2

Open Volumetric Air Receiver: Literature Review

2.1 DESIGN AND EXPERIMENTS

Open volumetric air receiver comprises of high temperature resistant absorbers that are made of metal wire, metal or ceramic open-cell matrix structures like monolithic honeycombs or reticulated foams. Ávila-Marín (2011) has reviewed the reported designs of the open volumetric air receivers (see Table 2.1). They are generally highly porous, allowing incident radiation to penetrate and eventually absorbed deep into the structure. Thin substructures (wires, walls, or struts) ensure good convective heat transfer. The design of volumetric receivers is a trade-off between conjugate heat transfer processes with interconnected optical and thermal requirements. The performance of an open volumetric air receiver or its thermal efficiency or thermal effectiveness is defined as in eq. (2.1). It is the ratio of useful heat gain by the air to the input thermal power. The air is driven by means of a blower or suction.

$$\eta_{th} = \frac{\text{Useful heat gain rate by air passing through receiver}}{\text{Input thermal power}} \tag{2.1}$$

The target operating conditions of such a receiver for the widespread deployment in industrial are demanding [Mehos *et al.*, 2016]. For instance, the thermal energy conversion efficiency of about 90% at a working fluid temperature in the excess of 1000 K, minimum service life of 10,000 cycles and the overall cost below 150 US Dollar per kilowatt of thermal power delivered. A high operating temperature leads to substantial radiation and convection based heat loss. Thus, the need for an efficient downstream thermochemical or power cycles is foreseen.

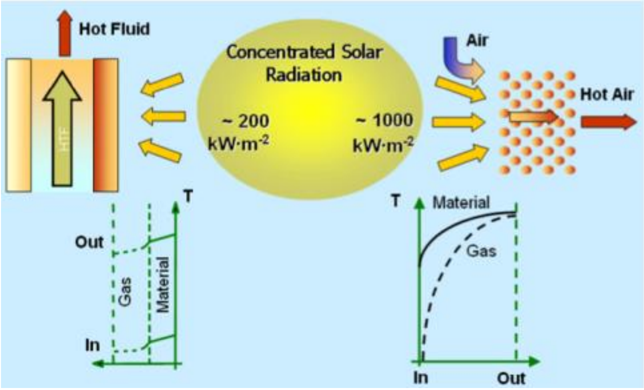

Figure 2.1: Temperature distribution in tubular and volumetric receiver [source: Ávila-Marín, 2011].

A volumetric receiver should, ideally, work on the principle of volumetric effect, which means that the irradiated side of the absorber is at a lower temperature than the heat transfer fluid (air) at the outlet [Boehmer *et al.*, 1991]. The same is illustrated in Figure 2.1 and this reduces the heat loss from the absorber surface to atmosphere. There exists, however, scarce experimental evidence of solar receivers achieving such a volumetric effect. The exception is a double-layer selective receiver composed of an external silica square-channel monolithic honeycomb and an internal layer of silicon carbide particles [Menigault *et al.*, 1991]. A similar double-layer configuration wherein the internal particle layer was replaced by a ceramic silicon carbide monolith concluded otherwise [Pitz-Paal *et al.*, 1992]. A comprehensive review on the receiver is provided by e.g. Romero *et al.*, (2002), Ávila-Marín (2011), and Ho (2017). SANDIA foam is one of the earliest developed absorber made of a ceramic material with a thermal efficiency of ~ 54%. Later on, other receivers were developed viz. MK-I, Suzler-I/II, Catrec_I/II with the reported various issues during their operation. Although the thermal efficiency was improved in these designs but the local overheating and the flow instability remained some of the inhibiting factors to achieve the desired high temperatures.

Table 2.1: Reported designs of open volumetric air receivers.

Name	Year	Material	Absorber type	Efficiency (%)	Max. outlet temp (◦C)
SANDIA FOAM	1979	Alumina	Foam	54	730
Mk-I	1983	AISI 310	Thin wire mesh	70-90	-
Sulzer 1	1987	AISI 310	Thin wire mesh	68	830
Sulzer 2	1988	AISI 310	Coiled knit wire	79	800
Catrec 1	1988	Stainless steel	Honeycomb foil	80	826
CeramTec	1989	SiSiC	Foil	59	782
Conphoebus-Naples	1991	SiSiC	Straight pores	60	788
Selective receiver	1991	SiSiC	Straight pores	62	750
TSA	1992	Inconel 601	Coiled knit wires	79	950
Bechtel 1	1993	Nichrome	Thin wire mesh	69	-
Bechtel 2	1993	Nichrome	Thin wire mesh	66	656
Catrec 2	1993	Stainless steel	Honeycomb foil	70	560
HiTRec I	1995	re-SiC	Straight pores	68	980
HiTRec II	1998	re-SiC	Straight pores	72	800
SIREC	2001	Alloy 230	Thin wire mesh	48	973
SOLAIR 200	2002	re-SiC/SiSiC	Straight pores	75	815
SOLAIR 3000	2003	re-SiC	Straight pores	75	-
IIT Jodhpur	2015	Brass	Straight pores	70-80	350

