Optica Applicata, Vol. XL, No. 2, 2010

High porosity materials as volumetric receivers for solar energetics

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This paper gives a brief overview on the research activities of the Solar Technology Department of the German Aerospace Center on porous materials for solar tower technology. Firstly, a brief introduction to solar tower technology is given. Then, the function of the central component of tower technology, the volumetric air receiver, is described in detail and examples as well as experimental results of receiver tests are given. Results of numerical studies are presented, which have been carried out to characterize air flow stability in receiver systems. Approaches presently used to model the interior temperatures of the receiver are described. Next spin-off applications such as particle filters or cooling systems are presented, which are dominated by similar physical phenomena and which can be treated with the same experimental and numerical methods. Finally, information is given about the Jülich Solar Tower, which is the first test power station that makes use of the solar air receiver technology.

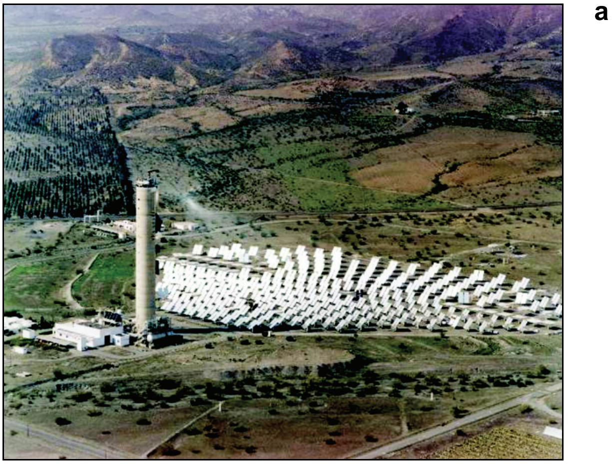
Keywords: solar tower technology, porous materials, volumetric air receiver, concentrating solar power.

1. Introduction

Solar tower technology is a promising way to generate large amounts of electricity from concentrated solar power in countries with high solar resources such as North Africa and the Middle East, India, Australia or parts of North and South America, countries known to belong to the so-called "sun-belt" of the Earth.

The concentrated radiation is generated by a large number of controlled mirrors (heliostats), each of which redirects the solar radiation onto the receiver as a common target on the top of a tower. Here, at the focal point the so-called "solar air receiver" is located, which absorbs the radiation and converts it into high temperature heat. Cellular high temperature resistant materials are used as receivers. As a heat transfer medium air is used, which is heated up by flowing through the open cells of the hot receiver material and which then feeds a conventional boiler of a steam turbine.

As an example, a 3 MW solar tower test plant in Almería, Spain, as well as a sketch of the working principle are shown in Fig. 1. A typical flow chart is shown in Fig. 2. This idea of the "solar air receiver" was first presented in 1985 [1]. Since then,



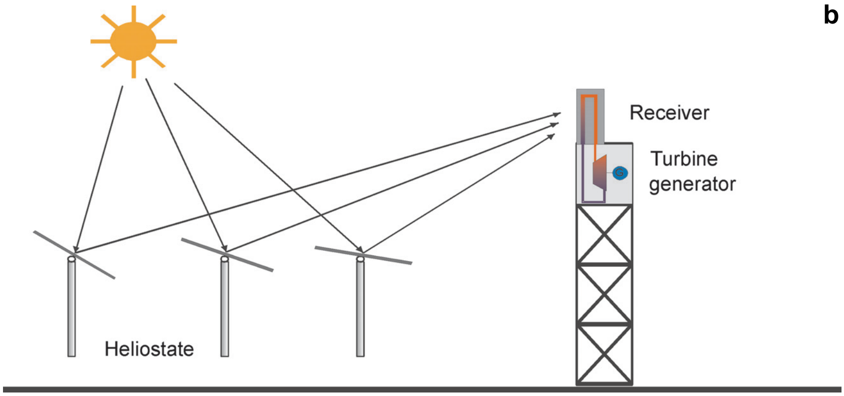


Fig. 1. Solar tower technology: photograph of the CESA 1 test plant in Almería, Spain (**a**) and working principle (**b**).

