Executive summary:

Heat recovery at a high temperature level is essential in industrial thermal processing. The use of ceramic materials yields higher temperatures and subsequently a higher efficiency. The project 'CEREXPRO' aimed to develop a new generation of ceramic heat exchangers for high temperature heat recovery. The heat exchangers are designed with a highly structured surface. The structuring is increasing the heat transfer on the surfaces of the heat exchangers. This leads to a higher efficiency or a reduction in size of the heat exchangers.

Textile materials already incorporating the structuring elements were used as precursors. Different fibre materials and textile technologies were tested to obtain three dimensional fabrics. A technical process was developed to transform the textiles into robust, high temperature resistant silicon infiltrated silicon carbide (SiSiC). The process needed to be adjusted to prevent a collapse of the structures, sufficient yield of ceramic material and to keep the geometric sizes necessary for integration of the ceramics into industrial gas burners. By altering the used polymers the production of solid ceramic structures without significant porosity was possible. The materials derived were intensively tested.

The selection of the structuring elements on the surfaces of the heat exchanger considered the following parameters: shape of the elements, pattern of arrangement, influence on heat transfer and on pressure drop, geometric restrictions of the planned applications and requirements coming up from the production processes. A half circle arc or loop was selected as the geometry mostly fulfilling all requirements. The thermal and fluid dynamical performance of the structuring elements was numerically calculated by modelling single repeating cells of the structure. The values for heat transfer coefficient and pressure drop were compared with values of existing recuperators for industrial burners. An increase in heat transfer by factors between 2 and more than 8 was found. The corresponding pressure drop increases by 7 till 18 times. Consequently the pressure drop of an industrial burner will be doubled. Selected geometries were also tested experimentally using a wind tunnel and laser diagnostics.

A new modular burner was designed using spare parts of existing recuperative burners combined with redesigned components and incorporating ceramic recuperators with structured surfaces. The installed power of the burner was 80 kW. This is a small to medium size industrial burner with integrated air preheating. Prototypes of the recuperators were produced using a plain recuperator and applying the textiles templates on both surfaces of the tube. Subsequently the textiles were transformed into ceramics. The recuperator was assembled into the burner. The burner was tested and the performance of the new recuperator was calculated. The prototype burners show a slight increase of firing efficiency compared to a state-of-the-art-burner with a corrugated recuperator of 3 to 5.5 %.

Especially at moderate inlet temperatures of the waste gas an increase in efficiency could be calculated.

The aim of the project was the development of ceramic heat exchangers with structured surfaces by using textile templates and converting them into ceramics. The necessary technical processes have been developed. Prototypes were produced. An increase in efficiency of the heat exchangers compared to the state of the art could be demonstrated.

Project Context and Objectives:

Industrial production is a major consumer of energy. The energy balance of the EU 27 in 2005 as reported by Eurostat shows a total end-energy consumption in the industry sector of more than 13.000 PJ representing 28 % of the overall end-energy consumption in all sectors. Based on data of the same year for Germany (Source: German Federal Ministry of Economics and Technology) one can asses that ca. 60% of the industrial end-energy use is spent for industrial process heating (total energy consumption in the German industrial sector of 2.550 PJ and 1.562 PJ for process heat), while more than 80 % of process heat is covered by fossil fuels. Assuming that the German distribution is representative and can be extrapolated to the European dimension, a total of more than 6.000 PJ are spent for process heat generated by burning of fossil fuels on the European level, representing more than 12% of the total end-energy consumption of EU-27 and at the same time approx. 9.7 % of the total fossil fuel consumption.

Consequently, an efficiency increase in process heating of only a few percent would result in a significant reduction of energy consumption and CO2-emissions at the European level. Industrial branches with high energy consumption are for example iron and steel making, metal processing and ceramics production. Most of the processes are operated at a high temperature level. Heat recovery at this high temperature level is essential in terms of efficiency. The most common way for heat recovery is preheating of air or other gas flows by using the energy 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.

