Hiller A.; Löser, J.; Schmid, Ch.; Nauditt, G.: New Possibilies for the Application of Ceramic Heat Exchangers in Processes with High-temperatures and Difficult Atmospheres. In: VGB-PowerTech (2008), Nr. 88. ISSN 1435-3199. Erschienen auch in: Proceedings of the International Conference on Incineration and Thermal Treatment Technologies - IT3, 12.05.–16.05.2008, Montreal (CA). ISBN 9781933474021

New possibilities for the application of ceramic heat exchangers in processes with high temperatures and difficult atmospheres

Andreas Hiller, Jan Löser, Dresden University of Technology, Dresden
Christoph Schmid, IBS Schmid, Hennef
Gotthard Nauditt, R & D Engineer Composites , Schunk Kohlenstofftechnik GmbH, Heuchelheim

Abstract

Ceramic was introduced as a material within many sectors of the economy. However some obstacles still bar the way for an extension of the operational area on energy engineering in terms of heat exchangers. Systematically all these obstacles can be reduced.

Good beginnings and solutions show the development of modular executed heat exchangers to discharge high temperature heat from corrosive atmospheres in different applications.

For the design of these heat exchangers silicon carbide is used due to its adequate material properties. From a trivial pipe up to complex geometry, like cross current heat exchanger modules, an optimal form is producible depending on the application.

The conventional methods of the shaping, as in the soft C/C-condition, are supplemented and broaden increasingly also by adding individual parts with special fluxes and repeated siliconizing and by laser joining technologies.

Beside the form of the heat exchanger the choice of materials must be adapted to the appropriate applications above all. Reducing, oxidizing or also atmospheres with water vapour require a monitoring in the ceramics selection in order to exclude damages.

Concerning the price the usage of ceramics in difficult application environments represents thereby an economic alternative. The operation of structure ceramics is accelerated by the high-grade steel price and its additions (e.g. nickel with actual 23,000 US$/t, in summer 2007 with 50,000 US$/t).

Kurzfassung

Keramik hat als Werkstoff in vielen Bereichen der Wirtschaft Einzug gehalten. Eine Erweiterung des Einsatzgebietes auf die Energietechnik in Form von Wärmeübertragern standen und stehen aber noch einige Hindernisse im Weg. Systematisch können und werden diese Hemmnisse abgebaut. Gute Ansätze und Lösungen zeigen die Entwicklungen von modular aufgebauten Wärmeübertragern zur Auskopplung von Hochtemperaturwärmen aus aggressiven Atmosphären bei verschiedenen Anwendungen.

Für die Ausführung dieser Wärmeübertrager kommt Siliziumkarbid auf Grund seiner adäquaten Materialeigenschaften zur Anwendung. Vom trivialen Rohr bis hin zu komplexen Geometrien, wie Kreuzstromwärmeübertragermodule, ist je nach Anwendungsfall eine optimale Form herstellbar. Die konventionellen Methoden der Formgebung, wie die im weichen C/C-Zustand, werden zunehmend auch durch Fügen von Einzelteilen mit speziellen Loten und nochmaligem Silizieren als auch durch Laserfügetechnologien ergänzt und erweitert.

Neben der Form der Wärmeübertrager muss vor allem die Materialauswahl den entsprechenden Anwendungsfällen angepasst werden. Reduzierende, oxydierende oder auch Atmosphären mit Wasserdampf verlangen ein Monitoring in der Keramikauswahl, um Schädigungen auszuschließen.

Die preisliche Konkurrenzfähigkeit von Strukturkeramik wird zunehmend durch die hohen Edelstahlpreis und dessen Zuschlagstoffen erreicht (z.B. Nickel mit 23.000 US$/t, im Sommer 2007 mit 50.000 US$/t) und der Einsatz in schwierigen Anwendungsumgebungen stellt damit eine ökonomische Alternative dar.

1 Necessity

By the use of biomasses in addition also coals and refuse-derived fuels (RDF) an inconsistency of heat exchanger materials is present at high temperatures and also aggressive media. With a ceramic heat exchanger the economic utilization of the flue gas energy from combustion and gasification of all kinds becomes possible also under unfavourable conditions.

The high thermal and chemical stability of the material silicon carbide guarantees an universal and long-term applicability.

