SURVEY ON PRESSURIZED AIR RECEIVER DEVELOPMENT

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Abstract

A combined cycle concentrating solar power plant, employing for example the SUNSPOT cycle, provides significant potential to increase efficiency and reduce electricity cost compared to current single-cycle plants. Such a combined cycle system requires a receiver technology, capable of effectively transferring heat from concentrated solar irradiation to a pressurized air stream.

This survey provides a critical technology analysis of existing demonstrated receiver technology for the application with pressurized air as heat transfer fluid. The need for further research and development is highlighted and the objectives for such a receiver are presented.

Keywords: Central Receiver; Pressurized Air Receiver; Literature Review; CSP; SUNSPOT

1. Introduction

A combined cycle (CC) concentrating solar power (CSP) plant, such as the SUNSPOT cycle [1], provides significant potential to increase efficiency and reduce electricity cost. A combined cycle CSP system requires a receiver technology capable of effectively transferring heat from concentrated solar radiation to a pressurized air stream.

The combustion temperatures of a Brayton cycle ranges up to about 1350 °C. High temperatures are typically achieved by cascading different receiver technologies, followed by a co-firing stage. The small number of central receiver pressurized air receivers demonstrated to date have practical limitations when operating at high temperatures and pressures. As yet, a robust, scalable and efficient system has to be developed and commercialized.

In the presented research, the progress to date and current work on pressurized air receiver systems is investigated. It is shown that state of the art pressurized air receivers have limitations for the application in solar thermal power stations. The review thus highlights the need for further developments in the field of pressurized air receivers and identifies objectives for a desired novel system.

Preceding the discussion of pressurized air receiver technologies is an introduction to important losses that affect a receiver's efficiency. Due to the variety of occurring losses, different receiver and absorber technologies have been conceived where the important categories are introduced in this study.

2. Receiver system introduction

A common goal for developing a central receiver is maximized central receiver system efficiency. This review describes initially the important optical and thermal losses influencing that efficiency. Following this is a brief overview of central receiver design categories and absorber systems.

Numerous criteria influence the design of a central receiver system. Among the most important are the choice of the heat transfer fluid, its required temperature, the receiver capacity and the heliostat field layout. A variety of concepts for different central receiver applications has been proposed in the past. Consequently, the review on existing concepts is limited to recently developed pressurized air receivers.

2.1 Important losses

The total losses affecting a receiver system efficiency are the optical losses, thermal losses and pumping losses [2]. The losses are in more detail:

- Optical: Reflection, spillage and secondary concentrator (also referred to as compound parabolic concentrator, short CPC)
- Thermal: Radiation, conduction and convection
- Pumping: Pumping power (as parasitic loss) or pressure drop

The *thermal efficiency* (η_{thermal}) is the most widely used figure in literature to compare different receivers, regardless of the concentrator configuration, e.g. heliostat type or heliostat field layout. Clear conventions whether to include or exclude a CPC seem not yet to be established. The thermal efficiency of a receiver system is described as the ratio of usable thermal energy generated $\dot{Q}_{\mathrm{out}}$ to the impinging concentrated radiation $\dot{I}_{\mathrm{in}}$ onto the receiver aperture (or CPC aperture):

$$\eta_{\text{thermal}} = \frac{\dot{Q}_{\text{out}}}{\dot{I}_{\text{in}}} \tag{1}$$

It is directly obvious that the thermal efficiency does not include optical characteristics of the heliostat field or a secondary concentrator or a system's pressure drop. These are incorporated in a total system efficiency.

2.1.1 Optical losses

Optical losses of a receiver are determined by reflection, spillage and the optical efficiency of a secondary concentrator.

Low reflective losses (equalling high absorptance in the spectrum of the incoming radiation) are achieved in two ways. One attempt is the application of a selective coating to the absorber surface, improving the absorptive capabilities of the absorber directly. Another way often employed, is the trapping of radiation by the application of coatings that form microscopic voids, thus increasing the absorptivity [3].