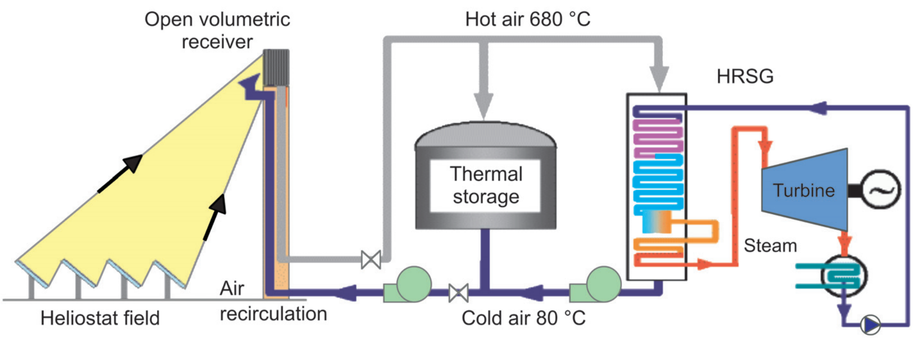


Fig. 2. Flow chart of a steam turbine driven by solar tower technology.

the technology has been successfully proven in a number of projects during the last 25 years [2–4]. A ceramic receiver with a thermal power of 3 MW was successfully tested by a European consortium in 2002 and 2003 within the SOLAIR-project [5]. Recently, a 1.5 MW_E[1] test plant was erected in Jülich, Germany, which is the first plant connected to the grid equipped with a solar air receiver [6]. A detailed description of the solar air technology is provided in [7].

2. The solar air receiver

The solar air receiver is often also called volumetric air receiver, because due to the porosity of the material the concentrated solar radiation is absorbed in part of the volume of the material. Its principle is illustrated in Fig. 3. A simple tubular absorber is shown for comparison. Because cold ambient air enters the material at the front of the volumetric absorber, where it is facing the radiation, the material can be kept relatively cool. In an ideal operation, the temperature distribution should be as shown on the lower right-hand side of Fig. 3. The low temperature level at the front minimizes thermal radiation losses.

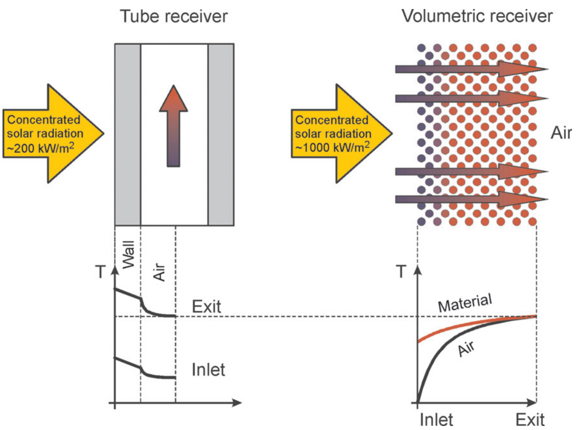


Fig. 3. The volumetric receiver principle compared to a tube receiver.

Reaching the inner absorber volume the temperature increases and the temperature difference between fluid and solid vanishes. Usually, this is already the case after a couple of cell diameters, for example, in the case of an 80 ppi[2] ceramic foam after 1–2 millimetres. In contrast to this increasing temperature distribution from the inlet to the outlet of the absorber module in the case of an ideal volumetric absorber the temperature distribution of a simple tubular absorber is disadvantageous. This is shown in the graph on the lower left-hand side of Fig. 3.

[1]Megawatt electrical power.
[2]The unit ppi (pores per inch) is a measure of the pore density of a foam.

Here, the fluid which has to be heated flows inside a tube. The solar radiation heats the tube which in turn heats the fluid. The temperature at the outer tube surface is significantly higher, leading to higher radiation losses. The temperature at the outer tube surface is limited by the temperature resistance of the material employed. To avoid destruction of the tube material, the intensity of the concentrated radiation must be kept low compared to volumetric absorbers. This makes it necessary to install larger absorber apertures to achieve similar amounts of total power.

The material requirements of volumetric absorbers are resistance to temperatures of 1000 °C and more and a high porosity needed to allow the concentrated solar radiation to penetrate into the volume of the cellular material. Further requirements are a high cell density to achieve large surface areas necessary to transfer heat from the material to the gaseous fluid flowing through the channels and a high thermal conductivity. Even though the extinction volume, that is, the volume of the receiver, in which the solar radiation is absorbed, decreases with smaller cell size, the increased surface area and the increase of heat transfer by smaller hydraulic diameters leads to the desire for structures with cells as small as possible.