The HiTRec-SolAir receiver at the pre-commercial industrial scale was designed to address some of the above-mentioned issues [Hoffschmidt *et al.*, 2001]. Here, the ceramic absorbers are supported on a stainless steel support structure, which forms the base of the receiver. The support structure is a double-sheet membrane, which may be cooled by either ambient or recirculating air. The spacing between absorber modules allowed their axial and radial thermal expansion during operation. Absorber cups are attached with the foot-piece, which pass through holes in the front sheet and are welded to the rear sheet. The cooling air circulates between the two sheets and, as it leaves through the sides of the segments. The return air reaches the absorber aperture through their intermediate gap. The outgoing air mixed with ambient air is sucked back through absorber pores as the primary air and the operation continues. The fraction of return air, which enters the receiver after mixing with the ambient air is called air return ratio. The non-uniform concentrated solar irradiance profile onto receiver aperture is follows a quasi-Gaussian profile over the front surface of the receiver. To promote thermal uniformity and mitigate the occurrence of flow instability the air mass flow rate through the absorber is regulated with an orifice. The introduction of modular ceramic absorber mitigates the effect of thermal shocks during start-up/shut-down and allows achieving a high operating temperature. Modularity also facilitates the cooling of the receiver internal with the help of return air flow in the gaps between absorbers. The first HitRec OVAR reached a maximum average outlet temperature of 980 ºC with a thermal efficiency of 68% [Hoffschmidt *et al.*, 1999]. The next milestone in the development of this type of receiver was the qualification of the 200 kW HiTRec-II receiver. During the course of the test program, the HiTRec-II receiver was operated over a period of 38 days, accumulating a total of 155 operating hours with a thermal efficiency of up to 76% at 700 °C [Hoffschmidt *et al.*, 2003]. However, a strong variation in outlet temperature and thermal efficiency was reported, which is undesirable. At the same time, a wide variation of temperature between different absorber modules was reported, which is detrimental to the receiver integrity.

These investigations lead to the pre-commercial design of SolAir 200 kW receiver [Téllez, 2003]. The SolAir-200 was able to achieve the thermal conversion efficiency of ~ 83% at an air outlet temperature of ~ 700 °C. Eventually, the SolAir 3 MW prototype was developed, installed, and tested at the Plataforma Solar de Almería, connected to a steam generator and a thermocline based heat storage [Hoffschmidt *et al.*, 2003]. The receiver was composed of 270 ceramic absorber modules with a total aperture of 5.67 m^2. The honeycomb absorbers were made of recrystallized SiC, with square flow channels and a normal open porosity of 49.5%. During the test, the average incident solar radiation on the ceramic volumetric absorber was ~ 500 kW/m^2. The SolAir 3 MW receiver system achieved a thermal efficiency of about 72 - 74 % at an air outlet temperature of ~ 700 - 750 °C. Efficiencies were estimated over 85% (and up to 89%) at an air outlet temperature of about 590 – 630 °C at an average irradiance 310 – 370 Suns. Although the operational flexibility and initial results were satisfactory, however, it is realized that the thermal efficiency may be improved up to 90% to design a cost-effective plant and for replacing the tubular design. In addition, the long-term endurance tests must be conducted, radiation losses must be further reduced, and the radial distribution of recirculating air in operation could be further optimized (Marcos *et al.*, 2004). The thermo-mechanical properties, including corrosion, of the SiC ceramic employed in the SolAir-200 solar receiver were investigated by Agrafiotis *et al.* (2007), who conducted extensive experimentation on both irradiated and non-irradiated samples. The use of siliconized SiC was recommended due to its superior mechanical strength, allowable operating temperatures, and corrosion resistance.

