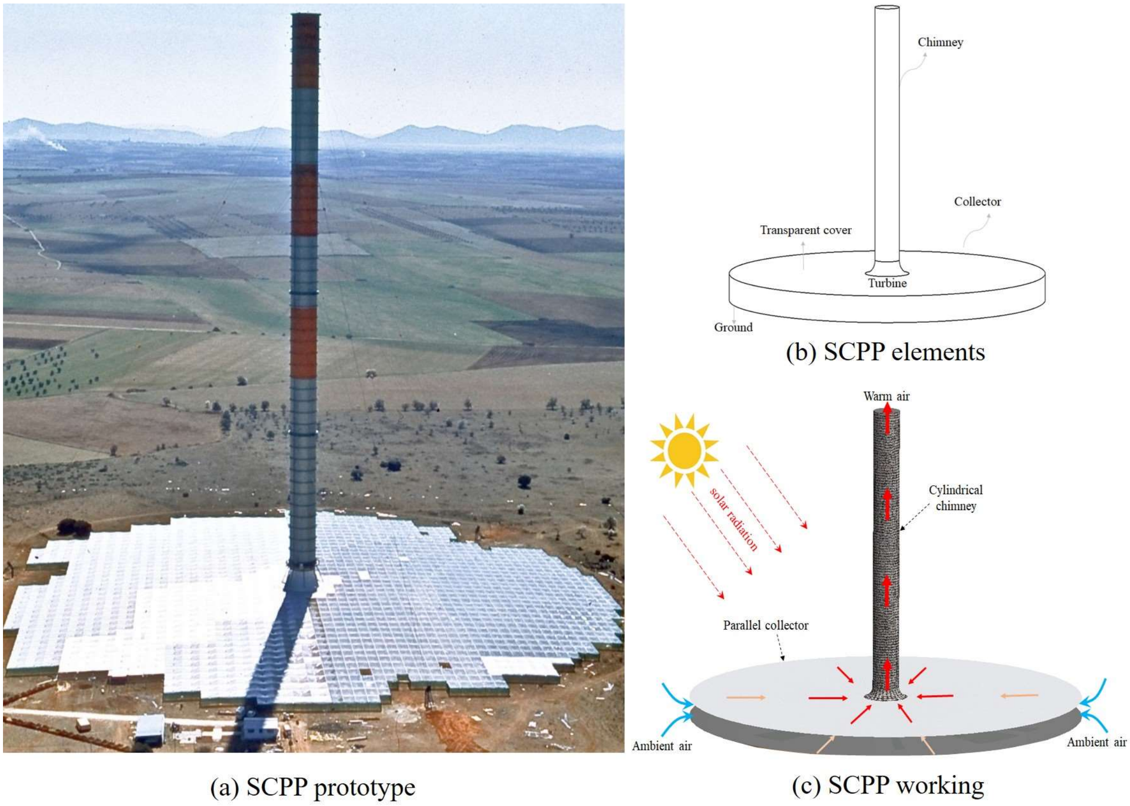

Figure 1.1: Solar energy in power generation application: (a) Solar chimney power plant [6], (b) SCPP key elements, (c) SCPP working. In this thesis, new design of a novel bell-mouth inlet has been proposed and investigated in detail. This new design has been investigated by integrating it to a solar chimney power plant and solar air heater.

1.2 Conventional solar devices: An outlook

Solar radiation available in day time used to serve many applications all around the world, such as electricity generation, air heating, water heating, crop drying, and many other domestic and industrial applications [137, 139]. In general, the solar devices receives solar insolation at the top transparent cover, which get further trasmitted to the collector bottom also called as absorber. The fluid (air/water) flows between the transparent cover and absorber gains the heat during interaction with the absorber, which provides the high enthalpy fluid at the delivery section of the device. The solar devices are classified based on its working principle as active and passive systems. In active solar devices such as air heater, water heater, etc., additional devices needed for its operation such as blower unit to pump the fluid in the flow channel, and the quick transformation of solar energy into more usable form occurs. On the other hand, passive solar devices such as Trombe-wall, air heater, space natural ventilation, etc. does not need any external device for its operation as they are self-driven under the effect of buoyancy.

