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New Possibilities for the Application of Ceramic Heat Exchangers in Processes with High-temperatures and Difficult Atmospheres°

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1. Necessity

Co-combustion of biomass, coal and refuse-derived fuel (RDF) causes an inconsistency in heat exchanger materials at high temperatures and aggressive media. Ceramic heat exchangers enable economically-efficient utilisation of the converted energy.
The high thermal and chemical stability of silicon carbide guarantees universal and long-term applicability.

This material can still be applied, when other materials have already encountered their limits. The material can be reinforced with fibre and meets all requirements. Compared to metallic materials such as Inconel and Hastelloy (high-quality nickel basis alloys), ceramic heat exchangers have a good price-performance ratio in this field of application.

For the increase of efficiency of thermal processes and for the use of heat in high temperature atmospheres, materials with special characteristics are necessary. For this purpose – supplementing or substituting to metals – ceramics are available, which guarantees universal applicability and longevity.

Enterprises have to dispose production-specific residuals and wastes economically. Thermal waste disposal – supplying a certain amount of heat and electricity – can be linked to the production process if a lot of energy is demanded.
If electricity and heat are needed during production, thermal refuse disposal could be coupled.

2. Material

The necessity for higher efficiency and changed operating conditions puts material selection the foreground in terms of design and realisation of procedure chains.
The implementation of technologies always fails due to the insufficient characteristics of conventional metals. Technical ceramics are an alternative to metals. It is to be ensured for each individual case of application whether the alternative materials dispose about the desired characteristics. Besides, pressure and temperature stability also thermal conductivity (ability), hardness and the coefficient of expansion belong to these characteristics.

Material Properties of SiSiC (Table 1)

- High temperature- and oxidation stability (up to 1350 °C)
- Steadily against all acids – except hydrofluoric acid
- Excellent temperature change resistance 600 K/s
- Very small thermal elongation 4 x 10^{-6} K^{-1}
- Outstanding heat conductivity (130 W/mK at ambient temperature –40 W/mK at 1200°C)
- Best radiation achievement at high temperatures
- Suitable for the lightweight construction, Small specific weight (2.8 to 3.1 g/cm^3)
- Very high rigidity (200 to 350 GPa)
- Outstanding firmness up to 1350 °C (150 to 400 MPa)
- Nearly as hard as diamond, Vickers hardness (25,000 MPa)
- No creeping under mechanical load
- Insensitively to dampness/humidity
- Nearly unlimited geometry and form variety
- Self cleaning effect when contaminated by flue gas.

Property	Method	Unit	Value
Density		g/cm^3	2.85
Porosity		%	< 0.5
Bending strength	20 °C	MPa	280
Bending strength	1200 °C	MPa	370
Elastic modulus	GPa	270	
Heat conductivity	100 °C	W/mK	110
	500 °C	W/mK	68
	1000 °C	W/mK	41
Thermal coefficient			
of expansion	DIN 51909	$10^{-6}K^{-1}$	
(typical values)	20 – 200 °C		3.55
	200 – 500 °C		3.9
	500 – 1000 °C		4.43

Table 1: Material properties of SiSiC

3. Manufacture

The use of C/SiSiC has key benefits concerning manufacturing, e.g. the workability in the soft C/C condition (Figure 1). The process of siliconisation changes geometry only slightly, thus, only minimum rework is necessary in the hard condition. Complex and large structures can be produced. If required the surface can be modified by coating. Application temperatures up to 1350°C do not pose any problem. Further characteristics are similar to those from SiSiC.

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4. New Application Possibilities for Ceramics

4.1 Heat Exchanger for Power Plant Engineering

Power plant engineering is confronted with metal-aggressive media and atmospheres. On the one hand very high temperatures in combination with very high pressures exclude the application of many materials. On the other hand aggressive media which are transferred from one process to another are a knock-out criterion for metallic materials. This mostly concerns crude product gas (gasification technology) or flue gas (waste incineration). However, these gases still contain energy (usually perceptible heat) that can be used. Application of this heat during the process fails due to the material requisition or leads to unacceptable material loss, respectively.

