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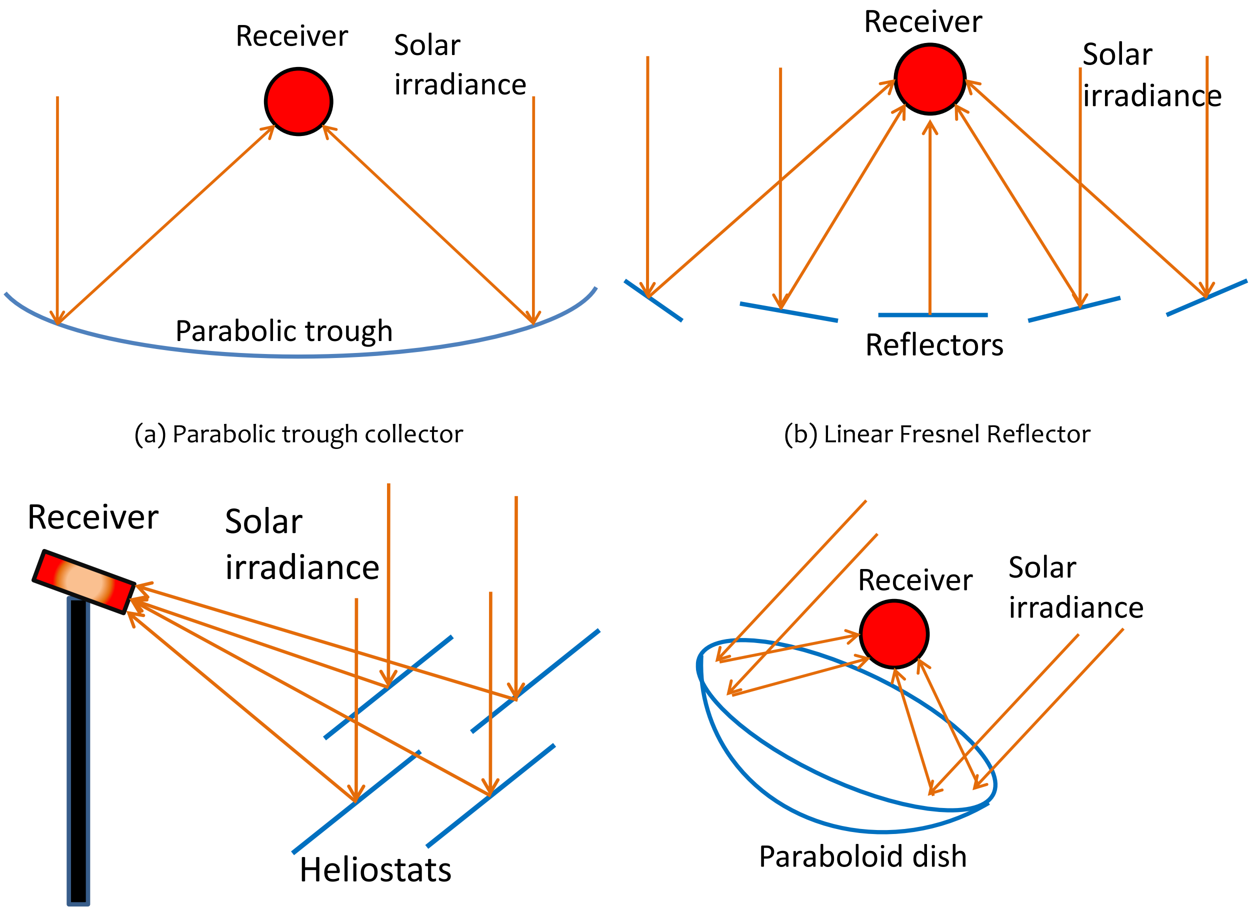
Introduction

