New ceramic heat exchangers with enhanced heat transfer properties for recuperative gas burners

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Heat recovery from waste gas is a major key process for increasing efficiency of thermal processes. The aim of the present work is to increase heat transfer coefficients of ceramic heat exchangers of recuperative burners using highly structured surface elements created from a textile precursor. The paper describes the chosen geometries and their thermal behavior, the ceramization process and the preliminary design of the new recuperative burners.

Heat recovery at a high temperature level is essential in industrial thermal processing. Ceramic components in heat recovery equipment offer the possibility to achieve higher temperature levels and subsequently, higher thermal recovery efficiencies. The aim of CEREXPRO, a research and development project financially supported by the European Commission within the 7th framework program, is to develop a new generation of ceramic heat exchangers for high temperature heat recovery with the target of significantly reducing the size and weight of the exchanger components while reducing the price of such components through simplifying the manufacturing process and allowing higher flexibility in heat exchanger geometry. The use of precursor/template materials taken from the textile industries and a subsequent ceramic conversion is the main technological path proposed to reach these objectives. Although the principal idea is not new, there are no known efforts into the development of such technology for the utilization of such an approach for industrial high temperature heat exchangers. The approach leads to a high flexibility in the heat exchanger geometry and design, while the costs for shaping are reduced.

The development/refinement of the conversion process for textile derived materials into a thermal-shock resistant gas-tight ceramic (e.g. silicon infiltrated silicon carbide - SiSiC) and the optimization in terms of size, geometry, material, and production costs is the major challenge of the ongoing research work. A technical concept facilitating this development is based on the combination of existing robust ceramic components already applied in industrial furnaces, like SiSiC tubes, with compatible ceramic heat exchanger enhancing elements built through the textile technology based manufacturing process. This approach leads to a high application safety and proven robustness. At the same time, a significant size reduction or, alternatively, an increase of the heat recovery level can be achieved due to the higher heat transfer rate of the geometrically flexible heat exchange enhancing elements.

The present paper gives an overview of the current status of the ongoing research efforts in the framework of the CEREXPRO project. The numerical studies conducted at the design phase provided promising results regarding energy savings for industrial burners. The first prototype ceramic plates have been manufactured with various geometries, and the experimental results show a good agreement with the numerical simulations. The validated basic geometries are used for the design of the integrated recuperative burner construction.

Concept

In industrial branches with high energy consumption, most of the processes are

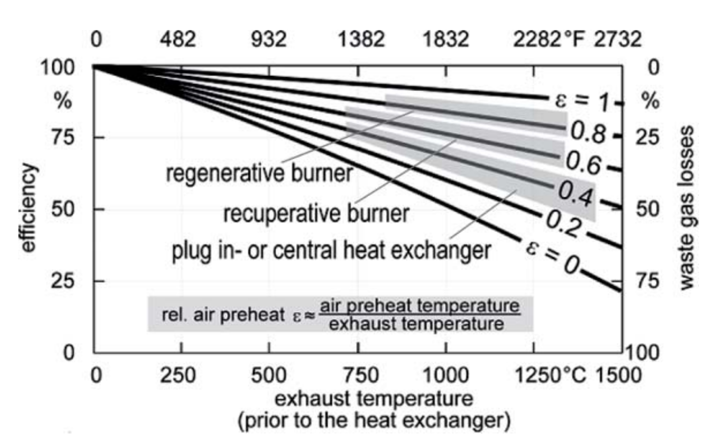

Fig. 1: Combustion efficiency with respect to the flue gas temperature before heat recovery; Practical performance for different types of heat recovery (source: Handbuch der Brennertechnik für Industrieöfen, Wünning J. G., Milani A. (Eds.), Vulkan, Essen, 2007)

Fig. 2: Typical burners of NOXMAT GmbH with ceramic heat exchanging parts

operated at a high temperature level. Heat recovery at this high temperature level is essential in terms of efficiency, especially if the thermal process is heated by burner systems. The most common way for heat recovery is preheating of the combustion air by using the sensible heat of the hot waste gas flows. Recuperative or regenerative heat exchanger systems, which may be integrated in the burner assemblies, are commonly used for this purpose and show typical performances as indicated in **Fig. 1**.