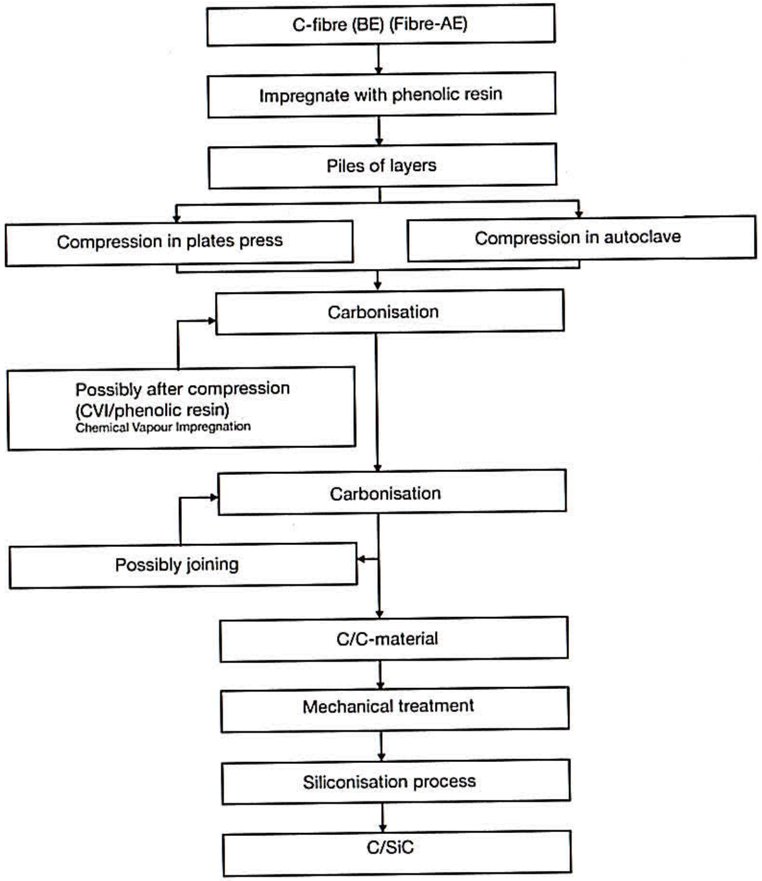

Fig. 1: Production of carbon fibre reinforced silicon carbide [4].

Nowadays an (optimum) heat exchanger is designed and dimensioned by computing technology (CFD) besides the conventional gauging of the heat transfer. Now it is possible to optimise material properties indices and geometry, thus, complexly-formed heat exchangers are now possible (Figure 2).

In order to connect the computational model and reality, a simplified heat exchanger was selected and described by FloWorks® and experimentally verified. The experiment was aiming at the proof of the k-value (thermal conductivity). On the exterior the flue gas was conducted, the cooling on the inner side was carried out with water or air.

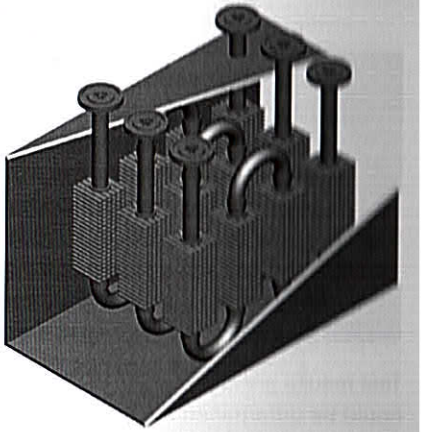

Fig. 2: Heat exchanger register in installation position in the flue gas channel [2].

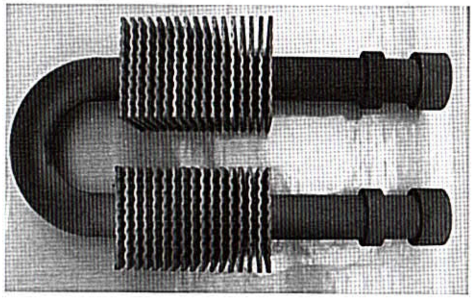

Fig. 3a: Heat exchanger original SiSiC [2].

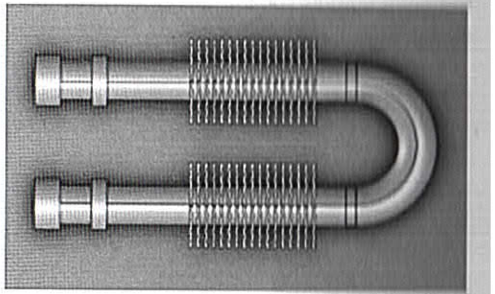

Fig: 3b: Simulation model without housing [3].