The increasing demand of energy and the depleting fossil fuel resources necessitates the use of renewable energy sources to fill the gap. This includes for instance, solar energy, wind energy, ocean/wave energy, and geothermal energy. Among these resources the solar energy has the highest potential being the primary source [Baharoon *et al.*, 2015; Bijarniya *et al.*, 2016] and expected to promote the low carbon emissions [Teske *et al.*, 2016]. Therefore, the use of solar energy will mollify the challenges associated with CO_2 emissions, to some extent. The received solar energy on the Earth exceeds 1000 times the total commercial energy demand [Tian and Zhao, 2013; Bijarniya *et al.*, 2016]. The solar radiation has two components viz. direct normal and diffused radiation. The undisturbed direct normal radiation incident onto the Earth's surface and the diffused radiation is the scattered fraction of the total extraterrestrial solar energy due to the gases and particles present in the atmosphere. The direct normal irradiance (DNI) is harnessed using the concentrated solar thermal technologies and the diffused radiation serves as an input to non-concentrating and photovoltaic systems. The north-western region of India, i.e. Rajasthan and Gujarat receives a DNI of about 5-5.5 kW/m^2/Day during a clear sky [Purohit and Purohit, 2010; Bishoyi and Sudhakar, 2017; Kumar *et al.*, 2017]. Thus, these regions are being preferred for installing concentrating solar thermal power plants. There are different types of concentrating solar thermal technologies, which are currently in use for power generation and for process heat applications [Asif, 2017]. These are discussed subsequently.

1.1 CONCENTRATED SOLAR THERMAL TECHNOLOGIES

In these technologies, the principle of operation is that the direct normal radiation is reflected from a larger reflecting surface (collector) onto a receiver with a comparatively smaller surface area. The concentrated solar thermal (CST) power technologies are categorized into line and point focusing. In the line focusing technologies, the direct normal radiation is focussed along the entire length of a receiver. The parabolic trough collector and linear Fresnel reflector based systems belong to this category. The area concentration, which is the ratio of reflector to receiver area, is generally of the order of 100. The heliostat based solar tower and paraboloid dish based systems are the point focusing technologies. In the point focusing technologies, the direct radiation is focussed onto a receiver with a much small aperture so that the flux concentration may exceed 1000 Suns. Thus, using such a system a temperature beyond 1000 K is achievable. The schematics of all these CST technologies are shown in Figure 1.1 [Behar *et al.*, 2013; Zhang *et al.*, 2013; Baharoon *et al.*, 2015]. These are represented using the different receivers and collector designs. In general, a receiver is the heart of CST system and is exposed to the concentrated solar thermal irradiance. A heat transfer fluid is used for removing the generated heat from the receiver and the same is transferred for an application viz. power generation, heating and cooling. The thermal efficiency of such systems depends on the involved heat transfer process including the losses to ambient via convection and radiation.



(a) Parabolic trough collector (b) Linear Fresnel Reflector

(c) Solar tower (d) Paraboloid dish

Figure 1.1: Concentrating solar thermal technologies.

The parabolic trough collector (PTC) based systems are the most matured and are widely deployed for the concentrated solar thermal power generation [see e.g. Behar *et al.*, 2013]. The linear Fresnel reflector (LFR) based systems are preferred for the direct steam generation and are being investigated for applications including process heat. The central receiver based solar towers are more versatile as a consequence of high temperature. These include power production, process heating and cooling. At IIT Jodhpur a novel application of the metals processing is being developed to mitigate the required electricity or for saving the conventional fuel. The paraboloid dish systems are used specifically in process heating and cooling. Recently, the solar tower has attracted the researchers in terms of its potential to achieve a high working temperature [Ávila-Marín, 2011]. Some of the operational and under construction solar tower power plants are summarized in Table 1.1 [Islam *et al.*, 2018].

Table 1.1: Operational and under construction solar tower power plants [Islam *et al.*, 2018].