The heat exchangers are manufactured in industrial numbers of pieces using technologies of primary shaping. Two different material groups are used. One group is highly alloyed steel grades. These materials can be casted and then joined by welding processes. A great variety in the shape and structure of the surface of the heat exchangers is possible. The metallic recuperators are limited in the application temperatures to about 1050 °C. The use of alloys with higher application temperature is avoided in industry due to the significant increase of the materials price by an only marginal increase in application temperature. A more recent development are recuperators using the effect of gap flow. These heat exchangers exhibit an increased heat recovery but are also limited in application temperature.

Ceramic recuperators used nowadays in industrial burners are tubular. The parts are formed using a slip casting process. This technology allows a moderate structuring of the outer surface of the heat exchangers. Due to the deposition conditions the structures at the inner surface of the heat exchanger are less sharp defined. Joining of flanges ore other additional parts can only be done in the green unburned state of the ceramic parts. The parts are subsequently transformed into ceramics and infiltrated with liquid silicon. A mechanical treatment of the hard ceramic parts is extremely difficult connected with great expenses and thus reduced to a minimum in industrial production. The ceramic is usually called SiSiC - silicon infiltrated silicon carbide. It contains some percent of metallic silicon what is limiting the application temperature to about 1350 °C. The ceramic heat exchangers are used in applications with higher process temperatures or with high thermal loads.

Common recuperator lengths are in the order of 0.5 m and hence longer than the thickness of the furnace wall. Heat enhancement with structured surfaces is limited due to limitations of the associated ceramic production technologies. Given the technological obstructions and the dimensional limitations the level of heat recovery is limited. State of the art recuperative burners show an air preheating and flue gas temperature level after the recuperator in the range of 500 to 700 °C resulting in heat losses through the flue gas of ca. 25 - 35 % [Gas-Warme-International 56(2007), 6, pp. 425-428]. Regenerative burners (typical nominal power range ca. 200 kW) operate with higher preheating temperatures of the combustion air. Due to the larger surface the regeneration temperature reaches 85 - 95 % of the flue gas temperature.

The project aims to develop a new generation of ceramic heat exchangers for high temperature heat recovery with the target of significantly reducing the size and or weight of these components. A reduction of production price of these components is aspired by simplifying the manufacturing process and allowing a higher flexibility in the heat exchanger geometry. The fundamental idea is the manufacturing of ceramic heat exchangers with a highly structured surface to increase heat transfer by permanently disturbing the formation of flow profiles of the gas flows (combustion air and flue gas).

The main resistance to heat transfer from a contact fluid to a solid surface (or vice versa) is due to slowly moving fluid layers adjacent to the wall. In order to increase the heat transfer coefficient without the drawback of high pressure losses of a turbulent flow at high velocities, artificially generated turbulent boundary layers, or generally boundary layers with very low thickness are generated by breaking them apart. Generally, a high heat transfer rate can be achieved by increasing the heat transfer surface area or the heat transfer coefficient or both of them simultaneously. The most effective heat transfer enhancement can be achieved by using fins (plate, interrupted or pin-fins) as elements for heat transfer area extension and also pending on the fin geometry and arrangement also increasing the heat transfer coefficient.

A variety of fin element designs and associated technologies are used for heat transfer enhancement like plate fin heat exchangers, tube fins, wavy fins, offset strip fins, louvered fins and also pin fins. These technologies allow high area densities typically in the range of

1500 m2/m3 up to over 5000 m²/m3. Fins are effective in heat transfer enhancement only if they exceed the boundary layer thickness, resulting in a major part of the heat transfer area being exposed to a free fluid stream. The heat transfer coefficient on the extended surface may be lower or higher than that on a not finned surface, e.g. plain fins increase the heat transfer surface but may result in a reduced heat transfer coefficient, while interrupted fins (strip, louvered) or pin fins (staggered or in-line arrangement) provide both an increased surface and increased heat transfer coefficient.

The use of precursors/template materials taken from the textile industries gives a great degree of freedom in the design of the surface structures. The first technical challenge is the production of three dimensional textiles with a very stable geometry. This must be combined with the use of fibres or filaments based on a polymer material which can be easily and with a high materials yield into ceramics. The structures must not lose their shape during the whole manufacturing process till they are finally converted into silicon carbide ceramics. The ceramic heat exchangers must be gas tight for application. It is predicted that this property cannot be achieved by transforming textiles into ceramics. The application of the textile structure on a plain ceramic tube made from identical material is the way solving the problem.