The operation of this material begins, where the application of other materials has long been over. With and without fibre reinforcement it hardly leaves nothing to be desired.

Compared to metallic materials such as Inconel and Hastelloy (high-quality nickel basis alloys) in this field of application ceramic heat exchangers have a good price-performance ratio.

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 an universal applicability and longevity.

Enterprises are confronted with the task to dispose production specific residuals and wastes economically. A thermal waste disposal - supplying a certain amount of heat and electricity - could be coupled to the production process for the case that there is a high demand on energy.

If there exists a larger need of electrical and heat energy in the production a thermal refuse disposal could be coupled.

2 Material

With the urge for more efficiency and changed operating conditions the material selection comes to the fore concerning design and realization of procedure chains.
The implementation of technologies always fails thereby at the limited characteristics of the conventionally used metals.
An alternative to the application of metals is the use of technical ceramics.
It is to be examined in each case of application whether the desired characteristics are carried by the material.
Beside the pressure and temperature stability also the thermal conductivity (ability), the hardness and the coefficient of expansion belong to the characteristics.

2.1 Material properties of SiSiC

- 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 $4 \times 10^{-6} K^{-1}$
- 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 – 3,1 g/cm^3)
- very high rigidity (200 – 350 GPa)
- outstanding firmness up to 1350 °C (150 – 400 MPa)
- nearly as hard as diamond, Vickers hardness (25000 MPa)
- no creeping under mechanical load
- insensitively to dampness/ Humidity
- nearly unlimited geometry and form variety
- self cleaning effect when contaminated by flue gas

Table 1: Material properties of SiSiC

2.2 Manufacture

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

The use of C/SiSiC has key benefits concerning manufacturing, e.g. the workability in the soft C/C condition.
The process of siliconization changes geometry only slightly. That has the advantage that only a minimum rework is necessary in the hard condition.

Complex and large structures are possible to produce. If required the surface can be modified by coating. Application temperatures up to 1350 °C do not pose a problem. Further characteristics are similar to those from SiSiC.

3 New possibilities for the use of ceramics

3.1 Heat exchanger for Power plant technology

The power plant technology is confronted with metal-aggressive media and atmospheres. On one hand very high temperatures in combination with very high pressures are the exclusion criterion for 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 unpurified product gas (gasification technology) or flue gas (waste incineration). However these gases still contain usable energies (usually perceptible heat). Getting out this heat during the process fails due to the material requisition or leads to a not acceptable material loss respectively.
Nowadays the dimensioning and design of a (optimal) heat exchanger is done by computing technology (CFD) besides the conventional gauging of the heat transfer.
Now it is possible to optimise material properties indices and geometry so, that also complex formed heat exchangers are now producible.

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

In order to connect the computational model and reality, a simplified heat exchanger was selected and described by means of FloWorks® and experimentally. A goal of the experiments was 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.
A special metallic insert was used on the inside to improve the heat transition. The use is possible on the side of the more uncritical medium.

Figure 3a: Heat exchanger original SiSiC [2]

Figure 3b: Simulation model without housing [3]

To test the heat exchanger the existing Circulating Fluidized Bed (CFB) of the chair at the TU Dresden was used. The polluted flue gas stream emanates from the CFB with close-to-reality conditions. The test rig is operated with original lignite and only a cyclone separates rough contamination before the installation place.

For further tests it is advisable to use a plant with higher gas temperatures in order to use the advantage of the ceramic material still better. For the tests the following preliminary work became necessary:

- construction of the housing, heat proofed refractory,
- installation of the ceramic heat exchanger into the existing construction,
- connection of the cooling media supply (water/air),
- test of the temperature behaviour at 5 measuring points,
- test of the deposition behaviour of fly ash on the heat exchanger,

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

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

Test results are in a good accordance of the prognosticated heat transition behaviour. The k-values could be determined, depending upon volume rate, between 17 and 29 W/m²K. A further increase is possible with higher flow velocities.

A significant increase could be achieved by the operation of an innovative inserts on the cooling agent side. The fouling behaviour was negligible by the designed high flow rate. The computed formation of eddies between the lamella packages could be proved very well as in the original streamlines in the fly ash showed similar patterns.

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, works at still higher temperatures likewise very favourably. With cooling adhering deposits bursts off.