Project	**Start Year**	**Country**	**Gross Turbine Capacity (MW)**	**Status**
ACME Solar Tower	2011	India	2.5	Operational
Crescent Dunes Solar Energy Project	2015	USA	110	Operational
Dahan Power Plant	2012	China	1	Operational

Gemasolar Thermosolar Plant	2011	Spain	19.9	Operational
Greenway CSP Mersin Tower Plant	2012	Turkey	1	Operational
Ivanpah Solar Electric Generating System	2014	USA	377	Operational
Jemalong Solar Thermal Station	2016	Australia	-	Operational
Jülich Solar Tower	2008	Germany	1.5	Operational
Khi Solar One	2016	South Africa	50	Operational
Lake Cargelligo	2011	Australia	3	Operational
Planta Solar 10	2007	Spain	11	Operational
Planta Solar 20	2009	Spain	20	Operational
Sierra Sun Tower	2009	USA	5	Operational
Ashalim Plot B	2017	Israel	121	Under Construction
Atacama-1	2018	Chile	110	Under Construction
Golmud	2018	China	200	Under Construction
NOOR III	2017	Morocco	150	Under Construction
Sundrop CSP Project	2016	Australia	1.5	Under Construction
Supcon Solar Project	2010	China	50	Under Construction

In a central solar thermal system, a receiver is placed on the top of a tower, which is surrounded by a field of heliostats. This is exposed to the concentrated solar irradiance and the heat is generally recovered with the help of a fluid (liquid/gas) for a thermodynamic cycle. The concentrated heat flux and the resulting temperature may exceed 1000 K and as a consequence a high thermal efficiency is expected. The receiver may consist of several absorbers, wherein the concentrated flux may vary between 300 kW/m^2 to 1000 kW/m^2. Such a high flux concentration offers a challenge for the receiver design and the sustained operation of the central solar tower based systems. The central solar tower receivers are broadly classified basing on the heat transfer fluid, such as gas, liquid and solid as depicted in Figure 1.2 [Ho and Iverson, 2013]. According to the geometrical configuration, the receivers are further divided into an external and a cavity-type. These may be directly or indirectly irradiated depending on the absorber materials [Becker and Vant-Hull, 1991]. Directly irradiated receivers make use of darkened fluids or particle streams for an efficient heat transfer from the concentrated flux. The small particle receiver, falling film receiver and falling solid particles receiver are some examples of such systems. The first type of receiver consists of the suspended carbon particles in air and is heated by the concentrated solar irradiance. The solid particles are selected based on their heat capacity to store the thermal energy. In the falling film receivers, the gravity driven flow of a heat transfer fluid may be heated directly or indirectly through a wall. The key design element in an indirectly heated receiver is the radiative-convective heat exchange surface. The tubular and volumetric receivers are indirectly heated receivers. In tubular receivers, the heat transfer fluid flows inside an array of tubes and the heat removal from the exposed surfaces is via conduction and forced convection. The maximum operating flux of such a receiver is around 600 kW/m^2 [Romero *et al.*, 2016]. In volumetric receivers, highly porous structures made of metal alloy or ceramics absorb the concentrated solar flux and operate as a heat exchanger. The heat transfer medium (mostly air) flows through the porous structure and is heated by the forced convection. The closed volumetric air receivers generally use pressurized gas as the heat transfer fluid.