The size and shape of the structures are defined taking into account limitation of the manufacturing process and of the geometry of the targeted applications. The structures will be examined intensively by numerical and physical experiments. The numerical investigations are used for calculating the influence of different patterns of the structures on the thermal and fluid dynamical properties of the heat exchanger elements. The technical efforts can be minimized by using commercial numerical simulation software. The aim of these calculations is a maximum increase in heat transfer connected with a moderate increase in pressure loss over the structures. The numerical models will be reduced to single cells reproducing the smallest repeating units that will create the heat transferring surfaces. The results will be extended to calculate greater structures.

Physical models of structured surfaces were produced using steel materials. This gives the opportunity to realise samples with a very good defined shape and pattern. In a second step ceramic samples are used. These samples are produced during the development of the ceramic conversion processes. The performance of the samples is examined in a wind tunnel at moderate temperatures. The results serve as proof of the numerical calculations and the extension of results for single cells to the behaviour of greater parts.

The transformation process of the textile templates into ceramic bodies can be performed following several technological paths. The technologies are based on industrial technologies for production of SiC foams: Schwarzwalder + Silicon Infiltration (SI), Chemical Vapor Deposition (CVD) and Polymer Impregnation and Pyrolysis (PIP).

The Schwarzwalder process is the oldest production technique to make replica ceramic foams. A starting foamed polymer, such as polyurethane, is deepened into a slurry (made of ceramic powders, solvent and binders) and shook to remove excess material. The preform is kept into a conditioned ambient for some time to evaporate slurry's solvents. It is then heated up at 800-1000°C in an inert atmosphere for binders' removal by pyrolysis and infiltrated with molten Silicon, in a vacuum furnace at a temperature above the melting point of silicon (1423°C). Binder choice is fundamental for component integrity during the first thermal cycle because its coefficient of thermal expansion should match that of the parent foam to avoid cracks formation in the ceramic body. In CVD the pyrolysed preform (at the same conditions as before) is placed into a reactor and coated with a β-SiC layer obtained from the decomposition at high temperatures (approximately 1200°C) and low pressures (approximately 50 mbar) of a ceramic organometallic precursor (e.g. methyltrichlorosilane CH_3SiCl_3). For this kind of application, the purpose is to increase preform stiffness and to enhance bulk material oxidation resistance. CVD is very expensive but, because effective, it should represent a benchmark for the other techniques. In Polymer Impregnation and Pyrolysis (PIP) the fibrous preform is soaked into a liquid polymer. Preform is drained and the remaining polymer onto it, cross-linked. Some polymers (Silanes) after thermal treatments yield amorphous SiC which should be later nano-crystallized with a high temperature treatment in inert atmosphere at around 1600°C. Adding ceramic powders, process efficiency can be further improved. Many of these polymers are made in Japan; from collaboration with a Japanese Company (UBE Industries) polymers and relevant processing know-how is available.

These techniques are adapted and optimized in order to obtain ceramic structures from weaved and/or knitted polymer fibers and filaments. Depending on the fiber employed, mostly because of its behavior during thermal treatments, one method will result more efficient than the other. For instance, if chosen fibers will be made of a polymer which disappears during pyrolysis, Schwarzwalder technique followed by Silicon Infiltration will be most likely employed.

Based on the above described methods a technology is developed which is cost, time and material efficient. The textiles are glued on ceramic parts. The tests for material and technology development are performed on smaller and plain parts. First tests are carried out only with textile based structures fixed on one surface of the plates. The final heat exchangers will be tube shaped and must have structured surfaces on the inner and outer surface of the cylinder barrel. All samples are intensively characterized using standard technologies in materials science. The results help to improve the manufacturing process. The samples are treated also in conditions similar to the final applications.

Final target is the development of ceramic heat exchangers with highly structured surfaces for industrial gas burners. A long term market study is performed to identify the market potential and the economic limitations of the innovative burners. The innovative heat exchangers will be integrated in existing industrial gas burners. A partial redesign of the burners is necessary. Performance tests of the burners shall demonstrate the increased efficiency of the heat exchangers in applications. The prototypes are operated in testing facilities of industrial burner manufacturers. The temperatures of flue gas and combustion air are measured at the input and output of the recuperator. Also the pressure drops in both ducts is continuously monitored. The formation of harmful gas components is monitored and compared to the emissions of existing burners and legislative limitations.