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

4 Further sample applications for the high-temperature technology

4.1 Cube module

The principal purpose of this application is to offer a modular heat exchanger with a high efficiency. The Reynolds number and connected with this the k-value is to be increased by moulded channels. The modular assembling method allows an adjustment to each flow rate. This can be archived by stacking of the heat exchanger modules. In this case the heat exchanger is to be used for low operating pressures in mbar range [2].

With this module is outstanding suitable for cooling of flue gases. The modules are joined by means of a silicon carbide adhesive. This adhesive can be loadable up to temperatures of 1200 °C. The range of performance of the modules begins at 200 Nm³/h and is nearly unlimited. By the wavelike interior the Reynolds number increases which leads to higher heat transmission.

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

4.2 Heat pipes

A further application is the use of ceramic heat pipes. It is designed for difficult atmospheres and can the heat exchangers be implemented modular. With heat pipes energy can be recovered from contaminated flue gases in heat displacement units. A fixed connection to metallic pipes is not necessary. Only the sealing between raw and clean gas channel has to be realized.

Heat pipe:

- closed on both sides of the pipe
- due to its structure it is a very effective in heat transfer
- works like a stick with very high heat conductivity
- heat transport takes place between both ends
- ends are immersed in media of different temperature
- the heat pipe is filled with a working fluid
- absorbs the heat from fluid 1 on the one side (end of pipe)
- releases the heat on the other side to fluid 2
- on the absorber side the working fluids evaporates (depending on the operation temperature)
- (concerning to the working temperature the working fluid can be evaporate)
- on the heat releasing side the working fluid condenses (other side it condense)
- inside the heat pipe the working fluid circulates

If the heat pipe is mounted vertical no inner capillary-structure is necessary.

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

4.3 Ceramic impeller

For new technologies, not only in the power plant technology, exhaust ventilators are necessary, which work under very high temperatures.

The required recirculation ventilators or hot gas exhaust fans are not available at many manufacturers for temperatures over 800 °C. Efforts are made to find substituting material.

How to produce a closed ceramic impeller:

- Siliconization process
- cleaning from Si adhering
- 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

Further applications of ceramics are in the semiconductor industry, in applications for space travel and research.

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

5 Prospect

The combination of conventional materials and ceramics leads to a substantial field of application. For reasons of economy the application of ceramic in lower temperature levels is reduced to minimum and other 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 joint without tension and non-contact to other construction units. Different thermal expansions can destroy the construction unit fast.

The mechanics must develop sensitivity for the ceramic material, because it differs substantially from handling metal. To develop a leak-proof stretch-steady ceramic to metal connection might be a main point of research in the near future.

6 Literature

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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

Contact information of the authors:

Dr.-Ing. Andreas Hiller
Dipl.-Ing. Jan Löser
Technische Universität Dresden
Chair Combustion, Heat and Mass Transfer
Walther-Pauer-Bau
George-Baehr-Str. 3b
01062 Dresden
Germany
andreas.hiller@tu-dresden.de
http://tu-dresden.de/die_tu_dresden/fakultaeten/fakultaet_maschinenwesen/iet/kwt/index_html