3. Results of solar air receiver experiments

Within several recent projects the performance of solar air receivers has been tested experimentally. The most interesting quantity of solar air receivers is their solar-to--thermal efficiency

$$\eta = \frac{\dot{Q}_{\mathrm{air}}}{\mathrm{POA}}$$

It may be calculated by dividing the useful thermal power inside the air circuit after the receiver $\dot{Q}_{\mathrm{air}}$ by the power of the concentrated solar radiation penetrating into the aperture area of the absorber POA (power-on-aperture). $\dot{Q}_{\mathrm{air}}$ is usually determined with the temperature difference, the air mass flow and the heat capacity:

$$\dot{Q}_{\mathrm{air}} = \dot{m} C_{\mathrm{PL}} (T_{\mathrm{out}} - T_0)$$

The experiments were carried out in a 20 kW solar installation capable to generate concentrated radiation of up to 5 MW/m^2 peak flux. Figure 4 shows the principle of the set-up used for efficiency measurements. Figure 5 shows examples of materials tested: a fiber mesh material, which is commercially available from SCHOTT under the name Ceramat (fiber ∅ = 25 μm), the HITREC-material, a siliconized silicon carbide (SiSiC) catalyst carrier with parallel channels of approximately 2 mm in width made by Saint-Gobain, a 20 ppi SiC foam and an 80 ppi/20 ppi SiC sandwich-like foam with the 80 ppi layer at the front being responsible for absorption and heat transfer, both made by the Fraunhofer Institute for Ceramic Technologies (IKTS).

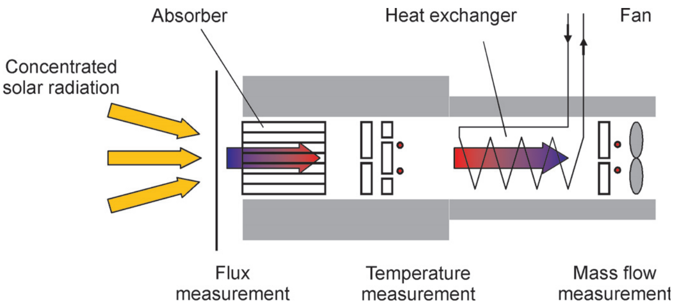


Fig. 4. Set-up used for efficiency measurements.

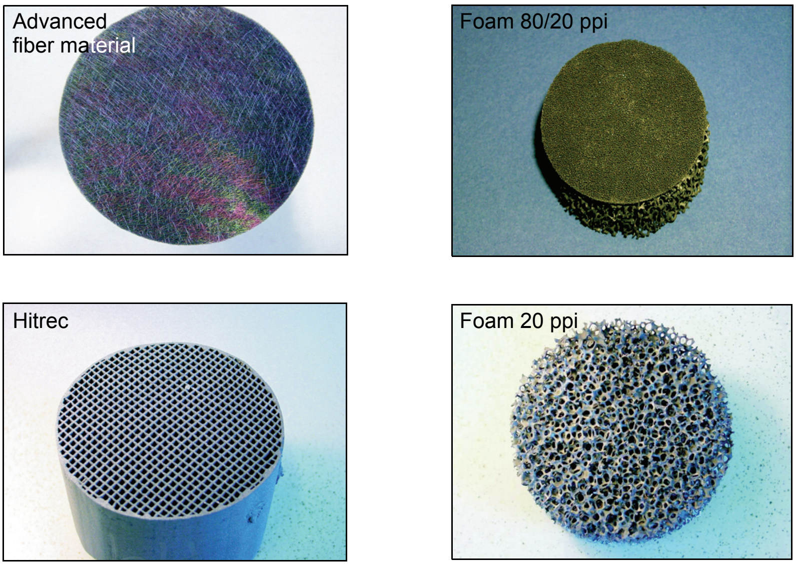


Fig. 5. Examples of porous materials tested as solar air receivers.

The results are shown in Figs. 6 and 7. The best performance was achieved by the fiber mesh absorber and by the 80 ppi foam. This indicates that at a given level of flux density the efficiency increases with increasing cell density. However, the HITREC--material was the material of choice for the modular receiver in the SOLAIR-project (Fig. 8) to be tested in a 3 MW_{th}[3] scale although it has shown limited efficiency results (Fig. 6) compared to the fiber mesh or the 80 ppi foam. The reason for that was a higher reliability as far as corrosion resistance and durability are concerned.

Some other materials did not withstand the high temperature exposure during the tests. This happened although the mean air outlet temperature was significantly lower than the allowed temperature for the material. As an example, a cordierite

[3]Megawatt thermal power.