The effects of high temperature cycling on the SiC thermo-radiative properties was reported by Rodriguez-Sanchez *et al.* (2016), who found that the absorptivity, generally, decreases with the prolonged cyclical exposures to concentrated solar radiation. Several computational investigations are conducted to explain the aerothermal behavior of the HiTReC-SolAir family of receivers, and to identify the ways to enhance their thermal efficiency. Research has focused on (a) the uniformity of air outlet temperatures downstream of absorber modules [Palero *et al.*, 2008], (b) the modifications of the honeycomb structure to increase the uniformity of air outlet temperatures and, thus, thermal efficiencies [Fend *et al.*, 2013], (c) the influence of wind velocity and direction on the air recirculation system and air outlet temperatures [Roldán *et al.*, 2016] and (d) the effects of receiver tilt angle, the channel aperture size and the air inlet speed on the volumetric effect and the thermal efficiency [Cagnoli *et al.*, 2017]. The last study was conducted at the single flow channel level and showed that a trade-off exists between operation under volumetric effect conditions and achieving high thermal efficiencies.

Two recent studies have proposed geometric modifications to the HiTReC-SolAir receiver concept with an objective of increasing overall thermal conversion efficiencies. The first one consists of substituting the ceramic absorber with a cellular metallic honeycomb built from pairs of flat corrugated metal foils [Pabst *et al.*, 2017]. An efficiency of about 80% at an air outlet temperature of ~ 800 ºC is reported based on the experiments with an incident radiative power of 500 kW simulating on-the-field conditions. The second study proposed the addition of a staggered pin-shaped micro-structure, additively manufactured in a Titanium-Aluminium alloy, to the aperture plane of the ceramic absorber [Capuano *et al.*, 2017]. Operation under volumetric effect conditions was numerically predicted for such geometry, but the current manufacturing limitations only allowed for the experimental assessment up to 3:1 scaled-up. Some of the performed analyses towards the performance assessment is presented subsequently.

2.2 HEAT TRANSER ANALYSIS

A number of modeling studies associated with the open volumetric air receivers are summarized in Table 2.2. Gomez-Garcia *et al.* (2016) reviewed the thermal and hydrodynamic behavior of conventional volumetric absorbers comprising of an open-cell foam-type and monolithic honeycombs. Capuano *et al.* (2016) presented a review on the available numerical models of volumetric solar receivers. Reuter (2017) reviewed the modeling investigations that are associated with the open volumetric air receivers.

Pitz-Paal *et al.* (1997) assumed a non-uniform heat flux profile on the irradiated front surface of the receiver. The absorbers are discretized into small parallel sections to ensure a homogeneous irradiation of each of these sections. The evaluation of absorber sections was performed using a one-dimensional model. They neglected the spectral dependency of the optical properties and the flow along the radial direction. Their steady state analysis revealed that the volumetric effect may be achieved in an absorber. However, it was reported that there was a deviation between the measured and calculated front temperature distribution. This was attributed to the fact that in experiments the desired steady state was not achieved. Marcos *et al.* (2004) performed the three-dimensional simulations with different receiver geometries and presented the effect of air return ratio on the performance of a volumetric receiver. They used FLUENT to analyze the effect of various geometries on the air return ratio for the recovery of waste heat from the return air. The HiTRec based receiver with alternative geometries like outer ring injection, cavity aperture and secondary concentrator were used for the analysis in the simulations. The cavity type, semi-cavity type and secondary concentrator type receiver showed a substantial increment in the air return ratio. Also, it was found that tapered corners cup shape also came out to be useful in increasing the air return ratio. However, the effect of heat flux distribution was not discussed. Bai (2010) presented a thermal analysis of SiC foam used for volumetric receiver. One of their result shows that the air flow resistance increases nearly three times at 1000 ˚C in comparison to that of 20 ˚C. The result of their one-dimensional analysis revealed that there exists an upper limit to the incident solar energy for the open volumetric systems. This will lead to limit the outlet temperature of air and capacity of the receiver. He suggested the use of a closed pressurized system to increase the power capacity.

