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GAS FLOW IN HOT POROUS MATERIALS: THE SOLAR AIR RECEIVER AND SPIN-OFF APPLICATIONS

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ABSTRACT
This article presents an overview on research results from various projects, which deal with one common problem: gas flow in hot porous materials. First, the solar air receiver, which converts concentrated solar radiation into heat in an air circuit, is described as far as the basic principle and the materials employed are concerned. Then, results from experiments in concentrated solar radiation are presented. Materials employed in these applications are extruded ceramic materials as well as metal and ceramic foams with pore sizes on the milli- and micrometer scale. As it turned out, the material properties significantly influence the efficiency of the solar air receiver. It is shown, that under specific conditions flow instability occurs, which may lead to a thermal overload of the material. Measures to avoid these overloads are proposed. Two approaches how to predict gas flow theoretically are reported. Additionally, it is shown, how material quantities such as pressure drop characteristics influence the flow behaviour and the temperature distribution inside the material. Finally, before a conclusion is given, two further applications, which have been dealt with because similar phenomena occur, are reported: an advanced cross flow particle filter and a gas turbine cooling system.

INTRODUCTION

The origin of the applications described in this article was the investigation of the use of cellular materials as absorbers in solar air receivers. This research work began in the 80ies of the last century. A solar air receiver is a central element of the so-called *solar tower technology* which converts concentrated solar radiation into high temperature heat.

FIGURE 1: The Cesa 1 tower at the 'Plataforma Solar de Almería' (PSA) used as test installation for solar air receivers

In general, cellular materials such as catalyst carriers consisting of straight thin channels or ceramic foams are employed as solar air receivers to absorb concentrated solar radiation and to transfer the energy to a fluid flowing through its open cells.

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. As an example, a solar tower installation at the 'Plataforma Solar de Almería' (PSA) in Southern Spain is shown in Fig. 1. There are different concepts to exploit the heat generated by a solar air receiver. In one concept, which was mainly investigated during the projects the author's were involved in, ambient air is forced through the open pores of the material and is heated to temperatures of about 700°C. It is then used to generate steam for a conventional steam turbine process. A typical flow chart is shown in Figure 2. In a first study, this idea of the "open volumetric air receiver" was presented in 1985 [1]. Since then, 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 has been successfully tested by a European consortium in 2002 and 2003 within the SOLAIR-project [5]. A detailed description of the solar air technology is provided in [6].

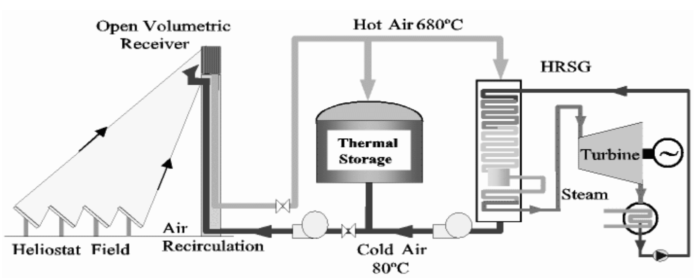

FIGURE 2: Flow chart of a steam turbine cycle fed with the heat of a solar tower

NOMENCLATURE

α	Heat transfer coefficient	$W{\cdot}m^{-2}{\cdot}K^{-1}$
A_V	Surface to volume ratio	m^{-1}
C_{PF}	Heat capacity of the fluid	$Jkg^{-1}K^{-1}$
ε	Emissivity	-
η	Efficiency	-
I_0	Heat flux by optical radiation	$W{\cdot}m^{-2}$
K_1	Viscosity Coefficient	m^2
K_2	Inertial Coefficient	m
L	length x-direction	m
$\dot{m}$	Mass flow density	$kg{\cdot}s^{-2}{\cdot}m^{-2}$
μ_{DYN}	Fluid Dynamic Viscosity	Pa·s
P	pressure	Pa
P_0	Pressure at the inlet	Pa
P_{OUT}	Pressure at the outlet	Pa
POA	Solar Flux (Power) on Aperture	W
$\dot{Q}_{AIR}$	Power into air flow	W
$\dot{q}$	Heat Flux	$W{\cdot}m^{-2}$
R	Gas constant = 287	$J{\cdot}kg^{-1}{\cdot}K^{-1}$
ρ_F	Fluid Density	$kg{\cdot}m^{-3}$
σ	Stefan-Boltzmann constant = $5.6697\ 10^{-8}$	$W{\cdot}m^{-2}{\cdot}K^{-4}$
T	Temperature	K
T_0	Ambient temperature	K
T_{OUT}	Air outlet temperature	K
U_0	Fluid Velocity	$m{\cdot}s^{-1}$
x	Direction of the main flow	m