A special metallic insert was used on the inside to improve heat transition. The use is possible on the side of the more uncritical medium (Figures 3a and 3b).
The heat exchanger was tested at the Circulating Fluidized Bed (CFB) combustor of the chair at Dresden technical university. The flue gas flow from the CFB has close-to-reality conditions. The test rig is operated with original lignite and only a cyclone separates rough contamination upstream of the installation.

For further tests it is advisable to use a plant with higher gas temperatures in order to better exploit the advantage of the ceramic material. The following preliminary work was necessary to carry out he tests:

- Construction of housing, heat proofed refractory
- Installation of ceramic heat exchanger into the existing construction
- Connection of cooling media supply (water/air)
- Test of temperature behaviour at five measuring points
- Test of deposition behaviour of fly ash on the heat exchanger.

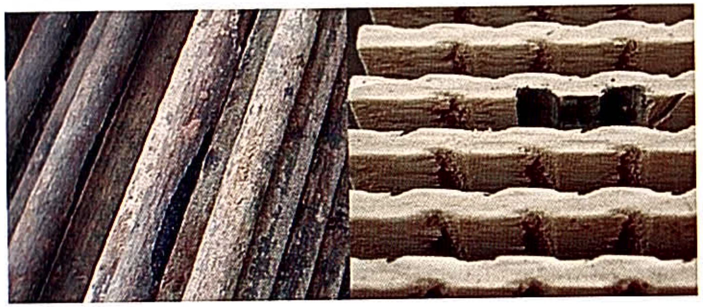

Fig. 4:
Tube bundle heat exchanger and heat exchanger from ceramics after a short operation time.

Test results are in a good accordance with the forecast heat transition behaviour. The k-values could be determined depending on volume rate between 17 and 29 W/m²K. A further increase is possible at higher flow velocities (Figure 4 and 5). A significant increase could be achieved by the operation of innovative inserts on the cooling side (Figure 6). The fouling behaviour was negligible at the designed high flow rate. The computed formation of eddies between lamella packages could be proved very well because the original streamlines in the fly ash showed similar patterns.

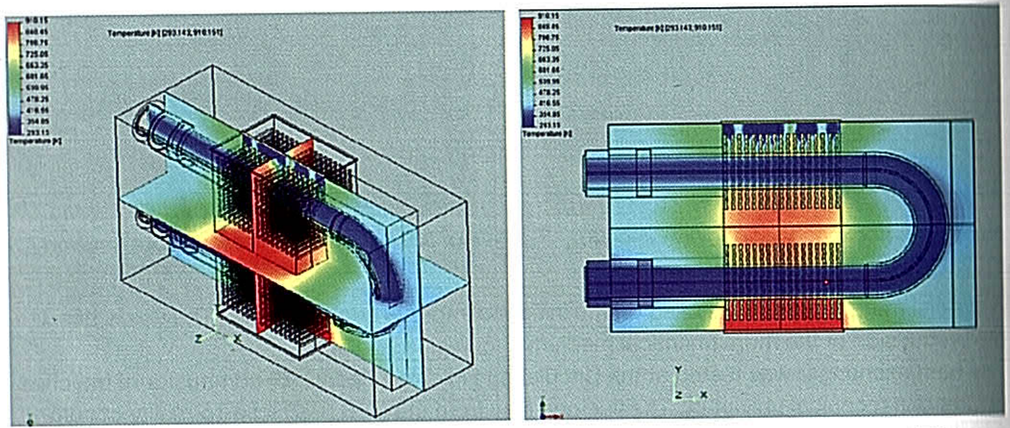

Fig. 5: Temperature distribution in the heat exchanger/housing, isometric/from above [3].

The self cleaning effect, caused by the different thermal elongation coefficients of silicon carbide ceramics on the one side and slag and ashes on the other side, also works favourably, even at higher temperatures. Deposits burst off upon cooling.

4.2 Further Sample Applications for High-temperature Technology

Cube Module

This application is to offer a modular, highly-efficient heat exchanger. The Reynolds number and connected with this the k-value is to be increased by moulded channels. The modular assembly method allows an adjustment to each flow rate. This can be achieved by stacking of the heat exchanger modules (Figure 7). In this case the heat exchanger is to be used for low operating pressures in the mbar range [2].