A solar chimney power plant (SCPP) is a well-known application for electricity production (see Fig. 1.1). A typical SCPP comprises of a circular collector to receive solar radiation with a tall vertical cylindrical chimney at its center. The wind turbine is generally mounted at the collector exit. The airflow through the collector drives the turbine to generate electricity. It works on the principle of greenhouse effect in which fluid naturally flows in the flow passage under the effect of buoyancy forces. Various hybridization techniques have already been studied to augment the system performance. Despite greater flexibility of the device, the system is economically unviable due to its extremely low energy conversion efficiency. The device efficiency is as low as 2% [6]. The turbine power output suffers due to low flow velocity at the turbine location. Since buoyancy forces are responsible for its operation, enhancing the system overall performance is a challenging task. Naturally driven solar air heaters (SAH) works on the same buoyancy principle as solar chimney power plant [6]. Design changes that enhanced SCPP performance have also been integrated and investigated for SAH performance in this thesis. The SAH has vast applications in agricultural drying, space heating, natural ventilation, chemical processing plants, laundries, etc [73, 87, 133]. The flow channel of the device comprises of a top transparent cover and a metallic absorber plate at the bottom. The solar radiation received by the absorber plate delivers energy to the flowing fluid in the channel. The forced circulation based air heaters attains high thermal efficiency at the expense of high hydraulic losses and external power sources. However, natural convection based air heaters, though less efficient, are self-sustainable. The passive systems are helpful in reducing heating/cooling loads of buildings, but there are various design issues. The rectangular cross-sectional inlet leads to higher entry hydraulic losses, which significantly reduces the overall performance [137]. The low mass flow rates is the major drawback of these natural heating devices and underperforms for the application where high mass flow rate is the primary requirement.

Issues related to conventional solar-thermal devices:

- Low thermal efficiency
- High hydraulic losses
- Low mass flow rates of self-driven systems
- Low energy conversion rate
- Hybridization is a challenge
- Large response time
- Less efficient

1.3 Novel efficient designs

Conventional design of solar-thermal devices has drooping performance characteristics. The thesis comprises of multiple novel designs in order to elevate the thermo-hydraulic performances of these conventional systems using experimentally validated computational fluid dynamics (CFD) models. A brief description of the thesis about various novel designs of solar chimney power plant and solar air heaters are discussed here to bring better insight and clarity. A SCPP is a highly versatile device and it has vast potential for electricity production if designed efficiently. Figure 1.2 shows new design of SCPP with downward bell-mouth design inlet integrated with converging flow channel and divergent chimney.

The integration of bell-mouth design at the inlet of the SCPP collector is first of its kind design investigation (chapter 2). Bell-mouth design reduces the inlet losses thereby increasing the velocity of buoyant heated air. The converging collector and diverging chimney further increases the system pressure potential. Further investigations have been carried out in hybridization of SCPP by integrating it with PV panel (chapter 3). The PV panel's performance deteriorates with increase in the solar cell temperature. With strategic hybrid SCPP designs, efficient cooling of PV panel has been achieved to maximize its energy conversion efficiency. This combination of PV panel with SCPP further enhances the electric power generation capacity. If multiple of such efficient SCPP designs are installed in a region which are rich in sunshine, it can power thousands of villages.

Furthermore, new designs of buoyancy-driven solar air heaters have developed to overcome the conventional designs limitations. The two major challenges in naturally-driven flow systems are: (a) to increase the thermal performance without incorporating fins/ribs in the flow channel; (b) augmentation of air mass flow rate. The novel designs of the curved flow passage namely convex and concave are proposed to achieve high thermal performance (see Fig. 1.3) (chapter 4). Beyond 40% improvement in thermal performance for curved SAH device has been observed in comparison to conventional parallel flow passage design.