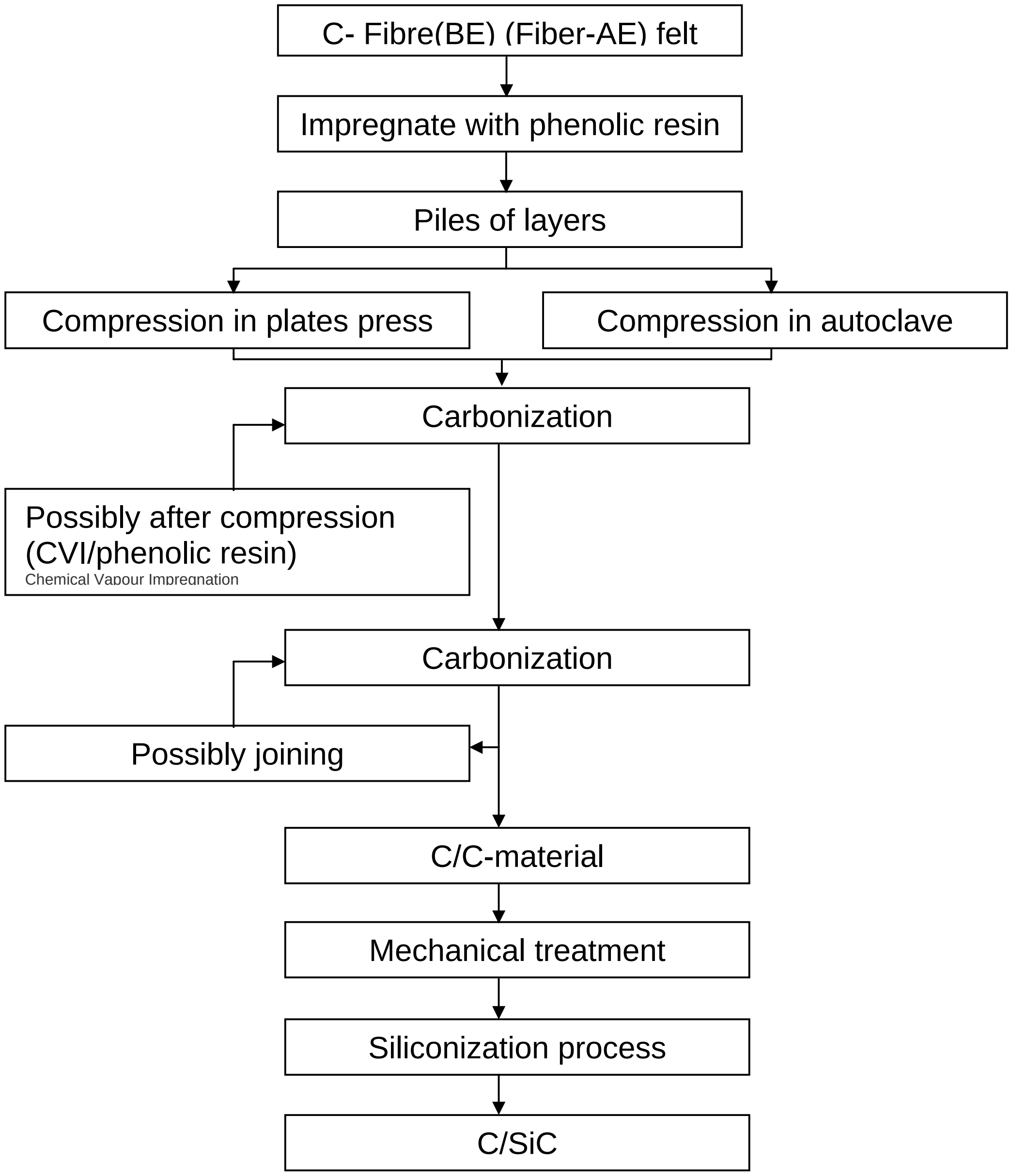
Dipl.-Ing. Christoph Schmid
IBS Ingenieurbüro Schmid
Im Burghof 12
53773 Hennef
Germany

Dipl.-Ing. Gotthard Nauditt
R&D Engineer Composites
Schunk Kohlenstofftechnik GmbH
Rodheimer Str. 59
35452 Heuchelheim
Germany

Table 1: material properties of SiSiC

Property	Method	Unit	Value
Density		g/cm³	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

Figure 1: Production of carbon fibre reinforced silicon carbide (e.g. FU2954P77) [4]



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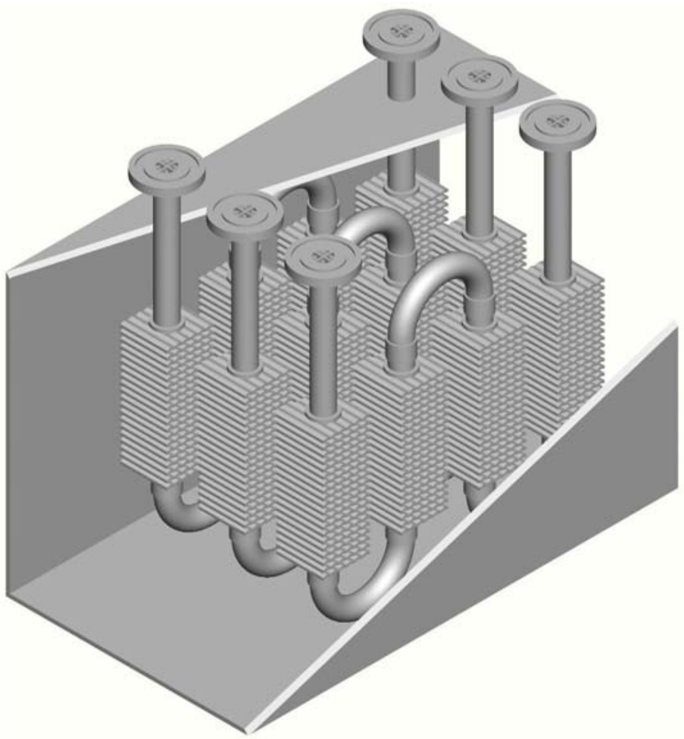