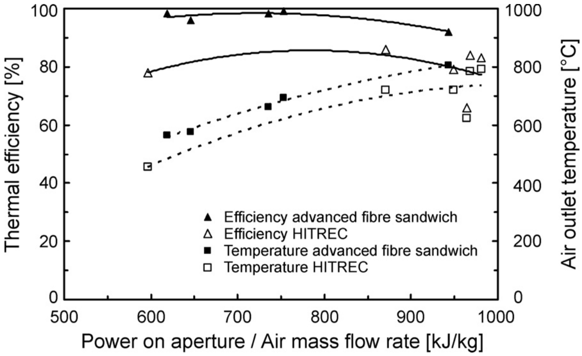


Fig. 6. Results of efficiency test of a receiver made out of silicon carbide (SiC) catalyst carrier material (HITREC) and a combined receiver additionally covered with an SiC fiber mesh material.

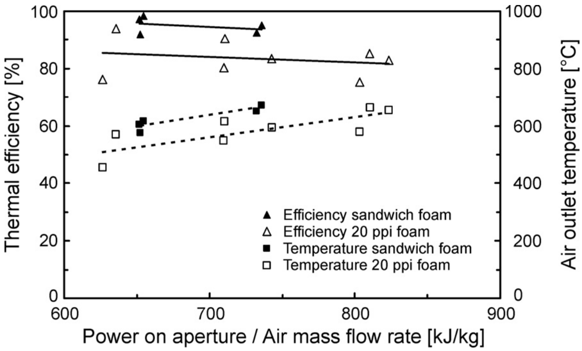


Fig. 7. Results of efficiency test of an SiC 20 ppi foam receiver and a combined receiver additionally covered with an 80 ppi SiC foam.

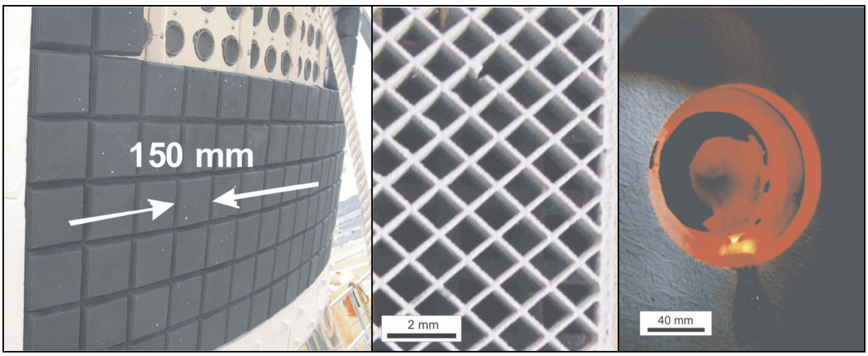


Fig. 8. Solar air receiver test within the European project SOLAIR. Each of the 150 mm HITREC modules absorbs 15–20 kW of solar power (left); photographs show a cordierite material before (middle) and after being tested as a solar air receiver in concentrated radiation ($I_0 \approx 2$ MW/m^2).

receiver melted, when the air outlet temperature was 900 °C, although the melting temperature of cordierite is 1450 °C (Fig. 8, right).

This effect is mainly due to flow instabilities, which have to do with the temperature dependent viscosity of air, which increases with increasing temperature. If there are temperature inhomogeneities at the front side of the receiver hot parts of the receiver have a lower permeability due to the more viscous air in these channels. Consequently, this kind of self-reinforcing effect may lead to hot spots and a material failure in severe cases. The occurrence of flow instabilities has been investigated in more detail in a recent study [8]. It turned out that a number of measures are efficient to prevent the occurrence of hot spots. These are a good thermal conductivity in the direction perpendicular to the main direction of flow, a high inertial coefficient in the Darcy−Forchheimer equation describing the pressure loss inside the porous material and the capability of the materials to allow fluid flow perpendicular to the main direction of flow (mixing). This last property is especially fulfilled for ceramic foams.

4. Numerical prediction of gas flow and temperature distributions

A sophisticated way to describe the problem in Fig. 9 is a numerical approach, which has been carried out by a research group at the University of Erlangen within the common project SOLPOR [14]. This approach provides a numerical solution of the basic conservation equations of mass, momentum and energy in a number of distinct control volumes. The heat transport in the porous material, which is composed out of heat conduction in the solid, grid, heat conduction in the fluid and heat conduction by mixing effects, is described by an effective heat conductivity, which has to be determined experimentally. The experimental method as well as data of various porous materials have been published by DECKER *et al.* [10]. The numerical method is described in more detail in an earlier publication by BECKER *et al.* [8]. As the method is a two phase calculation, solid-to-fluid heat transfer has to be treated as a separate physical quantity. A transient technique has been employed to determine this quantity for porous materials. It is described in more detail in [11]. An overview on experimental data of a number of various porous materials is given