The bell-mouth designs developed for solar chimney power plant as described earlier was integrated in solar air heater and its performance was investigated (chapter 5). The new designs of bell-mouth equipped SAH called as high flow SAH (see Fig. 1.4) exhibited 3-fold increase in the mass flow rate of the device. This

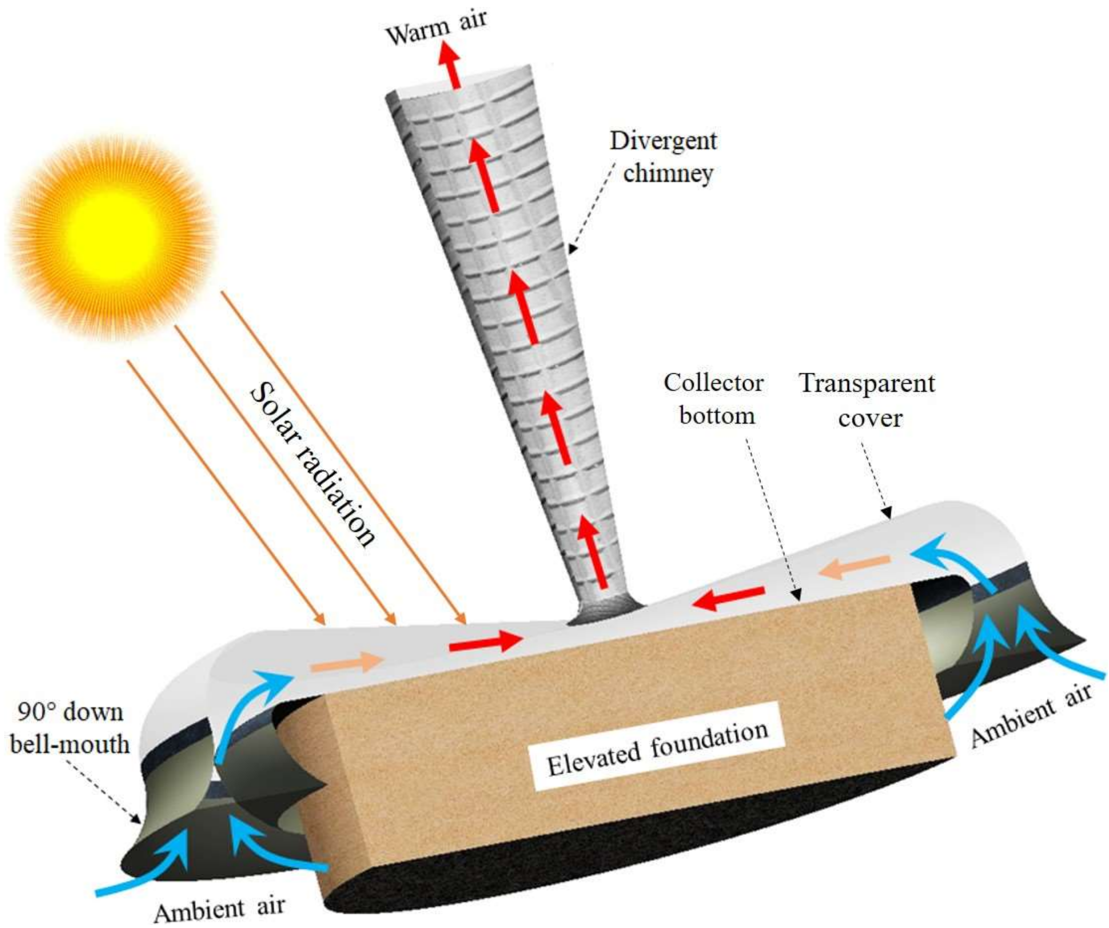

Figure 1.2: Isometric view of high flow solar chimney power plant.