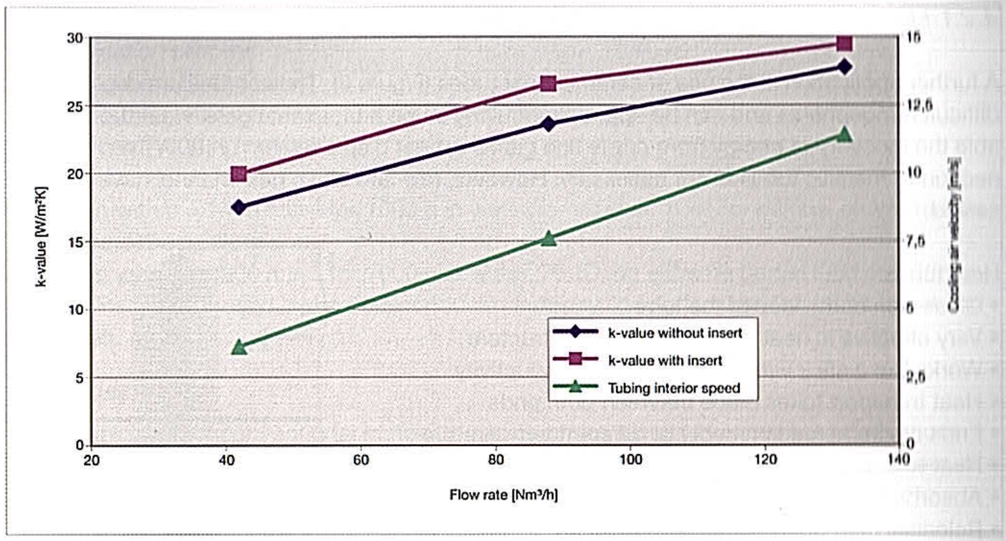

Fig. 6: k-Value with flue gas and cooling air, with/without inserts.

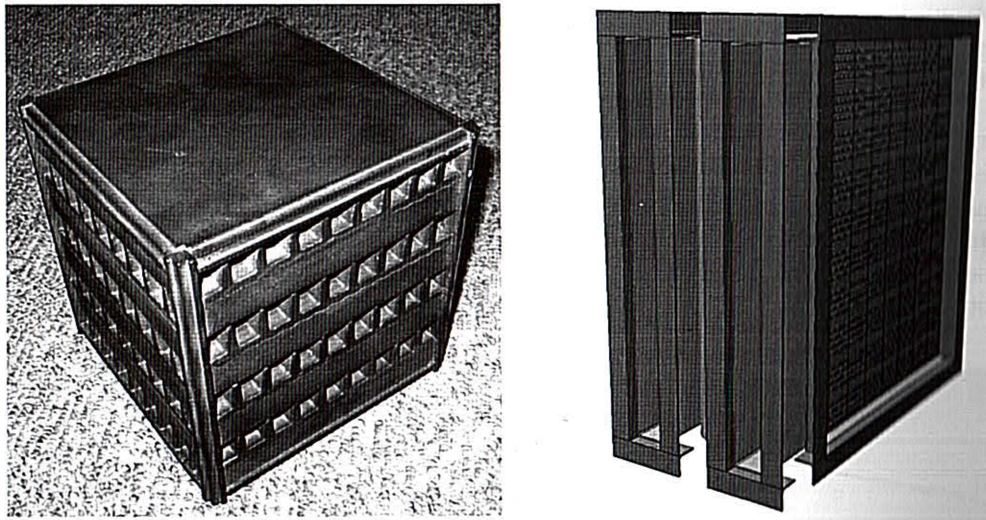

Fig. 7: Cross flow heat exchanger (left: single module, right: module stack with frame) [2].

This module is suitable for flue gas cooling. The modules are joined by means of a silicon carbide adhesive which can be used to a maximum temperature of 1200°C. The range of performance of the modules begins at 200 Nm³/h and is nearly unlimited. Due to the wavelike interior, the Reynolds number increases resulting in higher heat transmission.

4.2.1 Heat Tubes

A further application is the use of ceramic heat tubes (Figure 8). These tubes are designed for difficult atmospheres and can be applied modularly in the heat exchangers. Heat tubes enable the recovery of energy from crude flue gases in heat displacement units. A fixed connection to metallic tubes is not necessary. However, raw and clean gas channel have to be sealed.