The use of burners equipped with recuperators shows high efficiencies. It can be presumed that a 100 K decrease of the flue gas temperature after heat recovery results in an estimated reduction of total fuel consumption of about 5 %. However, the heat recovery of recuperators is limited by the overall volume and burner length restrictions, the required heat exchanger surface and the material limitations. The heat exchangers used nowadays are mostly built out of high temperature steel with corresponding temperature limitations. The use of ceramic materials (for example SiSiC) allows operation and heat recovery at higher temperatures and subsequently higher process efficiency. Ceramics also show a very good corrosion resistance. However, application restrictions due to dust transported with the gas flow may occur in practice. Heat recovery devices should be directly integrated into the thermoprocessing facility in order to minimize thermal losses and to utilize the energy in an immediate manner. Despite the obvious benefits of ceramic heat exchanger components for heat recovery at high temperature applications, the penetration of such technologies in industrial furnaces is relatively low. This is due to the comparatively high prices and large size of such components. Only a few, very simple ceramic heat exchanger geometries with large dimensions are currently used because of several manufacturing and operational obstructions.

Development of highly structured surfaces for the heat exchanger

The new recuperative heating element has been designed to be integrated in existing burners, while further work is needed towards its integration inside of the burner assembly. The elaborated geometry designs are robust and similar to existing heat exchangers and also consider constraints from available textile and ceramic technologies. A 180° loop was selected as the basic element for the structured surface. The aim was to reach a higher heat transfer coefficient by increasing the transferring surface and also by utilizing the increased dispersion and thermal boundary layer structures due to the resulting turbulent flow characteristics. **Fig. 3** shows different possible arrangements (staggered, not-staggered, inclined or not etc.) of such loops on a flat plate.

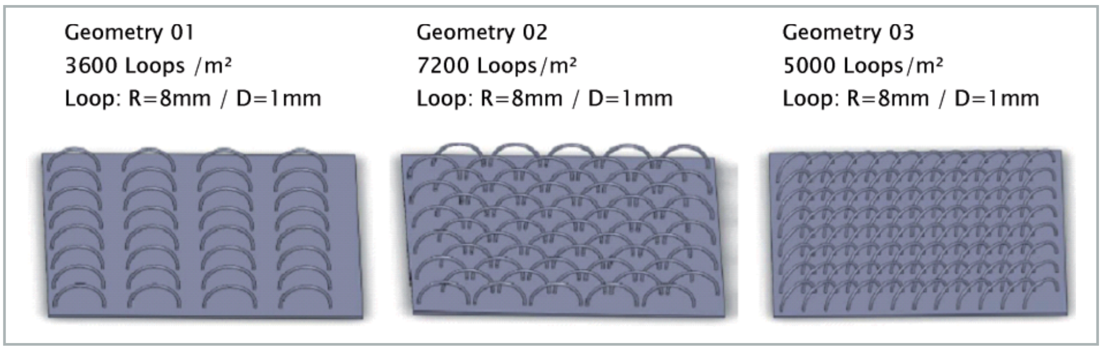

Fig. 3: Different basic designs/arrangements of heat enhancing elements

Numerical simulations using commercial CFD packages were performed for such basic geometries in order to assess the increase in heat transfer and drag coefficient. For the sake of simplicity and in order to facilitate the numerical investigations, a planar arrangement was selected as reference geometry, instead of a pipe, which is the typical application case. In order to simulate the fluid flow and heat transfer process a typical repeating module was defined. This module was used to represent the entire structure by geometrical symmetry to further decrease the computational efforts (**Fig. 4**).