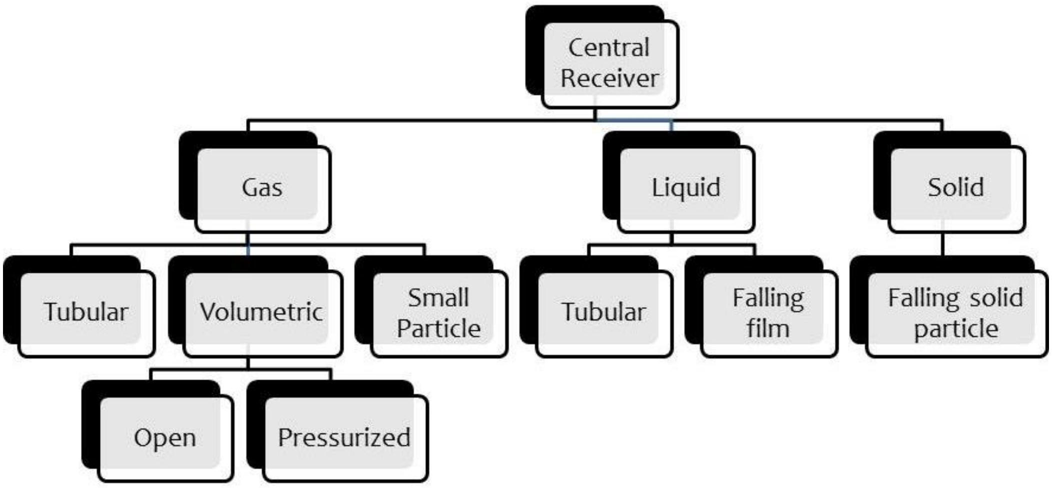


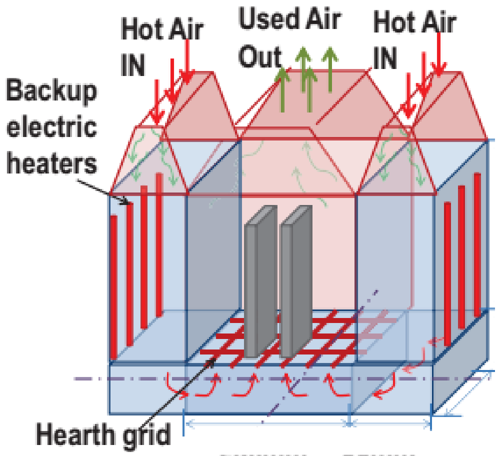
Figure 1.2: Classification of central receivers for solar tower [Source: Ho and Iverson, 2014].

Among these receivers, the tubular and volumetric receivers are typically employed in a central solar tower. The volumetric receiver has several comparative advantages, for instance, (a) ability to withstand a much higher heat flux due to volumetric absorption [Romero *et al.*, 2002], (b) a high specific surface area that allows the use of air as heat transfer fluid, (c) the desired volumetric effect will mitigate the heat loss by radiation and (d) finally, air is freely available and non-toxic. The developed solar air tower simulator (SATS) facility for experimental evaluation of an open volumetric air receiver is presented subsequently [Sharma *et al.*, 2015a, b].

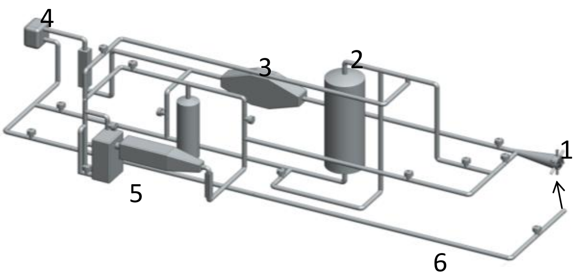
1.2 SOLAR AIR TOWER SIMULATOR (SATS) FACILITY

For the evaluation of an open volumetric air receiver a solar air tower simulator (SATS) is installed at IIT Jodhpur. This is used for investigating the concept of solar convective furnace (SCF) in 1:15 scale of an industrial furnace [Patidar *et al.*, 2015]. A schematic of the same is shown in Figure 1.3(a), which includes the side injection ducts, the hearth and the outlet vent besides a hearth grid for placing the metal ingots. Hot air is introduced at the inlet and the metal ingots are exposed to the same for the heat treatment, like annealing of Aluminum, which limits the required air temperature up to 750 K. These metal ingots are placed on the hearth grid as per the standard furnace design. Also, the backup electrical heaters are retained to ensure the required power input during a shortfall or inadequate level of solar irradiance. This retrofitted scale-down model solar convective furnace is included in the integrated SATS facility. The involved sub-systems in this facility are shown in Figure 1.3(b) and (c). This includes an open volumetric air receiver, a heat exchanger, thermal energy storage (TES) and a convective furnace. The atmospheric air is sucked in by a blower, which is installed at the rear side of the SATS facility. In this setup the obtained hot air from receiver is used for charging the pebble-bed based sensible TES. Subsequently, the heat is recovered with air from the TES for metals processing in SCF. The dimensions of the SATS sub-systems are given in Table 1.2 [Sarma, 2013; Kumar, 2013]. In this experiment facility hot air from receiver is transported to the primary sensible pebble bed thermal energy storage (TES1) for its charging. During the metals processing operation the stored heat in TES1 is recovered and transported to the furnace via the insulated piping network. A small (1:4 scale of TES1) secondary sensible thermal energy storage