A second application is the design and integration of innovative heat storage bodies in existing regenerative burners. A representative burner will be selected. A modified heat storage body will be designed applying the textile based ceramics. One property of the new heat storage bodies is a blocking of radiation inside the bodies. Subsequently the housing of the storage body must be adopted. A modified or new type of regenerative burner will be designed. The burner will be extensively tested like described above.

An additional task is the searching for new industrial applications for the ceramic heat exchangers. A first possible device is a preheater for protective gas. Industrial furnaces consume a considerable amount of protective gases. Preheating of these gases and injecting the gas in the chamber will increase efficiency and performance of the furnaces, since an injection of cold protective gases leads to a temperature stratification within the furnace and increased energy consumption in order to guarantee a minimum required temperature difference level. A new furnace component using high efficient heat exchangers will be developed at a laboratory level extending the preheater described above. This module aims to create a high convective gas flow for enhanced convective heating of protective furnace atmospheres. The described innovative application schemes are envisaged. However, in the course of the project possibly further more promising application schemes may appear and a corresponding reorientation of the developments in this work package would take place. The heat exchangers for the described innovative applications are developed and manufactured. The prototypes of the devices are built in original scale size and tested in laboratory. The performance of the heat exchangers is documented.

Several dissemination actions are undertaken to publish the results of the project and to help introducing the new technology in industrial applications. Activities are a public web page of the project, participations on national and international conferences, presentations of the project during trade fairs, publications in scientific journals and the organization of a work shop especially dedicated to the project and its results.

Project Results:

The following chapter describes the main results and the foreground. The documentation is split and describes the individual result for each partner. The beneficiaries being non-profit organisations and public bodies for secondary or higher education do by nature not focus their activities on commercial aspects. The work is focused on scientific investigation, development of knowledge and improving technologies.

TUBAF

Introduction

Relative thermo-hydraulic performance optimisation plays an important role in the design of heat exchangers and the choice of heat transfer augmentation technique. In general, heat transfer augmentation is brought about by disturbing the development of thermal boundary layer, which in turn, also disturbs the development of hydro-dynamic boundary layer and hence, increases the pressure drop and the required pumping power.

As far as heat transfer enhancement techniques from the flat surfaces are concerned, there are different alternatives available and their performances are also well documented in the open literature. These techniques include the use of surface roughness, various forms of ribs and turbulators, winglets, swirl generators (like twisted tapes, helical coils, etc.) and inserts, dimples, grooves, to name a few. In the context of the present project, it is proposed to use periodic loop structures, fixed on flat surfaces, as the method for heat transfer enhancement. The numerical study on pressure drop and heat transfer characteristics was made on an arrangement based n flow through parallel plate channels, with one of the walls being fitted with periodic array of wire-loop structures, in order to check the viability of these structures as a potential heat transfer augmentation technique.

Possible Geometries of Wire-Loop Structures

The geometric configuration of wire-loop structures can vary in density of loops per unit surface area for example. In principle, the gap between the plates could also be varied. For reducing the costs of the new developed burners, it is necessary to use the already existing burner housings, which cause the gap size. Therefore, as far as the geometry of the wire-loop structures is concerned one can vary their arrangement on the plate and their loop density, i.e., the pitch in both the span-wise and the stream-wise directions.

Numerical Simulations

Repeating Module

A careful look into the possible geometries considered for the present study, reveals that one can always find periodic modules for each of these configurations that repeat themselves in both span-wise and stream-wise directions.

Numerical simulations have been carried out for these repeating modules, corresponding to each of the cases listed before by assuming the flow to be periodically fully developed and by imposing appropriate boundary conditions.

Boundary Conditions

At the bottom wall (heat transferring surface), impermeable and no-slip boundary condition with specified temperature has been prescribed, whereas, at the upper wall, other than specifying similar boundary conditions for velocities, an insulated boundary condition has imposed. In the stream-wise direction, i.e., at the inlet and the exit of the computational domain, periodicity condition has been implemented. Further, the bulk temperature at the inlet has also been prescribed.