Spillage losses represent the fraction of sun beams reflected by the heliostat field that miss the absorber target. Typically spillage losses are not accounted for in the efficiency of a receiver. A secondary concentrator can be utilized to increase the flux density on receiver systems of limited size. A CPC's optical losses, which can be in the range of 15 % [4] are also typically not included in the receiver efficiency calculation. The thermal efficiency is then computed, based on the flux at the CPC outlet.

The optical losses of the CPC as well as spillage are not included because their magnitude depends on the heliostat field layout and the aiming strategy of the heliostats. While spillage losses are usually small [2] and apply to a certain degree to any receiver design, a CPC's losses can be significant [4,5].

2.1.2 Thermal energy losses

Thermal energy losses of a receiver system are composed of thermal radiation, conduction and convection losses. Conductive losses result from the absorber mounting to the tower structure. These are losses of minor nature and are often neglected [6]. Convective heat losses are losses to ambient air from heated exposed receiver surfaces. Radiative heat losses also occur from hot receiver surfaces towards the environment.

The magnitude of the different thermal energy losses depends on the absorber material properties, the receiver surface area and geometry, as well as the receiver temperature. Convective and conductive heat losses are directly proportional to the surface temperature. On the other hand, radiative heat losses are proportional to the difference of the fourth power of absorber temperature to the fourth power of ambient temperature.

The character and temperature dependency of the different thermal losses indicates that different system target temperatures may result in diverse ideal receiver designs, depending on the dominance of the particular losses in each situation.

2.1.3 Heat transfer fluid pumping losses

Heat transfer fluid pumping losses can be of relevance in terms of parasitic losses or, as in the case of a Brayton cycle, directly reducing the pressure ratio on the turbine side. The Brayton cycle efficiency is sensitive to pressure drop, therefore a low pressure drop forms a primary design goal when developing receiver systems.

2.2 Absorber technologies

An essential sub-system of the receiver of a CSP plant is the absorber. It is employed to effectively transfer the energy of the concentrated sun light into the heat transfer fluid. The tubular and the volumetric absorber types have found application in the relevant systems to date and are introduced below.

2.2.1. Tubular absorber

Current central receiver technologies for molten salt and direct steam generating systems use a multitude of steel tubes to form the absorber surface. A number of parallel tubes is used to form a billboard receiver or cylindrical receiver (as shown in Fig. 2). The heat transfer fluid is pumped through the tubes and is heated up in the process. To minimize absorber surface area and temperature, fluids with high thermal conductivity are preferred, as they maintain an efficient system.

As shown in section 3, innovations in pipe manufacturing, heat transfer enhancements and intelligent receiver design can make tubular receivers viable for low thermal conductivity fluids.

2.2.2. Volumetric absorber

Increasing attention has recently been given to volumetric receiver/absorber systems. A volumetric receiver utilizes the geometric configuration of a porous absorber material to improve the receiver efficiency.

A porous surface, allowing the radiation to penetrate into the depth of the absorber, reduces reflection losses. The heat transfer fluid, which is forced through the porous absorber from the irradiated side, provides the highest cooling effect at the exposed surface. The volumetric effect can be described by the peak surface temperature occurring deep in the structure. This results in a lower irradiated (front) surface temperature than the maximum heat transfer fluid temperature [7], thereby reducing heat losses.

The described volumetric effect is illustrated in Fig. 1 in comparison to a tubular absorber. The volumetric absorber can also be summarized as a radiation trap for reflected light beams and radiated heat.

A volumetric receiver can suck in ambient air in an open configuration if atmospheric pressure is desired. If higher pressures are required, as with the implementation in a Brayton cycle, the absorber needs to be sealed from the ambient by a window to maintain the system pressure.