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 Figure 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 cool. In an ideal operation, a temperature distribution shown on the lower right side of Figure 3 should be realized. The low temperature level at the front minimizes thermal radiation losses, which occur following the well known Stefan-Boltzmann law

$$\dot{q} = \varepsilon \sigma T^4 \qquad (1).$$

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 ceramic foam after 1-2 millimetres. In contrast to this increasing temperature distribution from the inlet to the outlet of the absorber module in case of an ideal volumetric absorber the temperature distribution of a simple tubular absorber is disadvantageous. It is shown in the graph on the lower left side of Figure 3.

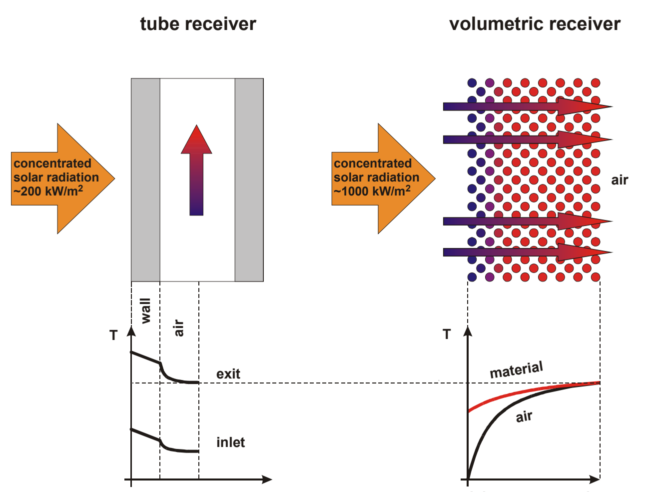

FIGURE 3: The volumetric receiver principle compared to a tube receiver

Here the fluid which is 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's requirements of volumetric absorbers are a resistance to temperatures of 1000°C and more, 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/channel 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 decreases with smaller structure sizes, the increased surface area and the increase of heat transfer by smaller hydraulic diameters leads to the desire for as small as possibly feasible structures as long as the porosity can be kept high.

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

$$\eta = \frac{\dot{Q}_{AIR}}{POA}. \qquad (2)$$

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

$$\dot{Q}_{AIR} = \dot{m} C_{PL} (T_{OUT} - T_0) \qquad (3)$$

The experiments were carried out in a 20 kW solar installation capable to generate concentrated radiation of up to 5 MW/m² peak flux. Fig. 4 shows the principle of the set up used for efficiency measurements. Fig. 5 shows examples of materials tested: a fiber mesh material, which is commercially available from SCHOTT under the name Ceramat (fiber ∅ = 25µm), the HITREC-material, a Silicon Carbide (SiC) catalyst carrier with parallel channels of approximately 1 mm width made by St. 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).

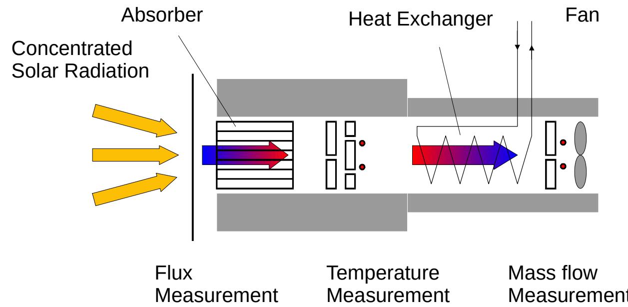

Figure 4: Set-up used for efficiency measurements

The results are shown in Figs. 6 and 7. 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} scale although it has shown limited efficiency results (Fig. 6) compared to the fibre mesh or the 80 ppi. The reasons were a higher reliability as far as corrosion resistance and durability are concerned.