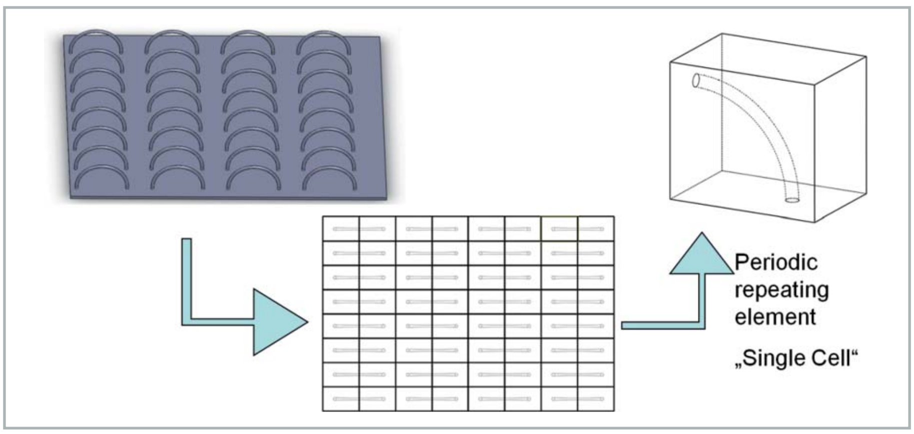

Fig. 4: Path from ceramic structure to one repeating single cell

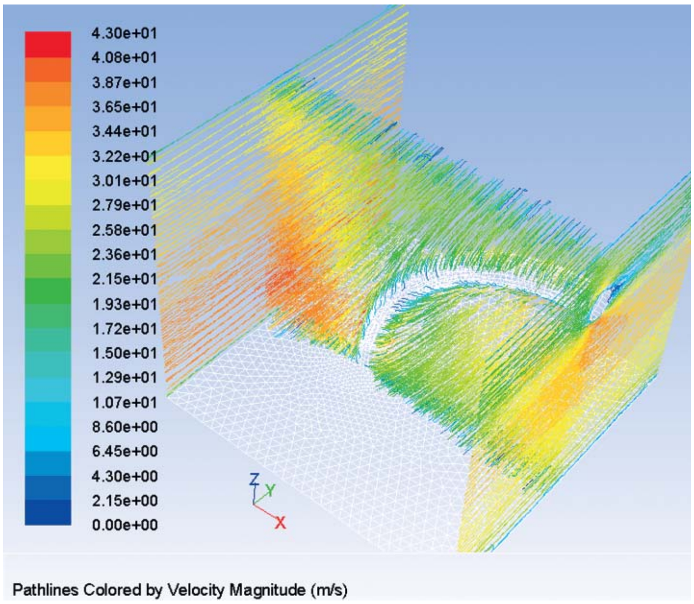

Fig. 5: Result of a simulation with 3600 loops/m^2, here velocity field

01, the pressure drop of the recuperative elements and overall pressure drop is 30 mbar and 75 mbar, respectively. Comparing the two, the pressure drop of the recuperative elements is six times higher and the overall pressure drop is 1.5 times higher for Geometry 01 than for the burner. However, the heat transfer coefficient of Geometry 01 is 4.8 times higher.

This example calculation indicates, that the targeted recuperator design will result in either significantly higher heat recovery levels at the same overall burner size as the current recuperative burners and slightly higher pressure losses, or alternatively to approximately the same heat recuperation level at significantly smaller size and lower pressure losses.

Ceramization process

Advanced ceramic materials are extensively applied for high temperature applications in oxidative as well as reductive environments. For this very special application, some ceramic Silicon Carbide is the most appropriate material. It is already employed in many furnaces parts because it withstands burner operating conditions for long time. SiC bulk material was optimized by selecting a suitable composition and the relevant processing. The available methods are shown in **Table 1**.

The governing equations were solved using finite volume methods assuming a forced convection situation. The minimum dimensions of the elements were considered to guarantee robust manufacturing and long term stability. For each side of the cubic cell a boundary condition is required. For example, a constant temperature at the bottom of the cell is assumed, which must be lower than the inlet temperature of the air flow in order to generate a heat flux from the hot air to the cooled heat exchanger surface. Based on this numerical experiment with a single cell the heat transfer coefficient of the reference heat enhancing element was calculated.