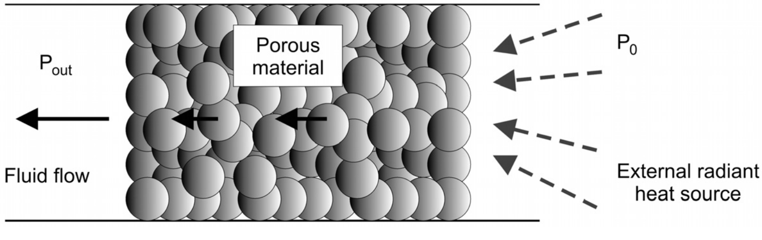


Fig. 9. Flow problem through a heated porous medium with $P_{out} < P_0$.

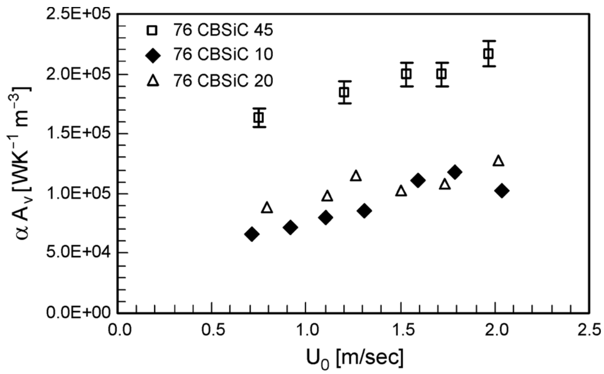


Fig. 10. Volumetric heat transfer data determined for a set of ceramic foam materials. (Various pore diameters were investigated.)

in [12]. As an example, heat transfer data of a series of silicon carbide foams is shown in Fig. 10.

Performing a detailed numerical study as roughly described in the last paragraph enables us not only to show a rough tendency how certain properties influence the probability of hot spots but also to generate two dimensional distributions of the front temperature of the porous sample. Such an investigation has been carried out within the German SOLPOR-project by researchers from the University of Erlangen. It is described in more detail in [8]. They considered the situation shown in Fig. 9 and assumed a cylindrical geometry. The external radiant heat source of 1 MW/m^2, a typical value for a solar tower installation, was assumed to be absorbed in some thin layers of the porous body corresponding to the extinction coefficient of the material employed. It was further assumed that the heat flux is homogeneously distributed on the circular front of the sample. The resulting flow and temperature distribution were calculated. To study possible flow instabilities a "static hot spot" was created by using a small area of higher flux as starting conditions. After a while the flux was switched to homogenous flux but the temperature calculation continued. Depending on the material properties, the hot spot maintained or it vanished. In this way, a parameter study was performed and it could be observed at which levels of thermal conductivity and inertial coefficient flow instabilities occurred. An example is shown in Fig. 11. On the horizontal axis the inertial coefficient was varied, on the vertical axis, the thermal conductivity. For $K_2 < 1\times10^{-4}$ no hot spots could be observed. Also for materials with a flow, which is completely dominated by viscous flow ($K_2 = \infty$) the probability for hot spots vanishes, if the effective thermal conductivity is high enough (>10 $Wm^{-1}K^{-1}$). By varying three parameters and looking for permanent hot spots, a detailed parameter field could be determined, in which no hot spots can occur.

The results confirm the experimental results, which were obtained from a test with the cordierite catalyst carrier material already mentioned in Section 3. Here the sample