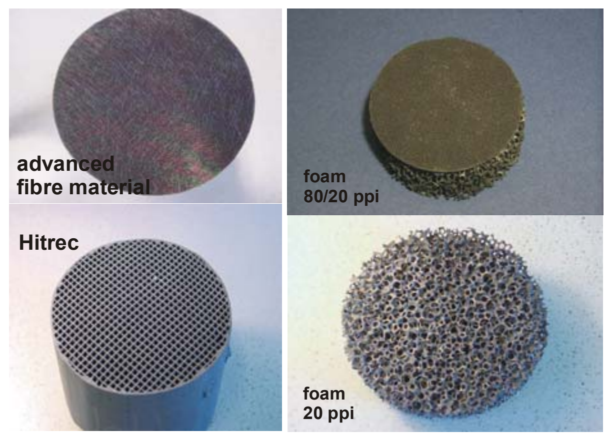

Figure 5: Examples of Porous materials tested as solar air receivers

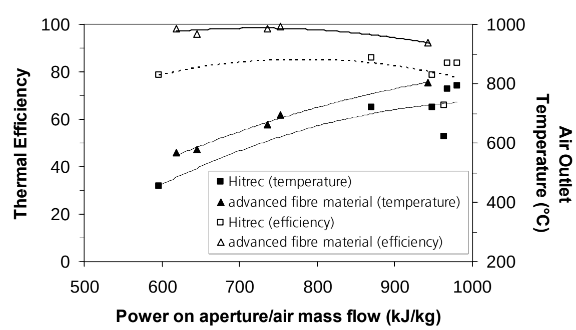

Figure 6: Efficiency test results of a receiver made out of Silicon Carbide (SiC) catalyst carrier material (HITREC) and a combined receiver additionally covered with a SiC fibre mesh material

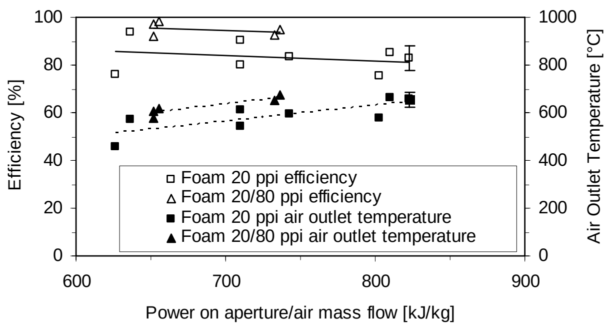

Figure 7: Efficiency test results of a SiC 20 PPI foam receiver and a combined receiver additionally covered with an 80 PPI SiC foam

However, several materials failed, although the mean air outlet temperature was far below the allowed temperature constraint given by the material. As an example, a cordierite receiver melted, when the air outlet temperature was 900°C, although the melting temperature of cordierite is 1450°C (Fig 8, right).

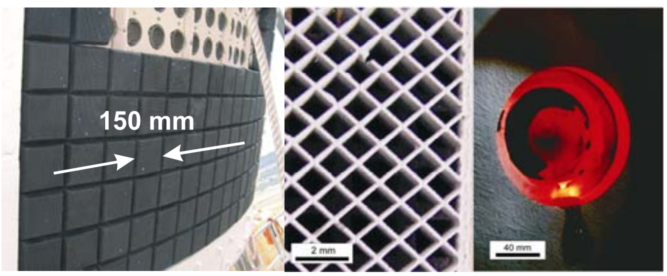

Figure 8: Solar air receiver test within the European project SOLAIR. Each of the 150 mm HITREC modules absorb 15-20 kW of solar power (left) and photographs from a cordierite material before (middle) and after tested as a solar air receiver in concentrated radiation (I_0≈2MW/m²)

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 in-homogeneities 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 have been investigated in more detail in a recent study [7]. 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.

APPROACHES TO PREDICT GAS FLOW AND TEMPERATURE DISTRIBUTIONS

Analytical Approach

In all the applications mentioned we have the problem of flow through a porous medium, which is heated by internal or external heat sources. The flow through the medium, which can be imagined as being inside a section of a fluid pipe, is caused by a higher pressure P_0 at the entrance side of the medium and a pressure P_{OUT} at the outlet side (Fig. 9). As depicted in the Figure, an external radiant heat source exists, which can be imagined as concentrated solar radiation as well as heat radiation from the hot gas in the combustion chamber. So the main physical phenomena occurring during this process are the momentum and heat transfer inside the material.