(TES2) is installed at the outlet of solar convective furnace. The warm air from furnace outlet is introduced in TES2 for recovering the otherwise waste heat. Thus, an in-situ waste heat recovery mechanism is inbuilt in the SATS facility.



(a)



(b) (c)

Figure 1.3: (a) A schematic of the designed solar convective furnace (b) Solar air tower simulator facility, 1) open volumetric air receiver; 2) thermal energy storage; 3) heat exchanger; 4) blower; 5) solar convective furnace; 6) air return system. [Sharma *et al.*, 2015a, b] and (c) the installed SATS facility at IITJ.

Table 1.2: The details of SATS sub-systems with their respective dimensions.

SATS sub-system	Component of sub-system	Details
Open Volumetric air receiver	Absorber	No. of absorbers: 7, , Length: 25.4 mm, Diameter: 25.4 mm, Porosity: 52-62 %, Diameter of pores: 2mm.
	Foot-piece	No. of foot-pieces: 7, Convergent angle: 40°, Length of extruded portion: 25.4 mm.
	Mixing chamber	Length 20 mm.
	Perforated plate	No. of pores: 14 (staggered arrangement), Diameter of pore: 14.4 mm.
	Nozzle	Convergent angle: 9.54°, Length: 137 mm.
	Return air injection ports	No. of ports: 6, Diameter of port: 11 mm.

Heat Exchanger	-	Dimensions: 150 mm x 350 mm x 108 mm, Tubes arrangement: Staggered, No. of tubes: 24.
TES 1	-	Height: 1000 mm, Diameter: 250 mm, No. of chambers: 4, Thermal storage material: Pebbles.
TES 2	-	1:4 scale model of TES1
Blower	-	Twin lobe type blower with variable feed drive.
SCF	-	Furnace hearth dimensions: 235 mm x 235 mm x 235 mm.

The metal absorber based receiver is designed in view of the limiting temperature requirement for the solar convective furnace system. A two-dimensional cut view of the designed receiver is shown in Figure 1.4(a). This shows the path of return and primary air denoted by dotted and solid arrows. The three dimensional receiver model and the manufactured absorber module are shown in Fig. 1.4(b) and (c). Brass is selected as the absorber material considering the manufacturing aspects, high thermal conductivity and the required temperature range. The porosity (ε) of these absorbers is in between 42-62 %, which is comparable to HiTRec II and SolAir 200 ($\varepsilon \sim 49.5\%$). Also, Brass has nearly the same thermal diffusivity as of SiSiC, which is employed in most of the receivers. The absorber is made of straight circular pores lowering the chances of dust deposition are in comparison to the foam-type. Moreover, the straight pores offer a lower pressure-drop as compared to a foam-type absorber, which will reduce the parasitic losses. The length and diameter of the designed porous absorber is 25.4 mm with the pore diameter of 2 mm. The dimensions are based on the analysis performed by Sharma *et al.* (2015a).