Numerical Details

As mentioned before, the numerical simulations have been obtained using the commercial CFD code FLUENT 12.1. Since all the simulations have been carried out at higher Reynolds number and the flow is expected to be turbulent, a realizible model with enhanced wall function has been used. Other than this, the following settings have been used:

1. SIMPLE algorithm has been used to deal with the pressure-velocity coupling.

2. In general, an overall unstructured grid, with structured grid near the solid surfaces, has been used.

3. Second order upwind differencing has been used for all the convective terms.

4. In general, transient solutions have been obtained, if steady state solution is not found. Time marching has been continued till either the steady state solution or the sustained oscillatory solution in time is obtained.

It is worth mentioning that since the solutions have been obtained only for repeating modules by employing the periodicity condition in the stream-wise direction, the flow has been implicitly assumed to be periodically fully developed. It is also evident that such assumption is valid only for constant property flows and hence all the properties of the working fluid have been assumed to be constant. For all the simulations, air has been considered to be the working fluid. For Cases - I to III, properties of cold air at standard atmospheric condition have been used. For Case - IV, however, simulations for parallel arrangement have been obtained using the properties of both cold air and hot air at 600oC. The results for the same case (loop density) with in-line arrangement of loops are currently being simulated with properties of hot air and hence, these results are not presented in this report. Once obtained, however, these results would be quite useful for comparison at later stage in order to decide upon the orientation of the loops with respect to the flow direction.

Results and discussions of numerical simulations

Variations of friction factor and Nusselt number

The variations of friction factor and Nusselt number as functions of Reynolds number for some cases, a steady state solutions have been obtained but on the other hand, for some other cases no steady state solution could be obtained and hence, computations have been carried out until sustained oscillations in time have been reached. This is due to the vortex shading behind the cylindrical loop structures. It is also evident that for cases of oscillatory solutions in time, one can identify the time-averaged value, the maximum and the minimum values of friction factor and Nusselt number. The variations of these quantities as functions of mean Reynolds number were identified.

The results of the multi objective parameter study clearly show that:

1.Average Nusselt number increases with the increase in loop density

2.Average Nusselt number for staggered arrangement is appears to be higher than the other geometric arrangements

3.The average Nusselt number for opposed diagonal arrangement is higher than that for normal diagonal arrangement

Relative enhancement in friction factor and Nusselt number

The friction and heat transfer characteristics, show that as expected, the enhancement in heat transfer is always related to the increased pressure drop. Therefore, the enhancement of these values, relative to those for empty parallel plate channel has to be checked. The friction factor and Nusselt number for empty channel are calculated according to semi empirical correlations of Dittus-Boelter, Gnielinskie and Blasius.

The relative increase in friction factor is higher than that for Nusselt number. Out of the considered arrangements of loops, it appears that the performance of staggered arrangement is better only at lower Reynolds number, although its performance deteriorates quite remarkably with the increase in Reynolds number. For diagonal configurations, the opposed diagonal arrangement seems to perform better than the normal diagonal arrangement.

For calculation of the Nusselt number and friction factor, the inlet and outlet of the computational domain are selected as the reference surfaces.

Conclusions and outlook for numerical simulation

From the present study, the following conclusions can be drawn:

1.The average Nusselt number, as well as, the average friction factor increase with the increase in loop density.

2.Average Nusselt number for staggered arrangement is appears to be higher than the other geometric arrangements. The performance of this arrangement seems to be better than the other geometric configurations only at lower Reynolds number but deteriorates sharply with the increase in Reynolds number.

3.For opposed diagonal arrangement, the average Nusselt number is higher and the overall performance is better for opposed diagonal arrangement as compared to the normal diagonal arrangement.

In any case it is obvious that the aims of the project are achieved. With the same length of the recuperating element a higher amount of heat can be recovered or the pressure drop can be reduced by transferring the same amount of heat with a shorter recuperating element.