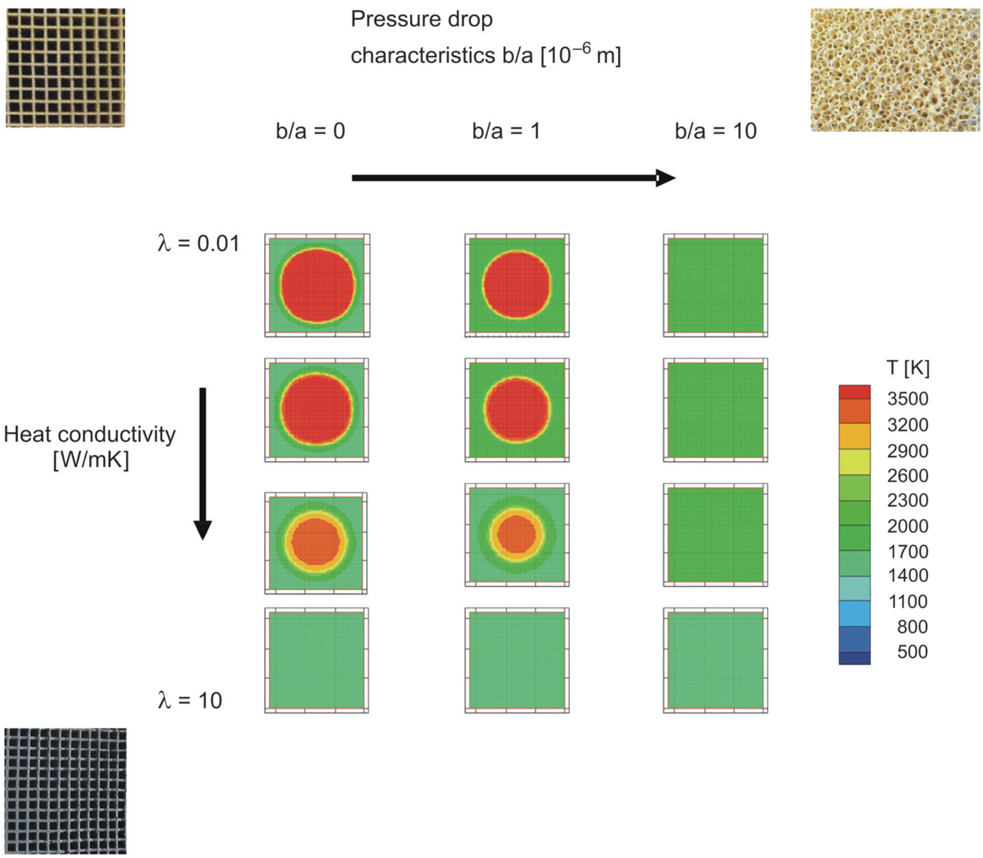


Fig. 11. Temperature distributions at the front side of various homogenously heated porous material samples obtained from numerical calculations.

melted although the average air outlet temperature was 800 °C and the melting point of cordierite is 1450 °C. The thermal conductivity ($\lambda \approx 1$ $Wm^{-1}K^{-1}$) and the inertial coefficient ($K_2 = 0.05$ m) of the cordierite sample were in a range where hot spots are allowed.

5. The Solar Tower Jülich

In Section 2, the technology of the solar air receiver was described in detail. The most recent application of the HITREC Technology (Fig. 8) is the Solar Tower Jülich, a power plant of 1.5 MW electrical power erected in Jülich in West Germany. It was launched in June 2009 and since then it has been delivering electrical power into the German electricity grid. It was erected by the company Kraftanlagen München with financial and scientific support of DLR. It is currently operated by Stadtwerke Jülich, the local utility.

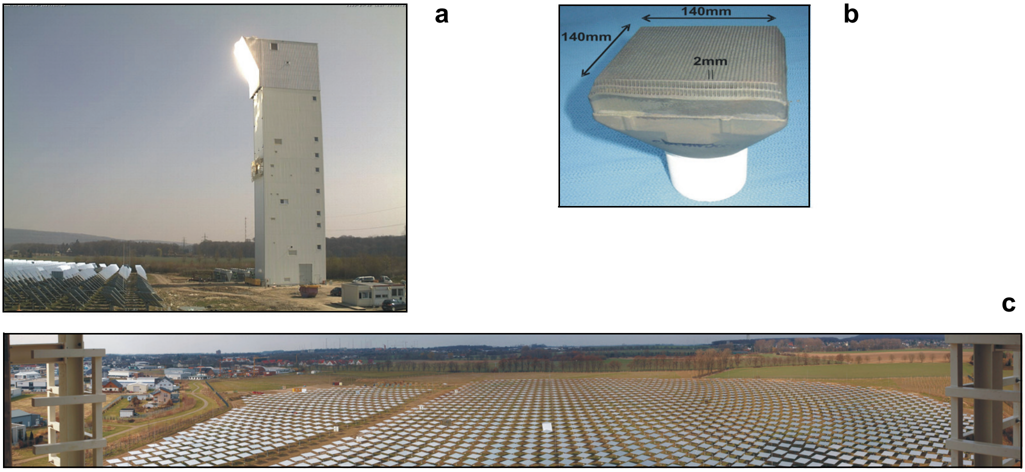


Fig. 12. The Solar Tower Jülich in operation (**a**), HITREC receiver element (**b**), view from the test platform of the tower (**c**).

It works according to the principle shown in Fig. 2. The total number of heliostats needed is more than 2000 and they comprise a mirror surface area of more than 20000 m^2. The receiver consists of 1080 HITREC receiver elements and covers a total area of 20 m^2.