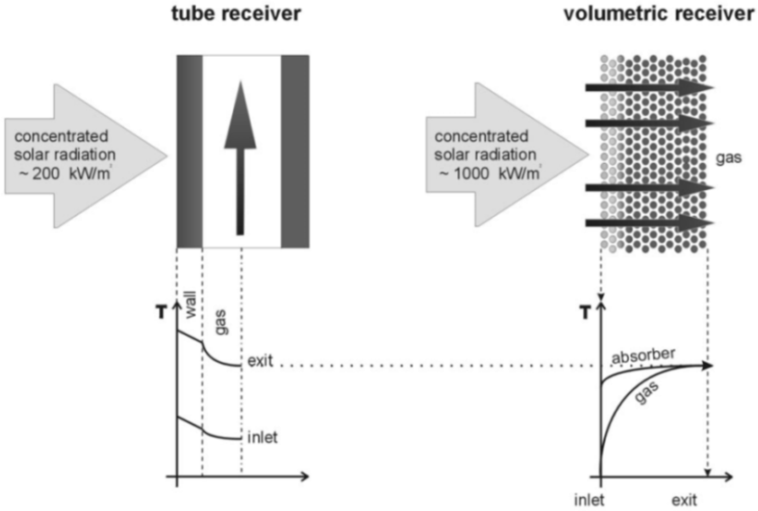

Fig. 1. Temperature distribution for tubular and volumetric air absorber ([8], based on [9])

2.3 Receiver concepts

The two most important categorizations for pressurized air central receiver concepts are the external and cavity receivers. These principles are discussed in the following.

2.3.1 External receiver

An external receiver is the simplest and cheapest receiver design, where the absorber system, usually consisting of numerous vertical tubes, is externally mounted to the receiver tower. This can be done in variations such as the so called “billboard” receiver, where a flat panel of parallel aligned tubes is exposed in the direction of a polar heliostat field. For a surrounding heliostat field multiple such panels can be mounted to cover larger areas, e.g. reproducing a rectangular or cylindrical shape (as shown in Fig. 2 for a direct steam generation (DSG) system).

The external receiver concept results in high exposure to heat losses by convection and radiation. Since these are functions of the exposed surface area and temperature, external receiver systems require heat transfer fluids with a high heat transfer coefficient in order to reduce absorber surface temperature, as well as reduce the total absorber surface. Presently external receivers are used for molten salt and DSG systems which operate below 600 °C. Thermal efficiencies in the region of above 80 % can be achieved with existing designs [10].

An advantage that a surrounding heliostat field has over a polar field is a stable solar field optical efficiency over the course of the day, while a polar heliostat field has a higher noon performance [11]. Hence, employing a surrounding receiver system can allow for an increased optical efficiency of the heliostat field. For large scale plants the polar field becomes unviable, as the distance of the farthest heliostats grows too large for efficient operation.

A conventional external receiver is not suited for low heat transfer coefficient fluids, such as air, as the required large exposed absorber surfaces would lead to significant heat losses. It finds application in molten salt as well as DSG sytems.