The reference surface for comparison and normalization purposes is the smooth cylindrical surface between the two flows. A smooth tube at typical recuperator operating conditions shows a heat transfer coefficient of approximately α = 51 W/(m^{2}K). Assuming the wavy surface as an increase in surface area the heat transfer coefficient of the wavy tube (see **Fig. 2**) rises to α = 82 W/(m^{2}K) on the basis of the plane tube surface. This number is used as reference for evaluation of the new structured surfaces, while the operating conditions are kept constant.

Fig. 5 shows the velocity field of a single cell for the layout with 3,600 loops/m^2. At the bottom and the top the velocity is less than in the free cross section of the model because of the "no-slip" boundary condition.

Pressure drop, Nusselt number and heat transfer coefficient can be calculated for different Reynolds numbers. **Fig. 6** shows the ratio of the expected performance in comparison to the reference conventional recuperator burner at nominal conditions.

Currently, a recuperative burner with 160 kW heating power operates with a pressure drop of 5 mbar at the recuperative elements and an overall pressure drop of 50 mbar. For Geometry

Table 1: Processing techniques of SiC ceramics

Process	Resulting SiC
Chemical Vapor Deposition (CVD)	β SiC
Sintering	α SiC
Polymer Impregnation and Pyrolysis (PIP)	amorphous SiC
Replica + Silicon Infiltration (SI)	Si-α SiC