6. Spin of applications

6.1. Cross-flow particle filter

Particle filters for Diesel engines (DPF), which are going to be obligatory in the future for passenger cars and large vehicles, are object of an intensive research activity all over the world. Most of the DPFs consist of inlet channels, a porous ceramic or metal wall, which enables flow of the exhaust gas through it and outlet channels. Particles are filtered and remain outside the walls in the inlet channels. In regular time intervals the DPF has to be regenerated to remove the particles. In this process, which is carried out during regular use of the engine, soot particles in the inlet channels of the filter are burned, partly with catalyst support. After burning, ashes remain in the channels. In many existing filters this leads to a slow blocking of the inlet channels (Fig. 13, left).

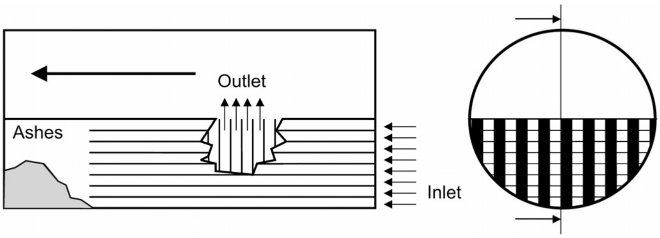


Fig. 13. Cross-flow particle filter principle.

During the regeneration heat is generated inside the channels. In so far, the physical processes are comparable to the processes inside the solar air receiver. In the common project INNOTRAP, which is carried out by the company DEUTZ AG, the University of Erlangen, the Fraunhofer IKTS, the Solar Institute Jülich, the DLR and some smaller industrial partners, these processes are investigated in more detail. Additionally, a cross-flow filter is proposed, which enables the ashes being removed from the inlet channels and entering into an ash container. This principle is shown in Fig. 12.

The cross-flow filter may be realized with ceramic foil technology, which has been approved for water filtering before, or with an advanced ceramic printing technology, which has been developed by the German company Bauer Technologies. Also this technology has been approved in a hot gas application as a solar receiver before [13]. An example of a possible filter design is shown in Fig. 14 (right).

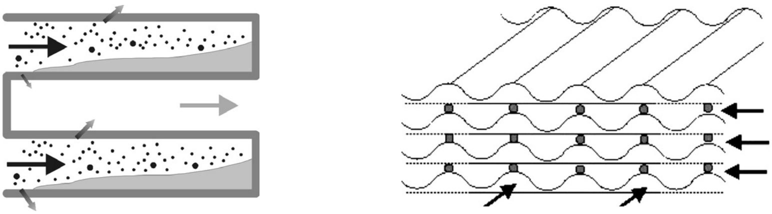


Fig. 14. State-of-the-art particle filter principle (left) and advanced cross-flow principle.

Besides testing new filter designs experimentally the objective of the project is to develop tools for a numerical simulation of the air and particle flow inside the filter.

6.2. Gas turbine cooling

To achieve higher temperatures in the combustion chamber of combined cycle power stations, the Collaborative German Research Project SFB 561 has been founded in 1998. One of the main objectives of the project is to investigate an active cooling of the combustion chamber walls by effusion of air into the chamber (effusion cooling). The principle is shown in Fig. 15. The wall is covered with metal foam and a thermal barrier coating (TBC). Cooling air is pressed through the foam and through thin

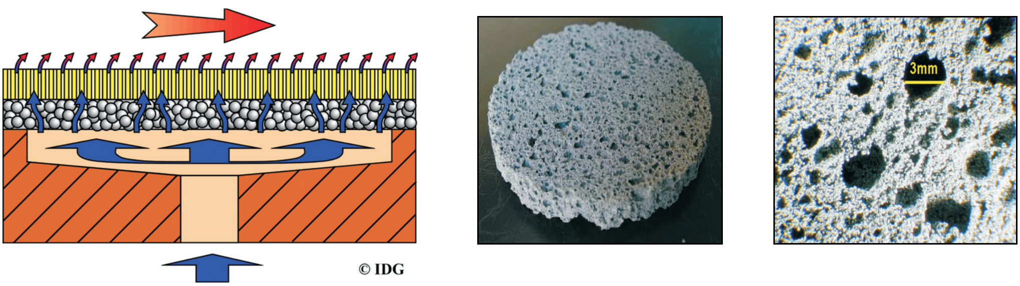


Fig. 15. Combustion chamber cooling with μm-scale porous metal foams.

holes in the TBC. In 2004, DLR joined the project and took over the responsibility for the characterization of the flow through the foam. Until now, a number of foam materials have been characterized concerning heat transfer and thermal conduction properties. Results are presented in more detail in [15] and [16]. Also this application deals with an external heat source, which is transferred into the porous material by convection and by radiation.