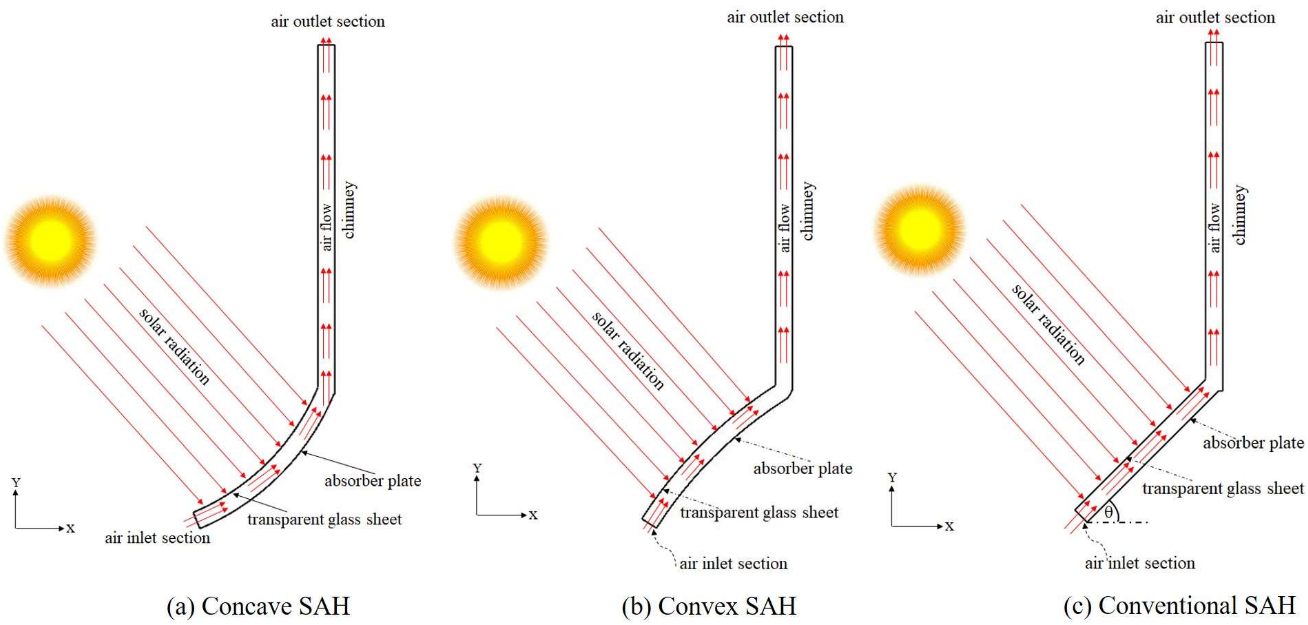

Figure 1.3: Schematic diagram of convex-concave buoyancy-driven solar air heater.

significant increase in the mass flow rate makes the SAH design suitable for the high flow rate applications. In a comparative analysis between high flow and conventional SAH in a building heating application, the former device attains the desired temperature 1 hour 10 minutes earlier than the conventional design which is quite significant saving of time. To further increase the air temperature of the high flow SAH, a taper flow channel in combination with optimum bell-mouth design was developed (chapter 6). It has several advantages in the applications where air at high flow rate - high temperature are essential such as giant dryers, large building heating, and many other applications.

Designs of curved SAH integrated with semi-down turbulators are also developed and investigated (chapter 7 and 8). The new designs of forced circulation curved corrugated SAH device attained 91% higher thermal efficiency and 10-12% improvement in the exergy gain compared to smooth conventional flat SAH. The device would be suitable for applications where continuous high mass flow rate is the basic need. An aerodynamic study of environmental wind condition impact on natural and forced convection SAH has also been performed for prediction of the overall dynamic performance of SAH device in a real environment (chapter 9). A detailed analysis with description of the above discussed solar-thermal devices are presented in various chapters of the thesis.