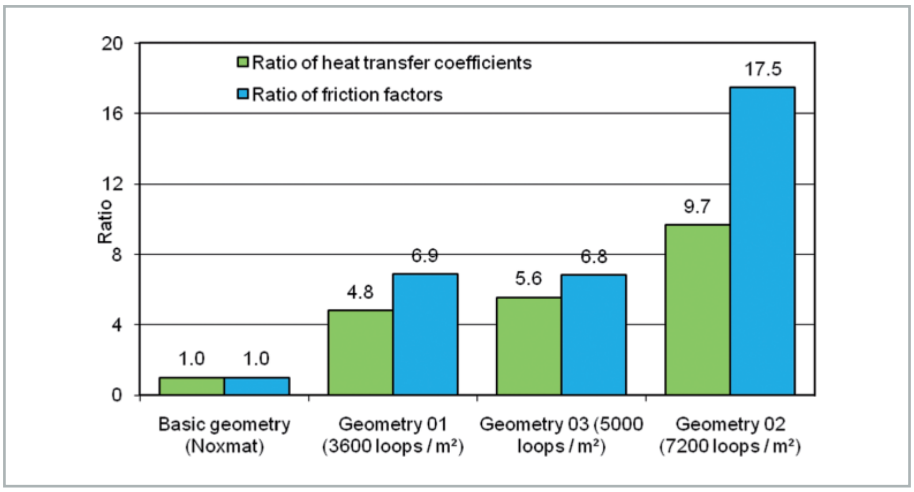

Fig. 6: Results of different layouts

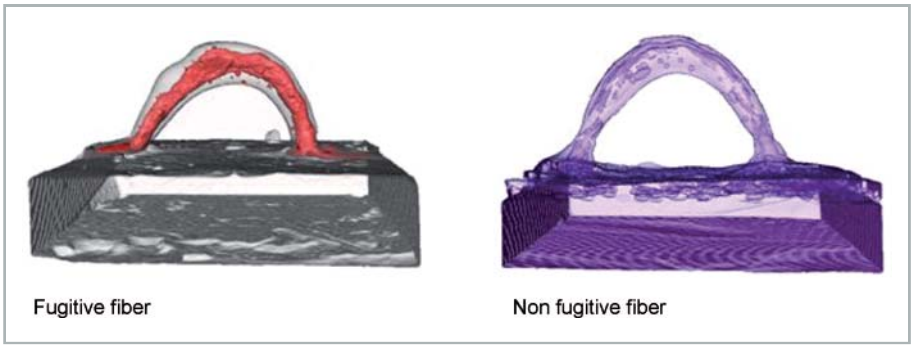

Fig. 7: Rendering of the loop structures

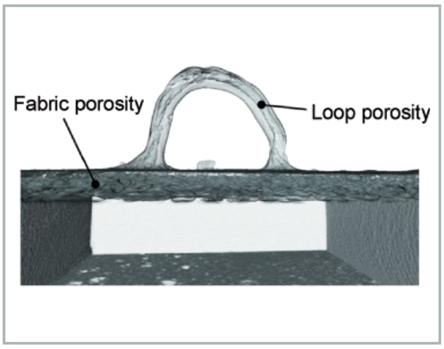

Fig. 8: Voids inside the loops and on the plate due by the supporting fabric

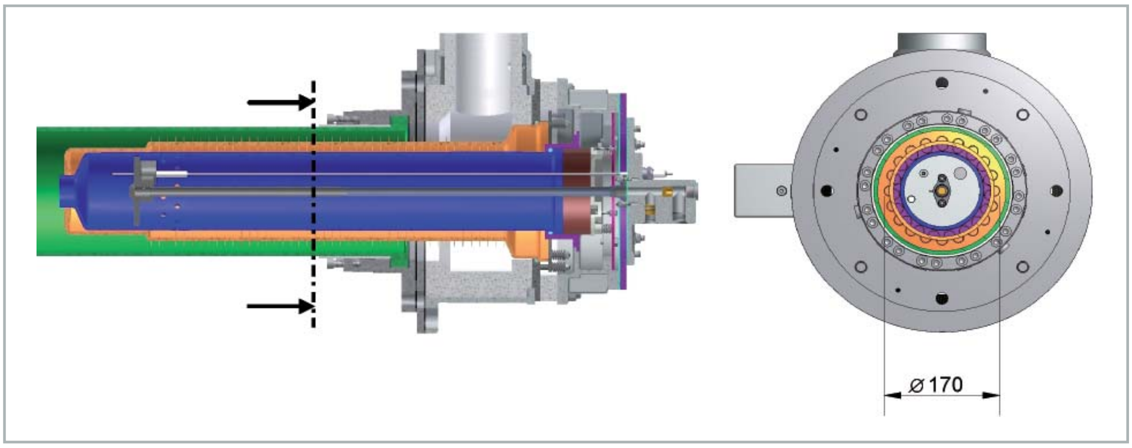

Fig. 9: Burner Model with loops assembled in a jacket tube

In CVD a base material is coated with a SiC layer obtained from the decomposition of a ceramic precursor (e.g. methyltrichlorosilane CH_3SiCl_3) at high temperatures and low pressures. Since CVD is a very expensive and long lasting process it was immediately discarded for use in the project. Sintering was also discarded for processing limitations (very high temperatures). In Polymer Impregnation and Pyrolysis (PIP) the preform is dipped into a liquid polymer. Excess polymer is drained and the remaining cross-linked. Several slurries were produced by adding ceramic powders and deposited onto weaved and/or knitted polymer fibers and filaments. PIP indeed leaves a ceramic body which is always interrupted by a pattern of cracks which appear upon polymer shrinking during pyrolysis. These cracks dramatically reduce the thermo-mechanical and oxidation resistance of the bulk material.