6.3. Cross-flow/counter flow heat exchanger

A new approach manufacturing a compact high temperature heat exchanger is shown in Fig. 16. A modified honeycomb structure was used to lead two separate gas flows through the open pores of the material. Every second row of channels was closed at the inlet and outlet with a high temperature cement. These closed rows were then opened from the side in the green state of the ceramics, as can be seen on the right photograph of Fig. 16. By using an appropriate canning a second flow could be led through the lateral openings. First experimental results as well as results of numerical calculations show excellent performance of prototypes of this technology.

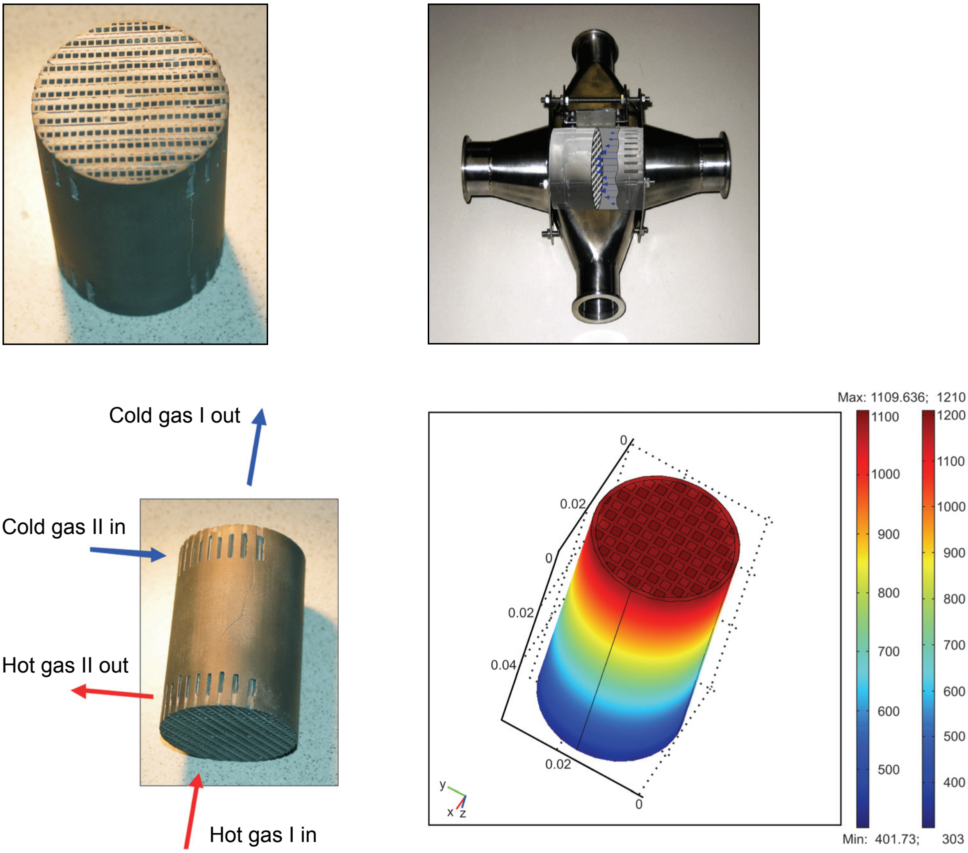


Fig. 16. Extruded SiC honeycomb-structure used as a cross-flow/counterflow heat exchanger.

7. Conclusions

Flow through hot porous materials has been investigated for a number of different applications. In the case of the solar air receiver physical phenomena like the occurrence of hot spots, which have been observed experimentally, could be explained theoretically and it could be shown how material properties such as thermal conductivity and permeability influence this phenomenon. From the design point of view the desired properties of an ideal solar air receiver are known, however, future activities have to focus on durability, corrosion resistance and simplicity of manufacturing to achieve low costs for the whole receiver system, which at last lowers the generation costs of solar electricity. In the case of the particle filter, the ceramic mixer and the effusion cooling of the gas turbine numerical approaches are subject of current research activities and first results should be expected within the next months.

Acknowledgments – The support of the Deutsche Forschungsgemeinschaft (DFG) for the projects PORENKÖRPER and SFB 561, the German Ministry of Education and Science for the projects SOLPOR and 3DKeSt as well as the German Ministry of Economy for the project INNOTRAP is gratefully acknowledged. Additionally we thank the European Commission for having funded the collaborative project SOLAIR.

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Received November 12, 2009
in revised form January 13, 2010