A simple way to describe the resulting fluid and solid temperature is an analytical approach firstly introduced by Kribus et al. [8]. It was also used to study the influence of material properties on the probability of the occurrence of flow instabilities [7].

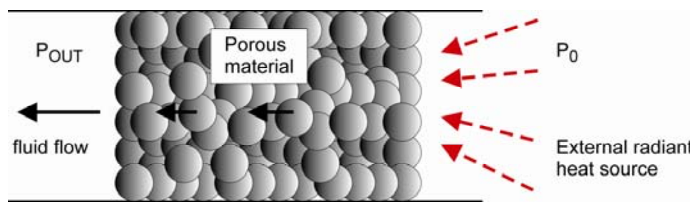

Figure 9: Flow problem through a heated porous medium with $P_{OUT} < P_0$

The momentum transfer in the main flow direction x may be described by the well known Darcy-Forchheimer equation:

$$-\frac{dp}{dx} = \frac{\mu_{DYN}}{K_1} U_0 + \frac{\rho_F}{K_2} U_0^2 \quad (4).$$

Here, p denotes the pressure, x the coordinate in the direction of the flow, K_1 and K_2 the viscosity and the inertial coefficient, μ_{dyn} the dynamical viscosity, ρ_F the density of the fluid and U_0 the velocity of the fluid. For air, the ideal gas law may be applied to determine the fluid density:

$$p = \rho_F R T_{OUT} \quad (5).$$

R denotes the specific gas constant R, 287 J/(kg·K) and T_{OUT} the air temperature. The dependence of the dynamic viscosity on the temperature of the air can be approximated by

$$\mu_{dyn}(T_{OUT}) = \mu_{dyn}(T_0)\left(\frac{T_{OUT}}{T_0}\right)^{0.7} \quad (6).$$

The mass flow density can be expressed as

$$\dot{m} = \rho_F U_0 \quad (7).$$

Rearranging gives:

$$-pdp = \left(\frac{\mu_{dyn}(T_0)}{K_1 T_0^{0,7}} T_{OUT}{}^{0,7} \dot{m}RT + \frac{RT\dot{m}^2}{K_2}\right)dx \qquad (8)$$

This equation can be integrated assuming that the heat sources are close to the inlet of the air. Then the temperature in each channel may be assumed as constant T_{OUT}. The integration yields:

$$\frac{p_0^2 - p_{out}^2}{2} = \left(R\frac{\mu_{dyn}(T_0)}{K_1 T_0^{0,7}} T_{out}^{1,7} \dot{m} + \frac{RT_{out}\dot{m}^2}{K_2}\right)L \qquad (9)$$

Here L denotes the length of the porous body, T_0 and T_{out} are respectively inlet and outlet temperature of the air. Now considering a porous body and its energy balance neglecting radial heat transfer

$$I_0 = \dot{m}C_{PF}(T_{out} - T_0) + \beta\sigma T_{out}^4, \quad (10)$$

with the heat flux I_0, which is absorbed by the material, C_{PF} the specific heat of the air, σ is the Stefan-Boltzmann-constant and β is a factor, which describes the thermal losses through radiation. Rearranging the energy balance for the mass flow density and putting it into the integrated pressure drop equation gives:

$$\frac{p_0^2 - p_{out}^2}{2} = RL\frac{\mu_{dyn}(T_0)}{K_1 T_0^{0,7}} T_{out}^{1,7} \frac{I_0 - \beta\sigma T_{out}^4}{C_{PF}(T_{out} - T_0)} + \frac{RLT_{out}}{K_2}\left(\frac{I_0 - \beta\sigma T_{out}^4}{C_{PF}(T_{out} - T_0)}\right)^2 \qquad (11)$$

This equation simply describes, what happens to the temperature of the fluid, if certain levels of pressure are chosen to move the fluid through the channels of the material and if the absorbed power I_0 is considered to be constant. As it will be shown in the next paragraph, where a plot of this equation will be presented at certain pressure levels, an ambiguity may occur in a way that more than one temperature value belong to one pressure level. This ambiguity, which is assumed to be the reason for the hot spots reported in the paragraph ‘results of solar air receiver experiments’, vanishes for certain material properties.