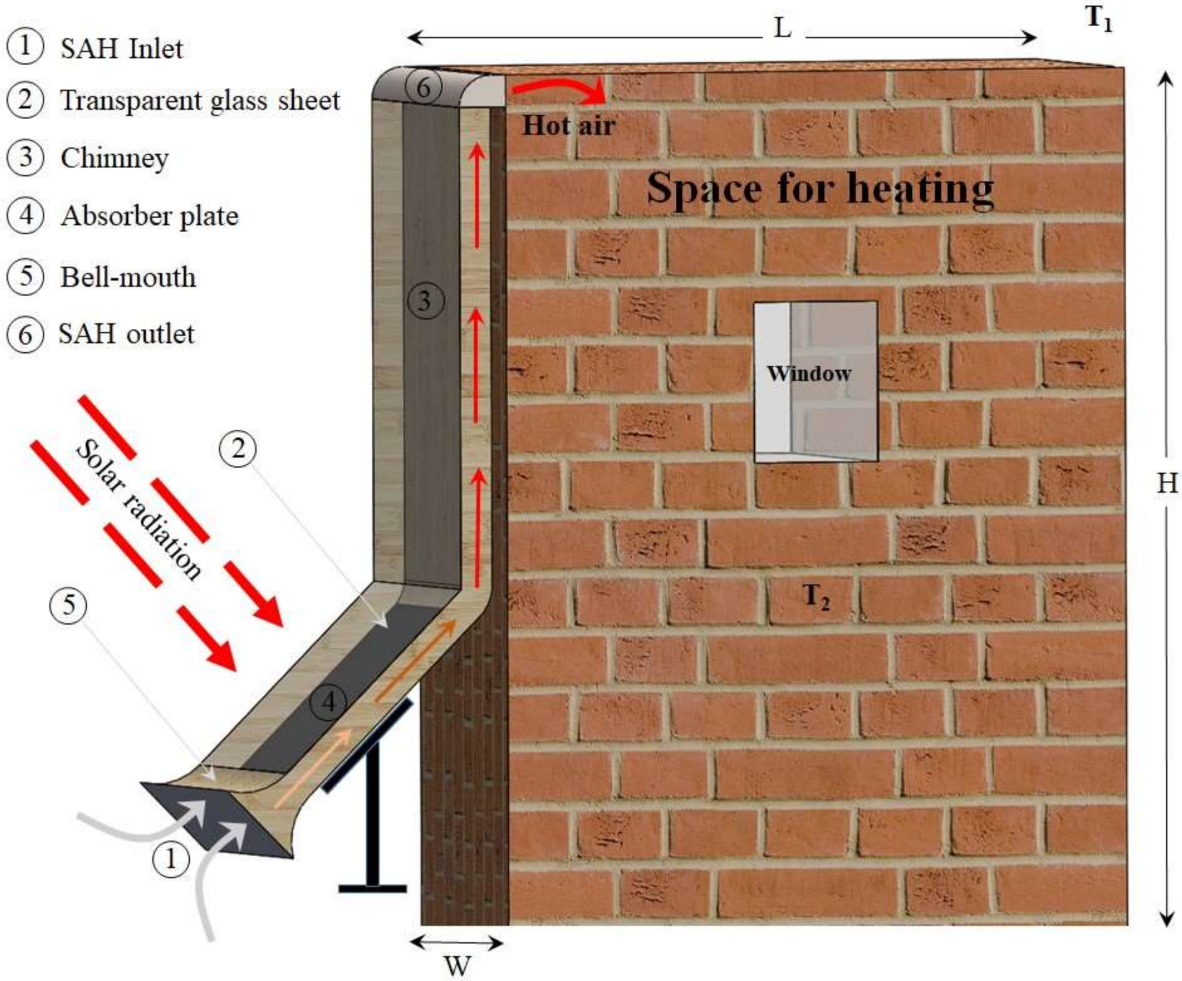

Figure 1.4: Schematic diagram of high flow solar air heater integrated with building.

1.4 Objective of the thesis

Since the efficiency of solar-thermal devices are significantly low, the main objective of this thesis was to develop novel designs to increase their efficiency to make them suitable for various applications such as space heating, agri-product drying etc. The objectives can be roughly categorized as:

- Develop novel designs of bell-mouth inlet and solar collector integrated in a solar chimney power plant and solar air heater.
- Develop validated CFD models of the novel designs.
- Analyse the new designs for: (a) Thermal performance; (b) Hydraulic efficiency.
- Analyse the system for range of governing and geometric parameters.
- Develop correlations as a function of various parameters.
- Analyse the performance of new designs under various ambient conditions.
- Studied the effect of integrating PV panel in the solar chimney power plant.