An experimental analysis of metallic and ceramic loop structures

General information about the test bench

The experiments were conducted using test bench designed specifically to test these loop structures and to verify the results of the numerical simulation. The test bench measures values such as volumetric flow rate, pressure and temperature. These properties in turn can be used to calculate useful analytical properties such as Reynolds number, Nusselt number and friction factor. To verify the results of the numerical simulation the same boundary conditions like in the numerical simulation were used. The loop structures are mounted on two water cooled plates opposite to each other. A very thin wall is in the middle to create adiabatic boundary conditions and to guarantee two undisturbed gap channels. A large number of repeating basic geometries is needed in order to avoid border effects on the two insulated (adiabatic) walls on the left and right side.

The overall length of the test bench is 4800 mm. The flow is caused by a side channel blower (maximum volume flow: 450 m^3/h and 300 mbar pressure drop) and heated with an electrical air heater (16 kW heating power).

For a high similarity in comparison to the numerical simulation it was necessary to avoid vortex structures by the use of a honey comb flow straightener and 3 different metal grids (coarse, medium, fine) for homogenization of the flow. To provide a nearly plug flow at the inlet of the measuring unit a jet nozzle was installed

Measured values are temperature using 32 thermocouples, pressure drop on six places and volume flow rate using the hot wire method. The loop surface is 150 x 625 mm^2 on each channel.

The range of Reynolds numbers varied between 1000 and 30000 in the measurements. For each different gap size, values were taken at different Reynolds numbers in two different ways. The first method is to keep the air heater temperature constant and then vary the blower volumetric flow rate and the second method is to keep the blower volumetric flow rate constant and vary the temperature of the air heater. With the data series from the experiment, properties such as friction factor and Nusselt number were calculated. Furthermore, these properties could be found at specific lengths of the test bench in the range from 125 mm to 625 mm.

Evaluation of the test bench

For evaluation purpose of the test bench experiments with an empty gap/channel (cross section area: 10.5 mm x 150 mm) are made.

The average Nusselt number over Reynolds number for measured and expected data based on semiempirical engineering correlations show a very good agreement. In the test bench only a 10 % higher Nusselt number were measured due to heat losses and small air leakages. The overall conclusion is that the hot air wind channel test bench is working very well and it is justified to make experiments for evaluation of the numerical results.

Experiments with metallic structures

Experiments with metal plates were realized in the next step due to the fact, that metal plates are very accurate in reflecting the geometry from the numerical simulation and ceramic plates were not available at this state of the project.

Geometry 01 with a heat transferring surface: 10.5 mm x 150 mm x 600 mm and a loop density of 3472 loops/m² were analyzed in order to validate the numerical simulation. The results for friction factor over Reynolds number show a very good agreement between experimental results and numerical calculated data.

IFTH

The main objective of this task is the elaboration of a non fugitive template (structure support) for ceramic conversion. This template is a textile structure obtained by processing SiC powder filled polymeric filaments or fibres. This process allows obtaining a continuous material after ceramisation if a sufficient rate of filler is added into the polymer (40 % in volume). But the SiC content has to be adapted to the melt spinning process in order to produce filaments with appropriate mechanical properties for textile processing.

First step is to define right raw materials: filler and polymer.

To be compatible with the slurry applied in next step, the chosen filler is SiC powder with particular distribution.

As the slurry starts to harden at 140°C, the polymer has to be chosen with a melting temperature higher than this point. It also has to have a smooth surface in order to get a good coating. IFTH has then decided to work with polypropylene, well-known and low cost polymer used in textile industry.

IFTH has run different trials in compounding on its spinning pilot plant.

The result of this step is a rod with a non homogenous diameter which was pelletized to transform it in multifilament yarn by melt spinning.

IFTH has reached a good proportion of SiC (50% in weight) in the rod but the dispersion of SiC powder in the polymer matrix was poor. Still IFTH has demonstrated the spinnability of this blend in monofilament, but the mechanicals properties are inconsistent with textile processing.

In order to obtain a materiel compatible with textile process, IFTH has produced multi-filaments from a 25% SiC in weight blend on its laboratory melt spinning pilot and from a 10% SiC in weight blend on its industrial melt spinning pilot.

The determination of the different component contents in the blend and the study of the morphology by microscopy show a poor dispersion of SiC powder in the PP matrix. This dispersion state can be attributed to the low compatibility between the matrix and the filler. Moreover, the use of a high content of fillers (25 wt.%) in fibres is not common in textile industry. This induces too low mechanical properties of multifilament yarns for textile processing.