Ahlbrink *et al.* (2010) used C++ with STRAL to optimize the air mass flow rate for a power plant with open volumetric receiver to maximize its thermal efficiency. Different flux densities were considered for the analysis of power plant which can occur during one year on a characteristic day. However, no validation of their optimization technique was provided in the text. Wu *et al.* (2011) analyzed the temperature distribution inside a foam-type absorber and showed its dependence on the working conditions and the material properties. They concluded the need of additional computational and experimental data. The foam type absorber was also analyzed by Michailidis *et al.* (2013) in which an analysis of flow and thermal behavior in Ni-foam specimen was reported. Smirnova *et al.* (2011) and Fend *et al.* (2013) numerically and experimentally investigated the heat and mass transport through a honeycomb structure of Silicon Carbide. Two models were developed namely, (a) a single channel model and (b) a porous continuum model. The single channel model predicted the possible areas of overheating in the samples. The temperature distribution along the flow direction revealed that the volumetric effect was not achieved. Schwarzbözl *et al.* (2011) derived a correlation between the geometrical parameter and the performance of honeycomb based absorber structure. Based on the same, absorber samples were produced with different cell densities and their performance were evaluated along with durability. The selected absorbers were passed in the test and the need of further evaluation with the scaled-up absorbers was concluded.

Achenbach *et al.* (2011) simulated a single channel model to predict the performance of various absorber designs in terms of the heat transfer. Flow measurements, performance and durability test were also performed with the corresponding 3D-printed absorber models. Lee *et al.* (2012) developed a ray tracing method to model the solar flux distribution in SiSiC multichannel absorber and analyze its performance and the radiation losses. They concluded that the combination of a high solar absorptivity and a small channel radius will be suitable for performance enhancement of a receiver. Wang *et al.* (2013) analyzed the effect of heat flux distribution, operating condition and geometry of the absorber on the performance and radiation loss. These were based on both a uniform and a non- uniform heat flux distribution. It was stated that the temperature of absorber material decrease with increasing emissivity. Also, the maximum temperature of the solid phase found to be increasing with increase in the particle diameter. Wu and Wang (2013) developed a transient model to analyze the time dependent behavior of volumetric receiver for estimating the heat- flux & losses. Additionally, the pressure-drop through the absorber reacts smoothly to heat flux change. The thermal gradients in the absorber and heat transfer rate can be acquired from this model. Kribus *et al.* (2014 a,b) presented a parametric study of the volumetric absorber performance. It was shown that the desired 'volumetric effect' is non-trivial to achieve. They stated that the pore size and the porosity of absorbers must be carefully selected for the desired temperature profile. Also, they recommended the use of low thermal conductivity materials for the volumetric absorbers. The materials with a low thermal conductivity reduce the heat conduction in the axial direction and keep the front side of absorber at a lower temperature than the rear side. Such situation is beneficial to achieve the volumetric effect, reduce radiation based heat loss and increasing the thermal efficiency.

Roldán *et al.* (2014a) performed thermal analysis of volumetric receivers under a non-uniform heat flux with a constant as well as gradually varying porosity along the radial and the axial directions. The absorbers with gradually varying porosities have shown a higher efficiency than that of the constant porosity. The absorber with a gradual porosity variation along the radial direction shows the overheated area in the absorber and hence, not suitable as a volumetric receiver. However, the receiver with gradual porosity variation along the axial direction shows a more homogeneous temperature and hence, it is proposed as an alternate option for the conventional constant porosity absorber. Gomez-Garcia *et al.* (2014, 2015) performed the numerical investigations on an absorber architecture based on the stack of square grids using the Monte Carlo ray tracing method. Their analyses revealed that the absorbers with wide layers show a higher penetration depth. They developed an exponential law to improve the available analytical relation for the radiation penetration depth along the mean air flow direction. The proposed law contains two coefficients related to the capacity to trap the incident flux and the extinction distance. For the classical honeycomb absorbers, these coefficients depend on the pitch size and the reflectivity. For the proposed multi-layer absorbers, the coefficients also depend on the length of layers and gap between the same. Roldán *et al.* (2015) selected two specimens of viz. recrystallized SiC honeycomb (HiTRec type absorber) with a porosity of 0.495 and an alloy 601 coiled knit-wire mesh with a porosity of 0.974 for their experimental and numerical characterization in laboratory. The average thermal efficiency is found to be ~ 90% in both the cases with a deviation of ~ 10%. However, a more homogeneous temperature distribution is observed with the alloy 601 absorber due to the higher porosity and thus the surface area for the heat exchange and a deeper radiation penetration than SiC.