Numerical Approach

A more 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 [13]. In contrast to the simple approach described before, which did not take into account any heat transport perpendicular to the main flow direction, this one 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 has been published by Decker et al. [9]. The numerical method is described in more detail in a previous publication by Becker et al. [7]. 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 [10]. An overview on experimental data of a number of various porous materials is given in [11]. As an example, heat transfer data of a series of Silicon Carbide foams is shown in Fig. 10.

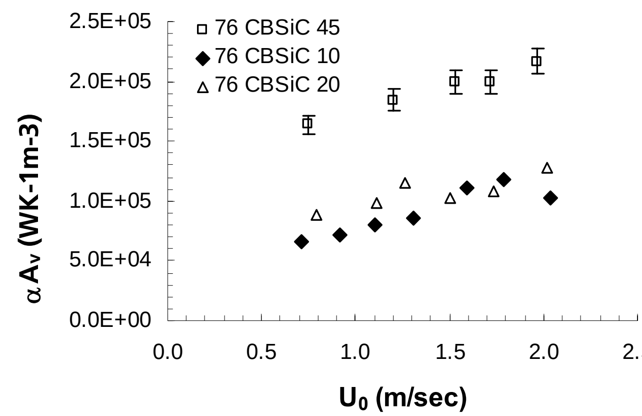

Figure 10: Volumetric heat transfer data determined for a set of ceramic foam materials. Various pore diameters were investigated

SELECTED RESULTS FROM THEORETICAL CALCULATIONS

Plotting equation (11) derived in the analytical approach described in the last paragraph (Fig. 11) enables us to receive some interesting results on the influence of various values of the inertial coefficient K_2 of the Darcy Forchheimer equation (4) on the general coarse of the function. K_2 may be imagined as a measure for the share of non-viscous flow inside the porous material. Employing straight channel geometry as in catalyst carriers leads to high values of K_2 whereas complex, tortuous flow paths as in foam materials or fiber meshes leads to low values.

The general course of the function in Fig. 11 is quite reasonable. High values of the quadratic pressure difference, which can be identified with the “blower power” used to press the air through the porous material, cause a high mass flow and low temperatures, low values of the blower power lead to low mass flows and high temperatures. However, in some cases this behaviour changes and more than one temperature value belongs to a certain pressure level. This ambiguity may be interpreted as the possibility to allow “hot spots” in single channels of the porous material or in restricted areas of the material. In these channels the mass flow rate goes down and cold by-pass flow may be observed around them. As can be seen from the series graphs in Fig. 11, this ambiguity vanishes, if the inertial coefficient decreases.

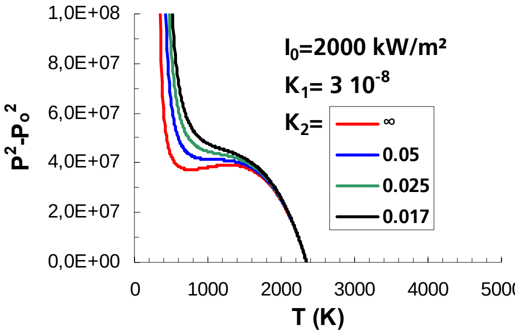

Figure 11: Quadratic Pressure Drop as a function of fluid temperature for various inertial coefficients derived from the analytical approach

Also other material properties are influencing this function. The next one can be studied in Fig. 12, which shows a series of plots of equation (11) generated by varying the absorbed power density from the external radiant heat source I_0.

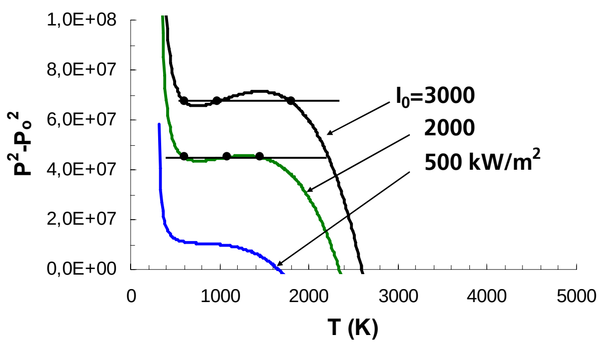

Figure 12: Quadratic Pressure Drop as a function of fluid temperature for various heat source intensities derived from the analytical approach

As can be seen, higher heat fluxes lead to an increasing ambiguity of the curve. Since hot spots are disadvantageous in the solar application and almost all other applications, these considerations may be helpful for a selection of appropriate materials as well as for the lay out of the whole process.