1.5 Organization of the thesis

This thesis discusses about retrofitting novel concept of bell-mouth and new collector designs of solar-thermal devices namely solar chimney power plant (SCPP) and solar air heater (SAH) (refer Fig. 1.5). The bell-mouth opening at inlet attenuates hydraulic losses and thereby bring considerable performance improvement of naturally-driven systems. Furthermore, converging collector designs proven to be the best in terms of electric power generation of SCPP and thermally efficient for SAH. A combined effect of bell-mouth inlet and converging collector has been analyzed with divergent chimney of SCPP for further enhancement of turbine power output, which is the very first study reported so far. Thermo-hydraulically efficient designs of natural convection SAH for high flow rate applications have been proposed.

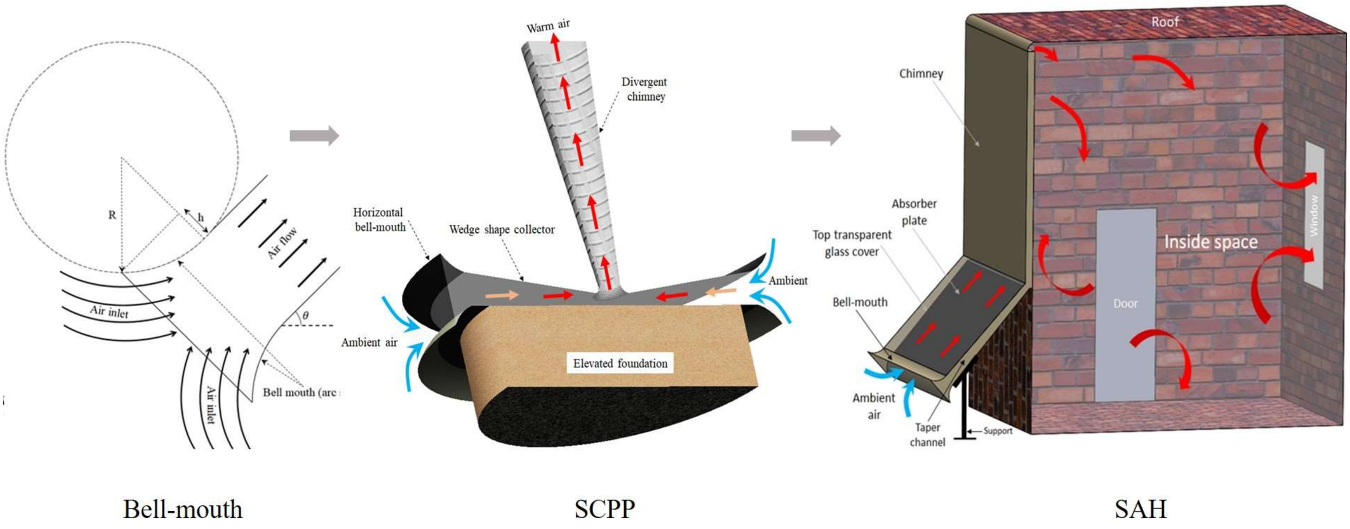

Figure 1.5: Bell-mouth inlet opening retrofitted with converging collector of solar chimney power plant and solar air heater.

This thesis contains ten chapters. Each chapter follows the other in such a manner to bring progressive improvement in operational efficiency of solar-thermal systems. Various possible ways have been examined to optimize SCPP and SAH designs to examine the feasibility in wide variety of applications. Its layout is as follows:

- In Chapter 1, introduction, motivation, and objectives of the thesis are presented.
- In Chapter 2, investigated the new concept of bell-mouth design inlet integrated with taper collector and divergent chimney of SCPP.
- In Chapter 3, examined the hybrid SCPP integrated with photovoltaic panel for dual power generation.
- In Chapter 4, novel designs of convex and concave buoyancy-driven SAH are presented.

- In Chapter 5, various designs of SAH integrated with bell-mouth design inlet to achieve high mass flow rates are investigated.
- In Chapter 6, has been discussed about the natural convection based taper SAH for high flow - high temperature applications
- In Chapter 7, a comparative analysis between curved and flat SAH has been presented.
- In Chapter 8, energy and exergy analysis of corrugated curved SAH with semi-down turbulators has been discussed.
- In Chapter 9, an aerodynamic analysis has been presented to predict the SAH performance under real environmental conditions.
- In Chapter 10, conclusion drawn from various chapters and suggestions for future work are presented.