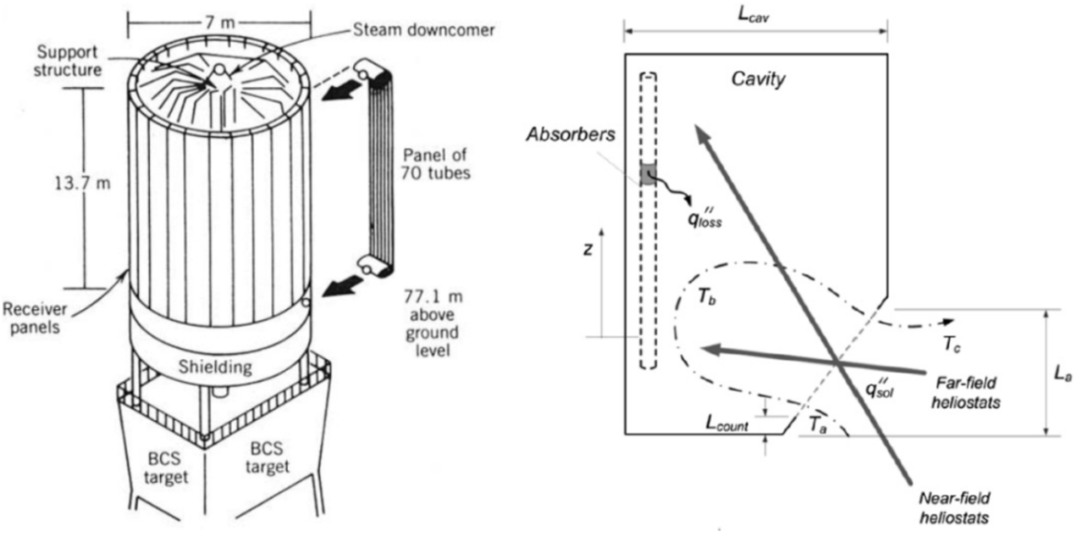

Fig. 2. Left: Cylindrical external receiver [2]; right: cavity receiver [12]

2.3.2 Cavity receiver

A cavity receiver is a receiver system where the absorber system is encased inside a space with an opening towards the heliostat field. A simple cavity receiver is an encased at absorber panel on one wall and an opening (aperture) on the opposing side as shown in Fig. 2 (right). Having the absorber system encased can improve the thermal efficiency by the reduction of the convective heat loss (which can further be enhanced by a window in the opening) as well as trapping of reflected light and radiated heat. At a technically more sophisticated level, high temperature systems such as pressurized air receivers have been conceived as cavity receivers.

3. Survey on existing pressurized air receiver concepts

The research area of air receiver systems for elevated temperatures, capable of supplying a Brayton cycle, is relatively young. To date, only the German Aerospace Center (DLR) and the Israeli Weizmann Institute of Science (WIS) have driven development, leading to demonstration scale systems with published findings. Both research institutions have developed cavity receiver systems with volumetric absorber technology, capable of reaching mean outlet temperatures of above 1000 °C. This review covers the progress to date and highlights important problems encountered.

Possible target outlet temperatures of receiver systems can be gas turbine operating temperatures in a range of 1000 °C to 1350 °C [13]. The gap between the lower air temperature downstream of a solar receiver and the required turbine inlet temperature is usually overcome by implementation of a fuel combustor.

Before describing the progress of the research on pressurized air receiver systems in more detail, a summary of the reviewed projects is provided in Table 1, emphasizing the recency of the research field.

Project	Receiver	Receiver type	Temperature achieved	Project start
DIAPR	DIAPR	Volumetric cavity	1200 °C	1992
REFOS	REFOS	Volumetric cavity	800 °C	1996
SOLGATE/ HST	Two REFOS and LT stage	Volumetric cavity and tubular cavity	1030 °C	2001
SOLHYCO	SOLHYCO	Tubular cavity	800 °C	2006
SOLUGAS	SOLUGAS	Tubular cavity	800 °C	2008
SOLTREC	SOLUGAS and REFOS	Volumetric cavity and tubular cavity	-	2010

Table 1: Important pressurized air receiver projects

3.1 Attempts by DLR

The DLR began tests on volumetric pressurized air receiver systems in 1989 with the PLVCR5 receiver, which employed a dome shaped quartz glass window [14]. The receiver concept has since been continuously improved, and the current version is known as the REFOS receiver, sketched in Fig 3 (left). For the volumetric absorber material in the receiver a silicon-carbide ceramic mesh (Si-C) for high temperatures or a metal wire mesh for pre-heating purposes have been used.

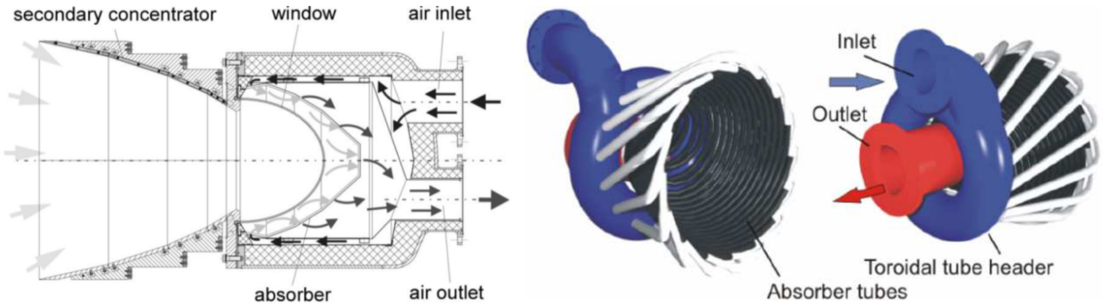

Fig 3. The REFOS receiver (left) [20] and the SOLGATE LT multi-tube coil receiver (right) [6]