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 [7]. They considered the situation shown in Fig. 9 and assumed a cylindrical geometry. The external radiant heat source of 1 MW/m², 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 was 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. 13. On the horizontal axis the inertial coefficient was varied, on the vertical axis, the thermal conductivity. For $K_2 < 1\cdot10^{-4}$ 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.

Concerning the inertial coefficient, the results confirm the ones from the analytical calculation.

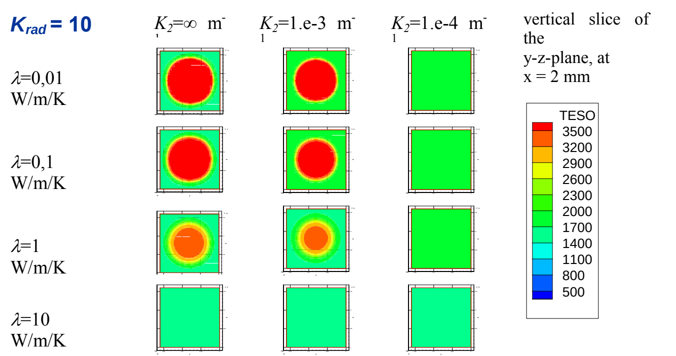

Figure 13: Temperature distributions at the front side of various homogenously heated porous materials sample obtained from numerical calculations.

The results also confirm the experimental results, which were obtained from a test with the cordierite catalyst carrier material already mentioned in the paragraph 'Results of Solar Air Receiver Experiments'). Here the sample 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.

PARTICLE FILTERS

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. 15, left). 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 more 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. 14.

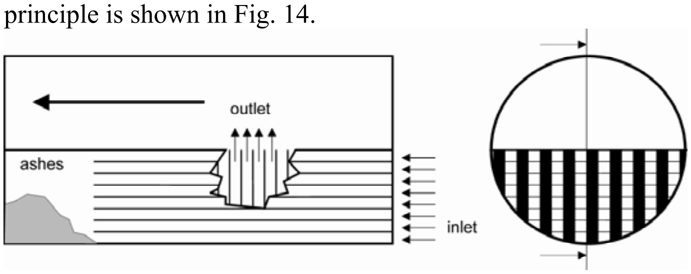

Figure 14: Cross-flow particle filter principle

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 [12]. An example of a possible filter design is shown in Fig.15 (right).

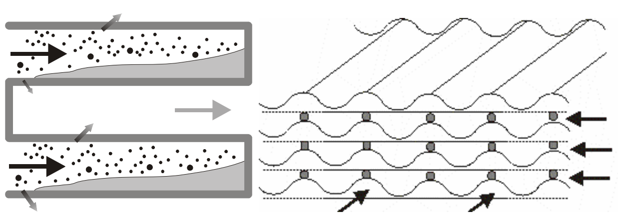

Figure 15: State-of-the-art particle filter principle (left) and advanced cross-flow principle

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.

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. 16. The wall is covered with metal foam and a thermal barrier coating (TBC). Cooling air is pressed through the foam and through thin 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. Two more articles of the conference (ICNMM2006-96135 and ICNMM2006-96136) deal with details of this work. Also this application deals with an external heat source, which is transferred into the porous material by convection and by radiation.

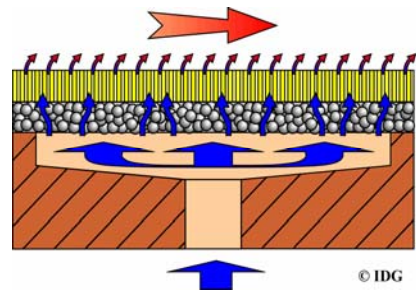

Figure 16: Combustion chamber cooling with µm-scale porous materials

CONCLUSIONS

Flow through hot porous materials has been investigated for a number of different applications. In 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 like 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 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

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