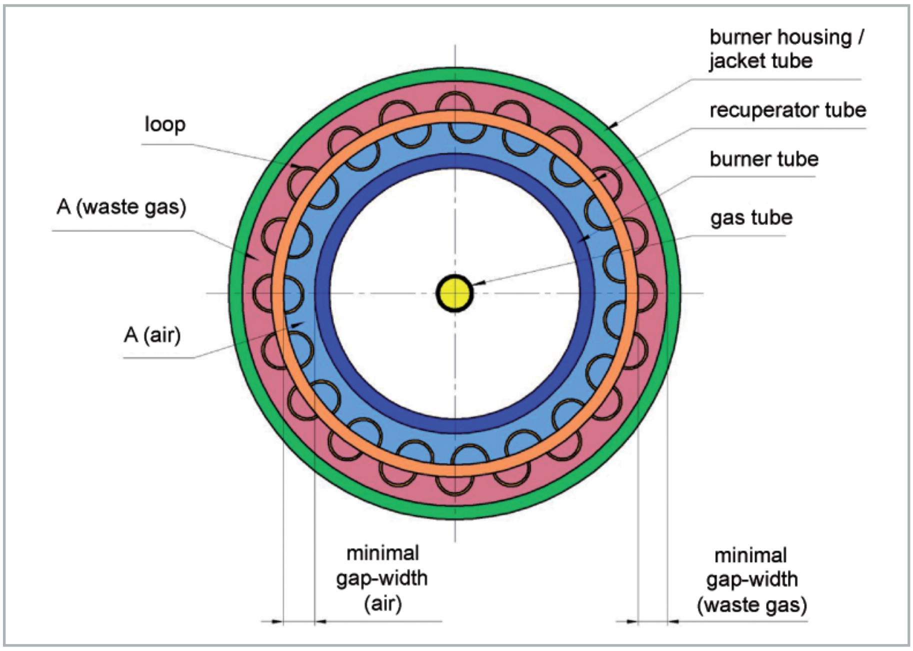

Fig. 10: Cross section of a "loop recuperator" for a new developed burner

In the replica production technique a polymer template is impregnated with ceramic slurry, pyrolysed and infiltrated with molten Silicon, at high temperatures in a vacuum furnace. This process is widely used to make Si-SiC material for high temperature applications. Due to the properties of the material produced and to the level of industrialization of the relevant production technique it was adopted to produce the loop structure.

Processing

Ceramization tests on both fugitive and non-fugitive textiles were performed; fugitive textiles (e.g. PE) degrade during firing leaving hollow loops. Non fugitive textiles (e.g. SiC fibers) do not degrade during heat treatment and remain inside the loop.

Fugitive textiles base fabrics with loops were coated with a ceramic slurry and placed on commercially available

Si-SiC plates (Schunk Ingenieurkeramik GmbH, Germany). After heating under inert atmosphere, they were then infiltrated with molten silicon as previously described.

Non fugitive SiC bundles were first loop shaped and then glued on the SiC plates. Plates were than coated with a ceramic slurry, pyrolysed and infiltrated with molten silicon.

Characterization

In this fashion flat plates decorated with loops were first produced. From both plates a significant portion, containing one loop and the plated underneath were cut with a diamond saw. These blocks were then inspected via Computed Tomography. CT data were acquired using a laboratory micro CT EasyTom 130 (RX Solutions F) with image resolution of 13 µm/pixel.

CT data were than processed using dedicated visualization software Avizo Fire (Visualization Science Group, Burlinton, MA, USA).

The loops rendering in **Fig. 7** shows the two approaches employed in this study. Fugitive templates are cheaper because the materials are common polymers employed in textiles. The drawback of this solution is that it leaves a hollow channel inside the loop which lowers the mechanical strength of it. Another drawback is that if a base fabric is employed to support the loops it will leave also a porous layer as per **Fig. 8**. The non fugitive solution leaves full loops but the fibers employed are more expensive and also shaping and weaving them is more expensive.

New recuperator design and outlook

Recuperative burners are available from several burner manufacturers in different power ranges of 10 to 300 kW and fitting lengths. Most manufacturers offer a metallic and/or ceramic design. The new recuperative burner design has many similarities in size and power requirements with pre-existing burners. Thus, the possibility exists to use parts (the burner housing for example) from the current burners.

Fig. 9 shows the section view of new burner with a "loop recuperator" and the design of the first burner prototype. In comparison to the burners with corrugated recuperator, the flow section is higher and as a result the flow velocity is lower. This will cause a reduction of the predicted pressure losses. **Fig. 10** shows the cross section of a "loop recuperator" for a new developed burner. Fabrication and tests of the burner prototype will follow in the near future.

Acknowledgement

The authors would like to thank the European Commission for the provided financial support for this work within the 7th framework program, project CEREXPRo, contract no. 227551.

The CEREXPRo project is presented at the Thermprocess fair in Düsseldorf (28.06.2011 - 02.07.2011) at the CECOF booth, Hall 10, C57, or at the booth of FOGI e.V, TU Bergakademie Freiberg, Hall 7, A01. Actual information can be found at www.cerexpro.org. ■

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