The REFOS receiver has been successfully operated at up to 1030 °C [15]. In the SOLGATE project a hexagonal compound parabolic concentrator (CPC) and two pre-heating sections (also using CPCs) were included into the test setup. The receiver cluster consisted of a multi-tube low temperature (LT) coil pre-heater (Fig 3 on right), a medium temperature (MT) REFOS pre-heater and a high temperature (HT) REFOS receiver.

The afore mentioned tubular LT section did not provide satisfactory results. One problem encountered was its high pressure drop of 70 % of the total cluster pressure drop of 120 mbar [6]. The tube surface temperature peaked at 400 K above the air outlet temperature [6] and more importantly, the cross-sectional temperature gradient between the radiated and unradiated pipe surface was calculated at up to 220 K, resulting in high thermal stresses, thereby reducing the receiver lifetime [15].

Following SOLGATE, a new tubular receiver type, the SOLHYCO [15] and SOLUGAS [16] (Fig. 4), receivers were developed in cooperation with amongst others, the Spanish company Abengoa Solar.

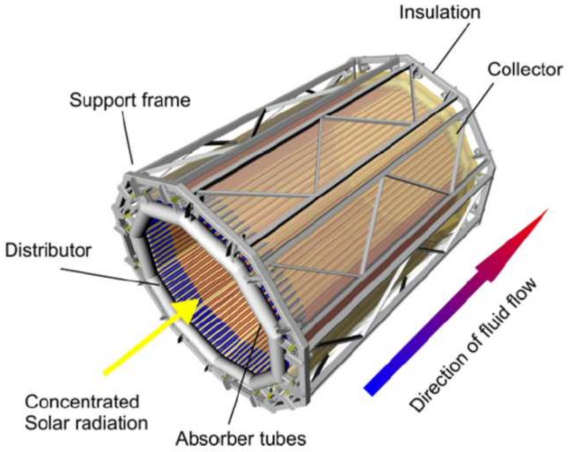

Fig. 4. The SOLUGAS receiver [16]

The new SOLUGAS receiver was meant to replace the tubular LT cavity pre-heater and the MT REFOS receiver pre-heating stage of the SOLGATE project in a single system. It was achieved to increase the pre-heated temperature in one step to about 800 °C [17]. The SOLHYCO receiver design was similar to the SOLUGAS receiver with the same target temperature, but designation as a sole heating stage for micro turbines. One innovation in the SOLHYCO receiver was a three-layered pipe (PML-pipe) of Inconel-Copper-Inconel, where the copper's high conductivity was employed to reduce the circumferential temperature gradient on the absorber pipe. However, thermal cycling caused cracking of the PML tube between metal layers [15]. It is not known whether the problems with the PML tubes were overcome to date (they are not used in the SOLUGAS receiver).

The following SOLUGAS project has officially ended in April 2013, with a final report yet to be published. The current follow up-project is SOLTREC, where the SOLUGAS receiver and the REFOS receiver technologies are installed in series at Abengoa Solar’s Plataforma Solar de Sanlúcar la Mayor (PSSM). Target of the SOLTREC project is to achieve a mean air temperature of 1000 °C. In the project outline it is stated that design limitations to date only allow operation of the SOLUGAS receiver up to a mean outlet temperature of 650 °C, where the reasons remain unclear [18]. The presented results by [17] suggest that some problems may have been overcome in the meantime.