T2200

The objective of this task is to design a textile structure which could be used as a template for subsequent conversion process as described in annex 1 of the project.

The first step of the work was to define the main specifications of the textile structure in order to select the material and processes.

In order to, IFTH has considered specifications from numeric simulation and downstream process. The textile structure has to respect the exchanger drawings from TUBAF. These drawings are not common in textile regarding the form, the sequence and the precision.

The prototypes structures have been produced through two main ways: structures using monofilaments and structures using multi-filaments or staple fibres yarns.

IFTH has experienced several textile technologies in order to produce the right prototypes.

The textile structures have been made with two type of products: a fugitive template, material bought on market and selected for its residual carbon rate after ceramic conversion and a non-fugitive template, material developed by IFTH in T2100.

Due to the ceramisation process and the design of heat exchanger, the material which would be used to produce textile structure has to fulfil some specifications:

-As it will be carbonized in ceramisation process, the polymer should not be too expensive,

-Because of the viscosity of slurry, fibres should have a smooth surface and a large enough diameter in order to get a good coating of fibres by slurry and to avoid air encapsulation between slurry and fibres,

-As the slurry starts to harden around 140°C, the filaments should have to melt at an higher temperature,

-The polymer shrinkage is also important and should be similar to the slurry one to create the same contractions or expansions and then avoid the formation of cracks,

-The polymer should be hard enough to support the slurry without subsiding.

It has also been defined that the base fabric which would maintain the 3D structure should be in the same material than the loops material but not in the same form (monofilament and multifilament).

IFTH has tried different technologies such as trimmings, non-weaving and braiding. These technologies do not allow to fulfil all the specifications in drawing and lightness. The best structures were obtained with weaving and knitting process.

Prototyping with weaving technology:

IFTH has carried out several trials with its own equipment or in industrial facility with different materials (fugitive and non-fugitive)

-PP monofilament, this material was difficult to keep in loops form due to its diameter (1 mm)

-PANox staple fibres yarn, the loops were to fluffy and the base fabric shrinkage during ceramic conversion caused cracks

-Polyester multifilaments, the loops were to fluffy and the slurry did not have a good adhesion on base fabric.

-Non-fugitive multifilaments (developped in T2100), the same problems came up with this material and it was juged by the consortium that not enough residual carbon was brought with this material to continue with.

Weaving technology allows to realise textile structures quite in adequation with all the specifications, but the base fabric was too closed to allow a good penetration of the slurry.

IFTH has then produced prototypes with weft knitting technology.

Prototyping with knitting technology:

First knitting trials have been carried out with monofilament (diameter 1 mm), this material does not allow a knitting process due to thickness and rigidity of the filament.

The main difficulty with the knitting technology is to fulfil the distribution and alignment of loops. Indeed, produce small loops in knitting technology is common, but produce loops with an 8 mm diameter asks specific developments.

IFTH has developed a specific drawing on a weft knitting using multi-filaments polyester yarns and solubilised yarn to reach the geometries of exchanger defined by TUBAF.

T3000

IFTH has produced samples in geometry 1 and 2 for final prototyping by downstream process.

Erbicol

A new manufacturing process has been developed based on the common Schwarzwalder method. Starting from a sacrificial template, a green body was obtained by impregnation of a textile in a silicon carbide based slurry. The ceramic intermediate was finally infiltrated with liquid silicon to obtain the final product. Following aspects were developed and/or optimized within the project:

Template material selection and optimization

Adaptation of the coating path to the new template

Development of a joining process of the green body to an already finished ceramic tube

Optimization of the pyrolysis step

Optimization of the liquid silicon infiltration to the new product

The experimentation performed on the textile template allowed to select a proper material for ceramization. The behavior during ceramic coating (mechanical properties) and the behavior during pyrolysis (thermal properties) were studied to obtain a ceramic intermediate similar or equal to the designed structure.