Cagnoli *et al.* (2017) analyzed the effect of some important parameters, such as the receiver tilt angle, the porosity and the wind speed on the performance of a volumetric receiver. The findings suggest that the receiver tilt angle around a reference value does not significantly affect the receiver performance. Zhu and Xuan (2018) proposed a novel receiver design and analyzed the effect of geometry and the spectral dependent emissivity on the performance of a receiver. Their analyses revealed that the wavelength related emissivity and strut cross shape may improve the receiver performance. They showed that the thermal efficiency of the volumetric receiver increase with the increase in absorber porosity and the Heywood circularity factor. Teng and Xuan (2018) proposed a solar receiver equipped with the metal coated mirrors. These mirrors enhance the outlet temperature of air and the thermal efficiency by reducing the radiation based heat losses. Barreto *et al.* (2018) performed an analysis of solar radiation absorption in a volumetric receiver based on the geometrical properties viz. pore size, porosity, distance between front of the receiver and focal point of concentrated irradiance. They used paraboloid dish based reflector for the heat input. Abuseada *et al.* (2019) performed the numerical analysis of a volumetric receiver with variable aperture using the Monte-Carlo ray tracing method. The variable aperture is introduced to control the receiver temperature under the continuously varying heat flux conditions or under the variable weather conditions. However, a due care is required while implementation of the variable aperture. They concluded that the thickness of aperture must be the minimum keeping in mind the robustness of the receiver. Reddy and Nataraj (2019) constructed a two-dimensional transient model to analyze the effect of different parameters, such as the porosity, the thermal conductivity and the inlet velocity on the performance of the receiver. They found that the receiver performance increases with porosity, which is consistent with literature. Also, a higher thermal conductivity of the receiver helps in transferring more heat to the working fluid. The inlet velocity may be employed as a tuning parameter to regulate the outlet temperature according to the material properties and other constraints.

Table 2.2: Modeling approaches used for open volumetric air receivers.

S. No.	**Literature**	**Approach/Software used**	**Study**
1	Kribus *et al.*, (1996)	Analytical	Flow stability in foam type absorbers using blow parameter.
2	Pitz-Paal *et al.*, (1997)	multi-shooting method with a commercial software package	Flow stability in a receiver based on foam type absorbers with non-homogeneous heat flux distribution.
3	Marcos *et al.*, (2004)	FLUENT	Effect of air return ratio and various geometries on the performance of the receiver.
4	Bai *et al.*, (2010)	Analytical	One-dimensional analysis of flow and heat transfer in ceramic foam.
5	Ahlbrink *et al.*, (2010)	C++	Optimization of mass flow rate for a target outlet air temperature.
6	Wu *et al.*, (2011)	FLUENT	Coupled radiation and flow modeling in foam type volumetric receiver.
7	Smirnova *et al.*, (2011)	COMSOL	Numerical analyses of heat and mass transfer in a Silicon Carbide honeycomb structure.

8	Schwarzbözl *et al.* (2011)	Analytical	Effect of geometry of the honeycomb absorber on the performance of receiver.
9	Achenbach *et al.*, (2011)	ANSYS CFX	Single channel model was used to predict the performance of volumetric absorber.
10	Lee *et al.*, (2012)	Ray tracing method	Effect of geometry and thermal properties on radiation propagation inside the absorber.
11	Fend *et al.*, (2013)	COMSOL	Single channel model for absorber was used to analyze the thermal aspects along with non-uniform heat flux distribution.
12	Michailidis *et al.*, (2013)	FLUENT	Thermal and hydraulic behavior of Ni-foam specimen for volumetric absorber.
13	Wang *et al.*, (2013)	Monte-Carlo Ray Tracing method and FLUENT	Effect of heat flux distribution, emissivity and particle diameter on temperature distribution and radiation loss
14	Wu and Wang, (2013)	FLUENT	A transient model was developed for analyzing the heat flux and pressure-drop variation.
15	Gomez-Garcia *et al.*, (2014)	Ray tracing technique using TracePro software	Numerical analysis of the radiation absorption by volumetric absorber based on stack of thin monolithic layers.
16	Kribus *et al.*, (2014a,b)	MATLAB	Effect of geometric and material properties on temperature distribution and performance of volumetric receiver.
17	Roldán *et al.*, (2014a)	FLUENT	Porosity and heat flux distribution.
18	Achenbach *et al.*, (2014)	MATLAB	Penetration depth and volumetric heat transfer coefficient.
19	Gomez-Garcia *et al.*, (2015)	Monte Carlo ray tracing method	Radiation propagation in square channel grid volumetric absorber.
20	Roldán *et al.*, (2015)	Two-dimensional CFD model	Experimental and numerical analysis of ceramic and metallic absorbers.
21	Sharma *et al.*, (2015a)	FLUENT and experiments	A methodology to design various components of an open volumetric air receiver is discussed.
22	Sharma *et al.*, (2015b)	FLUENT and experiments	Effect of thermal conductivity on flow stability and methodology of design of receiver components.
23	Cagnoli *et al.*, (2017)	ANSYS-FLUENT	Effect of geometrical variables and air mass flow rate on the receiver performance.
24	Zhu and Xuan, (2018)	Monte-Carlo method	A novel receiver is proposed based on the analyses.
25	Teng and Xuan, (2018)	Multiphysics simulations	A novel receiver with metal coated mirrors is