Limited information is published on the SOLUGAS receiver, neither with regards to cost, nor efficiency. The similar, but smaller, receiver of the SOLHYCO project had an expected thermal efficiency of 67 % to 80.8 % (without and with a quartz window enclosing the aperture). These values were grossly missed with measured efficiencies of 37 % to 45 % respectively [15]. Continued research on the SOLUGAS receiver in the current SOLTREC project suggests that some parts of that efficiency discrepancy and low target temperature performance are hoped to be eradicated.

The thermal efficiency of the SOLGATE cluster (including CPC) with the now abandoned tubular LT pre-heater was 78 % at 800 °C outlet air temperature and 72 % at 900 °C outlet air temperature [19]. [20] stated an efficiency goal for the REFOS receiver (without pre-heater system) of 80 % at 800 °C including the optical losses of the CPC but did not report test results. Deducting the CPC's optical losses, the mentioned value of 80 % suggests a high thermal efficiency of the REFOS receiver in the range of 90 %. A typical flux density for the REFOS receiver was below 1000 kW/m^2 after the secondary concentrator [6].

The quartz glass window

The quartz glass of the dome shaped window (see Fig 3, left) needs to withstand high temperatures and pressures in order to separate the hot pressurized air flow (up to 20 bar) from ambient. The quartz glass is barely addressed in publications regarding the REFOS receiver. It has, however, shown to be a limiting factor to receiver dimension. Quartz glass (fused Silica SiO_2) is the only glass of sufficiently high allowable temperature, high transmittance and low thermal expansion [21]. Observation of the REFOS receiver over a total operating time of 500 h at air outlet temperatures of 600 °C to 800 °C resulted in the following findings:

- Burning-in of surface contamination that cannot be cleaned out (resulting in absorptivity increase)
- Microscopic fabrication defects that grow during thermal cycling
- Active cooling requirement of the glass
- Sensitivity to thermal shock
- Size limitation of the glass due to manufacturing constraints

With the mentioned 500 h of test time, representing about 60 days of normal operation, deterioration was already visible within a fraction of a plant lifetime [21]. Concerns are that besides deterioration of the optical quality, cracking of the window occurs under pressure and high solar flux density [22].

The current diameter of the REFOS' quartz glass window is 620 mm [4]. However, unpressurized systems report higher diameters possible. The SOLUGAS receiver design has an opening of 5 m diameter and is covered with a (multi-element) quartz glass window.

3.2. The DIAPR receiver

In parallel to the DLR, the Weizmann Institute of Science developed a pressurized air volumetric cavity receiver, the Directly Irradiated Annular Pressurized Receiver (DIAPR). The DIAPR is based on the porcupine absorber concept, where concentrated solar radiation impinges on high temperature resistant alumina-silica pins [23]. The pressurized air stream is guided past the pins and is heated up in the process. The cross-section of a DIAPR is shown in Fig. 5.

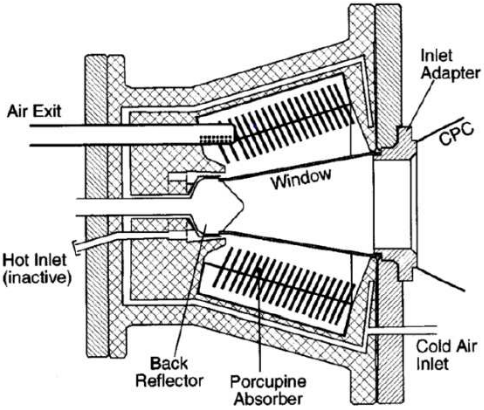

Fig. 5. The DIAPR receiver in cross-section [24]

The DIAPR was the first receiver to exceed test temperatures of 1200 °C [24] and was shown to handle extraordinarily high flux densities of up to 10 MW/m^2 [25]. In an attempt to increase the system efficiency, a multistage DIAPR was developed that employed, similarly to the DLR approach, a coiled tubular cavity pre-heater [26]. Efficiency information on the cluster or the pre-heater is not available. The DIAPR receiver without pre-heater has a stated thermal efficiency of between 90 % and 70 % for a temperature range of 850 °C to 1200 °C, while [24] expected values of 85 % to 90 % with improved optics to be viable. The presented thermal efficiencies are excluding CPC losses. These values were further provided for a flux density of 5 MW/m^2 on the receiver aperture. The downside of high flux densities is that the required concentration ratios lead to increased shading and blocking in a more dense heliostat field, as well as increased spillage losses at the CPC aperture [27]. In the case of the DIAPR prototype testing, 60 % of the concentrated beams were lost to spillage [24].