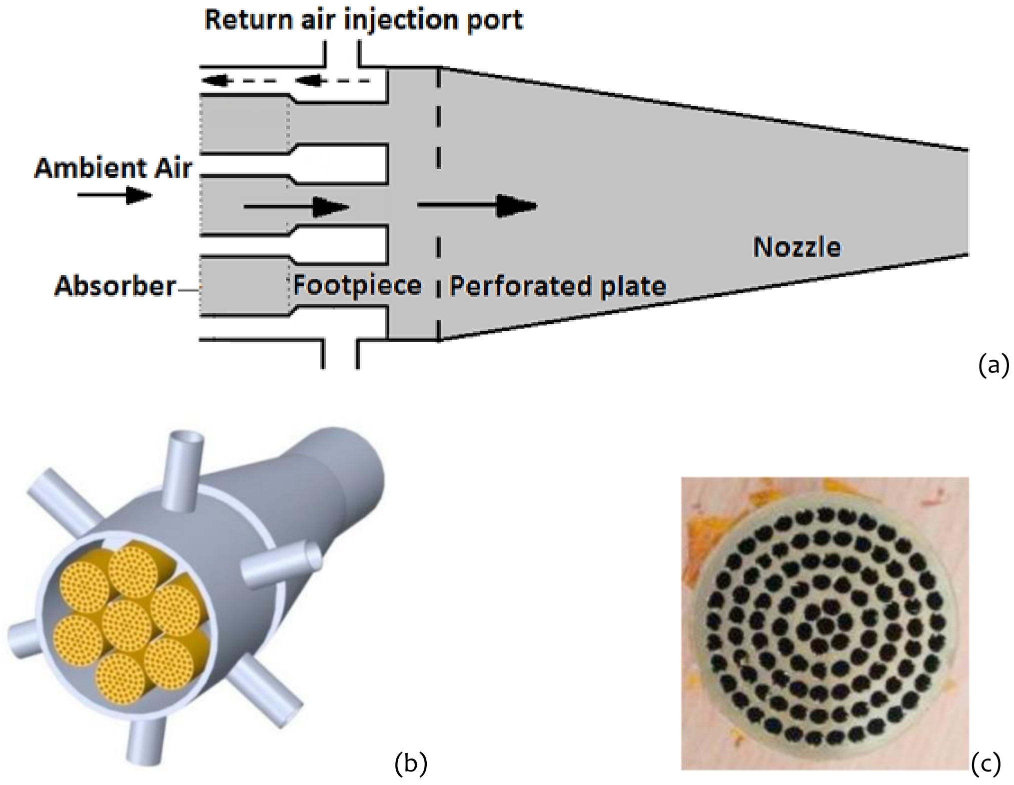


Figure 1.4: (a) A schematic of the designed open volumetric air receiver at IIT Jodhpur [Sharma *et al.*, 2015a,b]; (b) The designed model of receiver assembly; and (c) a manufactured absorber with straight circular pores.

The volumetric heating of receiver is desired (Hoffschmidt *et al.*, 2003). In laboratory, the same is achieved with the Joule heating using Nichrome wires wrapped around the circumference of absorbers; see Sharma *et al.*, (2015a, b) for more details. Simultaneously, the atmospheric air is sucked through the absorber pores for heat removal via forced convection. The resulting hot air is transported through the foot-piece to ensure its radial thermal uniformity at the absorber-foot-piece outlet. The space between anchor and perforated plate is envisaged for the cleaning and collection of dust that enters through the pores. This and the related aspects are discussed in subsequent chapters at greater details. The perforated plate with nozzle is used for the homogenization of air temperature at the receiver outlet. The relatively cold air through the convective furnace and thermal energy storage is returned through the six air injection ports provided on the circumference of the receiver as shown in Figure 1.4(a). The return air injection ports are provided to prevent the overheating of absorbers and foot-pieces, and to mitigate the thermal stresses over the absorbers. To summarize, the aim of the designed open volumetric air receiver is to (a) provide a uniform air temperature at its outlet and (b) ensure its stable operation under dusty environment. The dimensional and functional details of the design are explained in Sharma *et al.* (2015a, b). As explained, the air temperature is limited to 750 K in the first phase of development. The same may be relaxed with an appropriate selection of absorber material. The open volumetric air receiver is considered as heart of the system. Therefore, its detailed evaluation, the associated issues and challenges pertinent to its operation in arid deserts are considered in this thesis. These are explained in the next chapter based on a detailed literature review on the receiver followed by the objectives. The thesis, therefore, may be regarded as a step towards realizing open volumetric air receiver based solar convective furnace system in arid deserts.

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