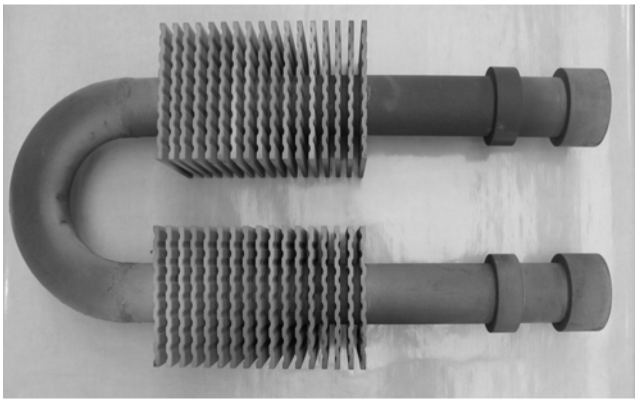

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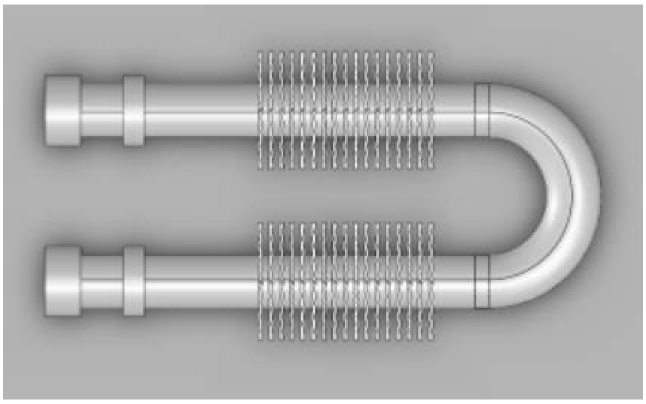

Figure 3b: Simulation model without housings [3]

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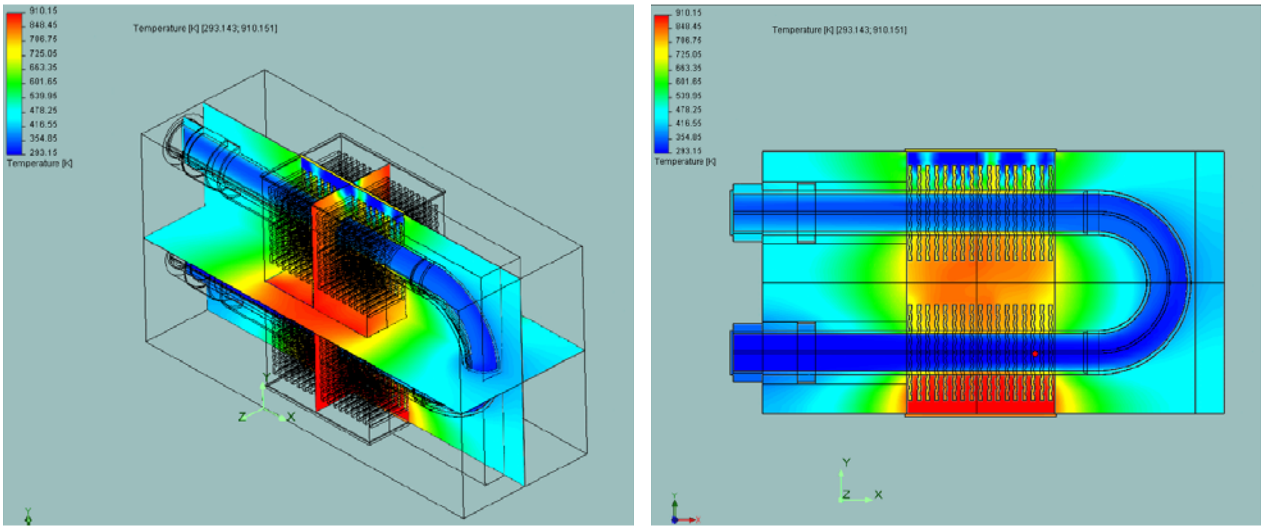
Figure 5: Temperature distribution in the heat exchanger/housing, isometric/from above [3]