The DIAPR also utilizes a pressurized fused quartz glass window (the FLHIP window), and the window manufacturing consequently also poses a limiting factor to up-scaling of the receiver. The capability of the window to withstand pressures up to 50 bar was stated and high temperature tests were conducted at 17 bar to 20 bar [24]. During the tests, the DIAPR receiver was operated for a significantly shorter time than the REFOS receiver. It is therefore unknown whether the DIAPR's quartz glass window can better sustain long term operation.

While further work has been proposed, no new information on development progress with regards to the DIAPR system has been published in recent years. The DIAPR technology was recently implemented in the 100 kW_e AORA Solar micro-turbine central receiver demonstration system [4].

4. Results and conclusions

It can be seen that there is room for innovation in the young research field of pressurized air receivers, with only two research institutions driving development to prototype and demonstration scale. No commercialized system for utility scale operation is available as yet.

Generally, limited information is available on the proposed systems. With regards to the high temperature volumetric cavity receivers this is especially the case for the DIAPR system. The limited long time testing of the REFOS receiver has already indicated limitations to the durability of the quartz glass window, adding to the problems with robustness and practicability of the window, which further restricts up-scaling of the receiver system.

The tubular pre-heating sections are equally insufficiently discussed in literature. Unfortunately the efficiency of the DIAPR’s pre-heater section is not known as the incidence flux could not be measured during tests [26]. The DLR's tubular SOLUGAS receiver seems to be the first pre-heater receiver that could achieve the 800 °C goal.

It can further be concluded that the volumetric receivers and tubular pre-heaters proposed by DLR and WIS are cavity receivers, mostly equipped with secondary concentrators (CPC). None of the reviewed receivers is designed for a large scale surrounding heliostat field, which provides higher annual energy collection, compared to a polar field [11]. A qualitative comparison of the investigated receivers is provided in Table 2.

	DIAPR	REFOS	SOLGATE LT-Receiver	SOLHYCO	SOLUGAS
Maximum op. temp.	+	+	-	O	O
Pressure drop	+	+	-	-	**N/A**
Optics (CPC)	-	-	-	+	+
Optics (accepting surrounding field)	-	-	-	-	-
Thermal efficiency	+	+	O	-	**O**
Robustness, durability	**N/A**	-	-	-	**N/A**
Cost/simplicity	**N/A**	-	+	**N/A**	**N/A**
Flux density	+	O	-	-	-

Table 2: Summary of current receiver technologies

The conducted review of developed receivers highlights that there is need for a central receiver that meets the following requirements:

- Effective transfer of the thermal energy that has been generated by the heliostat field
- Utilization of the higher efficiency of a surrounding heliostat field and avoiding optical losses of secondary concentration
- Robust, practical and cost efficient technology that is not dependent on sensitive plant elements such as quartz glass windows
- A low pressure drop in the receiver

It is shown that the pressurized air receivers demonstrated to date have practical limitations when operating at high temperatures and pressures. As yet, a robust, scalable and efficient system has to be developed and commercialized for the medium-temperature as well as the high-temperature range.

Further, current concepts mutually exploit the principle of a cavity receiver, limiting the acceptance angle of the receiver, hence resulting in the usage of a (or multiple) polar heliostat field(s). Receiver technologies utilizing an optically more desirable surrounding heliostat field layout have not been proposed.

The review illustrates a need for pressurized air receiver concepts providing a robust, optically and thermally efficient solution at low cost and a low pressure drop.

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