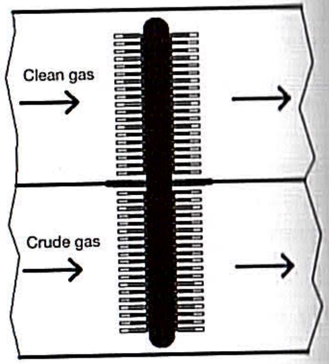

Fig. 8: Ceramic heat pipe in installation position in the channel [2].

Heat tubes:
- Closed on both sides of the tube
- Very effective in heat transfer due to its structure
- Works like a stick with very high heat conductivity
- Heat transport takes place between both ends
- Ends are immersed in media of different temperature
- Heat tube is filled with a working fluid
- Absorbs heat from fluid 1 on the one side (end of tube)
- Releases heat on the other side to fluid 2
- On the absorber side the working fluids evaporates (depending on the operation temperature, i.e. depending on working temperature the working fluid can evaporate)
- On the heat releasing side the working fluid condenses
- Inside the heat tube the working fluid circulates
- If the heat tube is mounted vertically, no inner capillary-structure is necessary.

4.2.2 Ceramic Impeller

For new technologies, not only in power plant engineering, exhaust ventilators are necessary, which work at very high temperatures.
The required recirculation ventilators or hot gas exhaust fans for temperatures over 800°C are not available with many manufacturers (Figure 9). Efforts are made to find substitute material.

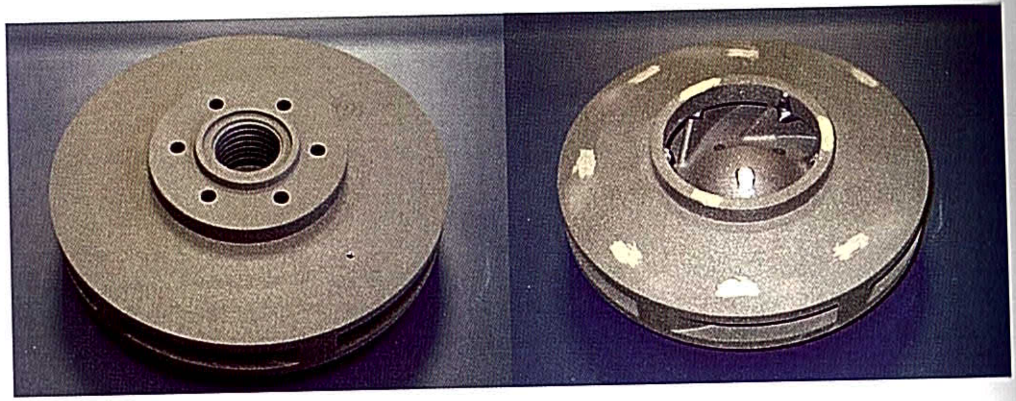

Fig. 9: Closed impeller from SiSiC with 300 mm diameter [4].

How to produce a closed ceramic impeller:
- Siliconisation process
- Cleaning from Si deposits
- Bonding the metallic thread into the silicated impeller
- Static load (1000 N for 1000 h)
- Balancing
- Test run with n = 1450 min^{-1} for 1000 h in water, in "normal" flow conditions, characteristic similar to PE impellers
- Test run with n = 2900 min^{-1} for 1000 h in water, 75 °C, on extreme partial load conditions
- Ceramics are also used in the semiconductor industry, in applications for space travel and research.

5. Prospects

The combination of conventional materials and ceramics results in numerous applications. For reasons of economy, ceramics are hardly used in the lower temperature range where different materials are preferred. The joining technique offers a lot of innovations.

There are three different principles [1]:
- inter-locking with cementing and casting in
- material connection (sticking, soldering or welding)
- frictional connection by clamps, shrinking or bolting

Special caution is necessary when the construction is assembled. The ceramic construction must be jointed without tension and with non-contact to other construction units. Different thermal expansions can quickly destroy the construction unit.
Mechanical engineers have to develop sensitivity for the ceramic material, because its handling is completely different to handling metal. The development of a "leak-proof stretch-steady-ceramic-to-metal connection" might be a main issue of research in the near future.

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C/C	Carbon-fibre-reinforced carbon
C/SiC	Carbon/silicon carbide
C/C-SiC	Carbon-fibre-reinforced
SiC/SiC	Silicon carbide fibre-reinforced silicon carbide
SiSiC	Silicon-infiltrated silicon carbide