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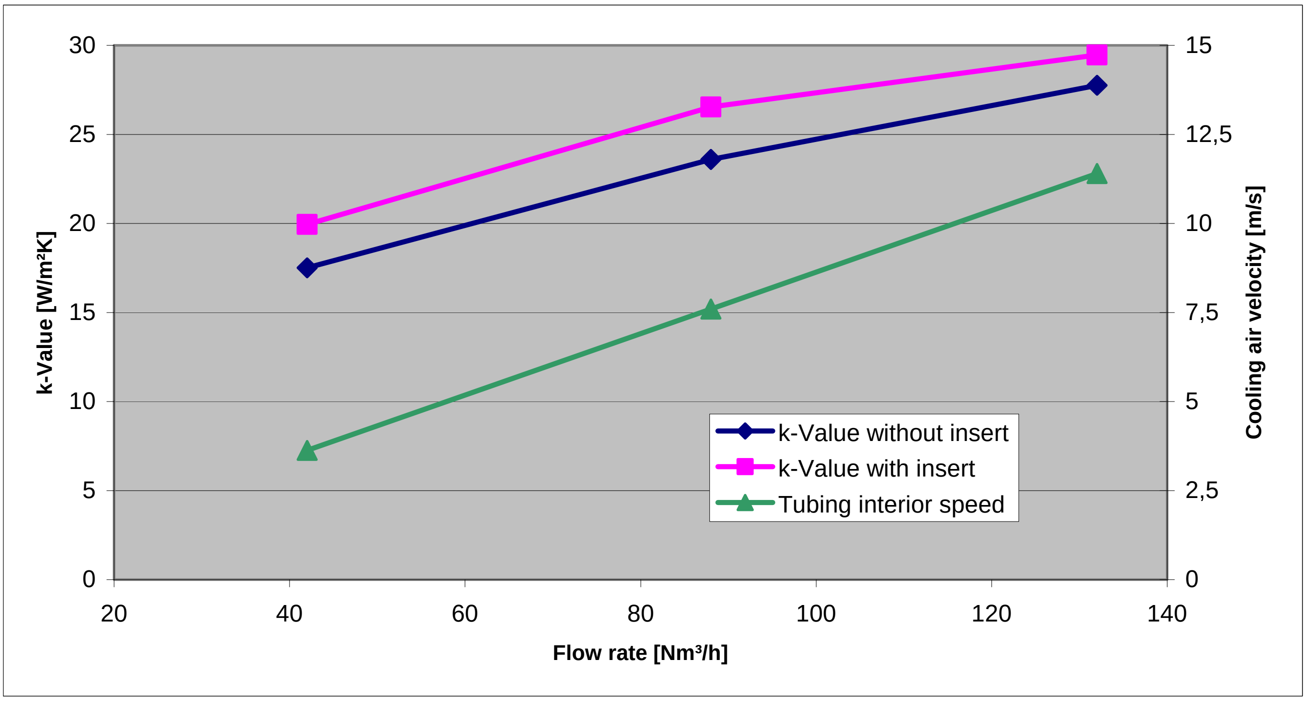

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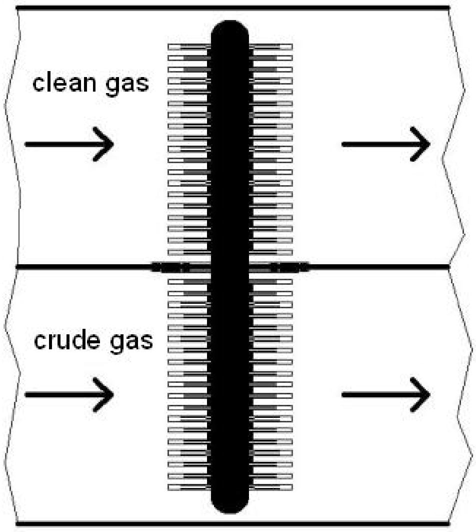

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