			proposed.
26	Barreto *et al.*, (2018)	Monte-Carlo ray tracing method	Three-dimensional modeling and analysis of solar radiation absorption in porous volumetric receiver.
27	Abuseada *et al.*, (2019)	Monte-Carlo ray tracing method	Analysis of a cavity type volumetric receiver with variable aperture orifice.
28	Reddy and Nataraj, (2019)	COMSOL multiphysics	Effect of porosity, thermal conductivity and inlet velocity on the performance of the volumetric receiver.

It is evident from the literature review that a comprehensive model for analyzing unsteady heat transfer in an open volumetric air receiver including the return air side is required. Apart from the inherent advantages of the open volumetric air receivers, there are various issues and challenges related to their operation, especially in the arid desert regions. Some of these are discussed subsequently.

2.3 ISSUES AND CHALLENGES

2.3.1 Dust deposition in an absorber pore

Rajasthan and Gujarat in India are blessed with a high direct normal irradiation (DNI) but at the same time, such dry and desert areas are rich in sand or dust. The size of dust particle varies from a few µm to 1000 µm. Analysis of the deposited dust on the roof-top panels at IIT Jodhpur has clearly revealed that the dust size at a height of about 10 m varies between 20 – 60µm [Yadav *et al.*, 2014]. This area is prone to dust storms, which are likely to transport and deposit the in an absorber pore. Probably, Rajasthan is the second most active area in terms of dust storm frequencies in Asia [Shao and Dong 2006; Wang *et al.*, 2007]. Figure 2.2 shows a *common dust storm* in Rajasthan and its scale can be inferred from the height of communication towers, which is of the order of few 100 m.

Figure 2.2: A dust storm at Bikaner, Rajasthan [source: Pinterest].

The particle concentration in sand storms is very high. The usual hourly maximum concentration at Dalanzadgad in Gobi Desert has been reported as high as 6626 µg/m^3 [Jugder *et al.*, 2011]. This will increase manifold during a dust storm. The deposition of dust in absorber pores of an open volumetric air receiver will impact the operation of entire system and may even lead to its failure due to the enhanced thermal stress, see e.g. Figure 2.3 [Hoffschmidt *et al.*, 2003]. Therefore, a proposal for including an in-situ clean device is provided by Sharma *et al.* (2015a, 2015b). This assumes that a dust layer may be deposited or transported through straight channels at a certain mass flow rate of air. Moreover, the dust deposition may alleviate the possibility of thermally-induced flow instability due to the local variation of air properties at a low flux concentration. This is attributed to a higher flow resistance causing a lower mass flow rates in the partially blocked channels. The deposited dust must be removed from the porous absorber and is externally collected to prevent its passage along with hot air. Thus, a dust collection device is required and to be installed with the open volumetric air receiver.

Figure 2.3: Failure of an absorber [Hoffschmidt *et al.*, 2003].

2.3.2 Flow instability at a high temperature

It is reported that some receivers failed during their operation even before the melting temperature. Such incident happened due to a phenomenon in which a porous sample showed the different mass flow rates while subjected to a given pressure-drop. This unexpected flow behavior is an indication of the so-called flow instability. Several authors have depicted and predicted the flow instability depending on heat flux and absorber material properties [Kribus *et al.*, 1996; Pitz-paal *et al.*, 1997; Fend *et al.*, 2005; Becker *et al.*, 2006]. Kribus *et al.* (1996) analyzed the flow instability using an analytical approach and found that there is an upper limit of allowable heat flux onto the porous receiver. This is based on (a) the difference between quadratic pressures at the inlet and outlet, (b) the absorber dimensions, and (c) the temperature dependent thermo-physical properties. He suggested that using a pressurized loop and by controlling the outlet temperature instead of a pressure difference can mitigate the chances of flow instability. Pitz-Paal *et al.* (1997) investigated the flow instability using a numerical approach for the different absorber structures. Instability was observed at a high flux and at a low Reynolds number in which a pressure varies linearly and Darcy's law is valid. In case where the quadratic relation between pressure difference and velocity follows Forcheimer's condition a stable flow is predicted. They found that the instability can be mitigated by increasing the heat transfer along the radial direction. Therefore, the size of the absorbers must be carefully selected. The experiments pertaining to the flow instability are reported by Fend *et al.* (2004). They analyzed cordierite ceramic foam having 20 ppi (pores per inch) and cordierite catalyst carrier having 400 cpsi (cells per square inch). Becker *et al.* (2006) derived a correlation based on the analysis to estimate the critical or the minimum heat flux and the same is illustrated in Figure 2.4 using the variation of the difference between quadratic pressures at the inlet and the outlet. The blue curve is an outcome at a heat flux of 500 kW/m^2 showing the usual behavior. Here, with the decreasing mass flow rate of air or the pressure-drop results in the increasing outlet temperature. When the heat flux is increased to 2000 kW/m^2, the non-unique values of the outlet temperature are predicted at a given mass flow rate. The same was pronounced as indicated by a wavy pattern when the heat flux is further raised to 3000 kW/m^2 These are the typical signatures of flow instability at a high heat flux condition and is detrimental to the operation and durability of an open volumetric air receiver. This important fundamental aspect needs to be addressed for the designed circular straight pore based open volumetric air receiver as in Sharma et al. (2015a, 2015b), which is necessary to ensure a stable operation of the solar convective furnace system.

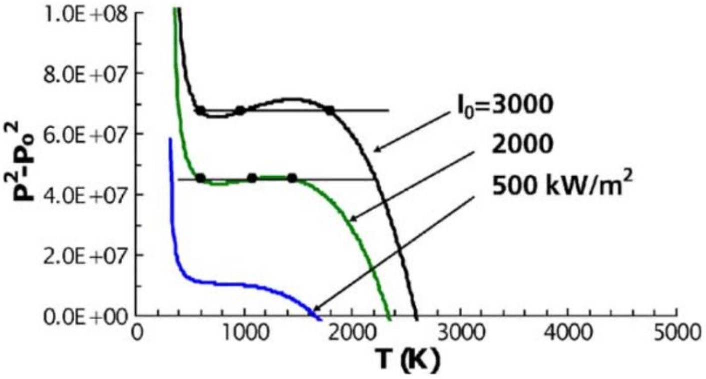

Figure 2.4: Difference in quadratic pressure-drop versus outlet air temperature [Becker *et al.*, 2006].

2.4 OBJECTIVES OF THE THESIS

The purpose of this thesis is to enable the integration of an open volumetric air receiver – thermal energy storage - solar convective furnace for the heat treatment of Aluminum. In this direction, being the heart of this system, the pertinent fundamental issues and practical challenges or limiting factors associated with the open volumetric air receiver based on a detailed literature review are addressed. The thesis is organized as follows:

1. Dust deposition in the absorber pores of an open volumetric receiver pose a serious challenge in the arid desert regions like Rajasthan. Therefore, the detrimental effect of dust deposition on the heat transfer is discussed in Chapter 3.

2. To mitigate the effect of dust deposition an in-situ cleaning strategy is necessary, which is discussed in Chapter 4. The use of an external device for cleaning lends to the increasing parasitic loss and thus, decreases the overall efficiency of the receiver. The presented analysis on this limiting aspect in Chapter 5 allows deducing an operating condition under such a scenario.

3. The existence of a critical value of heat flux that may initiate flow instability is reported. This is undesirable for the continuous operation of an open volumetric air receiver based system. Therefore, flow stability analysis is performed using both the analytical and numerical approaches. This limiting factor is investigated in Chapter 5.

4. The need of a comprehensive model for the assessment of an open volumetric air receiver is realized. Therefore, a zonal model is developed for the unsteady state heat transfer analysis in an open volumetric air receiver. This is discussed and validated in Chapter 6. Using the model, the effect of non-dimensional geometrical and operational parameters on the performance of the designed receiver is investigated.

Therefore, in this thesis some of the critical issues pertaining to operation and design of an open volumetric air receiver are presented. These are expected to be helpful in realizing such a system in arid deserts.

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