The first processing path, the impregnation (coating), was adapted to the new conditions. Industrially the manufacturing of SiC-based products varies depending on the final use and shape of the product. The most common production processes for SiC based products are mold processing, extrusion, hot press, CVD and Shwarzwalder. However, for the present shape and application, the only applicable process was the coating of the preform through immersion of the template in a ceramic slurry. Optimization of the process in order to obtain a replicable quality product with an inclination to scale-up took place. Following the ceramic coating, a process was developed in order to join the green ceramic-textile and the already finished tube. A high quality of the joining was obtained, resistant at high temperature. Finally, the two thermal treatments, pyrolysis and liquid silicon infiltration, were optimized to fit the new conditions.

As a result, the company was able to manufacture quality structures, whether in form of plate prototypes or as complete recuperative burners tubes, in a replicable manner. A process was developed and optimized that allows fast scale up and cost effective manufacturing of ceramic based loop structures added to a fix substrate like a tube.

Another technical result, even if of minor implication, was the adaptation of conventional machining of extra hard materials (diamond tools machining) to the new products. The company was able to precisely machine tubes, plates, foams and any other material used during the project, adding valuable know-how for this manufacturing path.

SUPSI:

In combustion environments silicon carbide ceramics are, for their outstanding thermal and mechanical properties, among the best materials . In fact they are commonly employed into high temperature furnaces because, if passive oxidation conditions are met, they withstand operating conditions for long time.

At the beginning of the project three processes were envisaged to fabricate highly structured SiC surface elements:

-Chemical Vapor Deposition (CVD)

-Polymer Impregnation and Pyrolysis (PIP)

-Liquid Silicon Infiltration (LSI)

Chemical vapour deposition produces by far the best material in terms of purity and compactness. It was though immediately abandoned because of their limitations in terms of processing (long times, high costs for thick loops, large furnace availability) and also because these materials in their monolithic forms have rather low thermal shock resistances.

Polymer infiltration and pyrolysis was thoroughly studied in the first part of the project: several preceramic polymers were acquired mixed with SiC powders to produce slurries for fibres loops coating. Slurry viscosity was optimized as well as the coating procedure and ceramization by thermal treatments. This technique showed its limitations in terms of final ceramic compactness and strength. Because the polymer upon pyrolysis shrinks and it shrinks on a stable support (i.e. the SiSiC tube) many cracks occurred. Another limitation is given by the non crystalline nature of the SiC produced by pyrolysis. This would lead to a lower oxidation resistance.

The main achievement is thus the set up of a production technique ready to be industrialized. In this sense, LSI showed to be the best performer also because of its industrial maturity and also because the commercial SiSiC tubes are made with a similar technology (proven to be the best performer in a combustion chamber environment) several slurries and coating techniques were thus tested and the optimal composition was chosen in terms of viscosity, green strength, pyrolyzed body microporosity, and final SiSIC microstructure.

The process was first optimized for planar samples in order to optimize the final product and produce samples for the experimental campaign. The process was further optimized on tubes and finally adopted for the production of functional prototypes and alternative design components.

The final product passed functional tests in a real burner environment and proved to perform significantly better than the standard component.

Interesting was also to notice the matching of the experimental results with that of the simulations despite the loop geometry which was slightly different than the nominal one.

NOXMAT/AICHELIN: First gas burner application

WP 3000. Work and results

T3100 Market Study

The main objective of this work was to collect geometric parameters and thermal properties of existing recuperators and heat exchanger components.

It was difficult to get detailed information, for example for detailed geometry, wall thickness, geometry of the ribs or heat transfer properties such as relative air preheating or pressure drop, about the recuperators.

All burners of the burner manufacturers are assembled modularly. That means that the ports for the media supply (combustion air, cooling air, gas and waste gas) can be staggered at 90 degrees to each other.

There are two different possibilities of flame control for gas burners. The first is to use only one electrode for ignition and ionisation. The second possibility includes one electrode for ignition and a UV sensor for flame control.

Recuperative burners are available from several burner manufacturers in different power ranges and fitting lengths. Most manufacturers offer a metallic and/ or ceramic design. The geometry of a metallic recuperator is mostly a ribbed geometry. Steel recuperators with a plain recuperator or a gap flow recuperator are also available.

The ceramic recuperator burners differ much more in their surface than metallic ones. The ceramic recuperators are generally produced by the process 'Schlickerhohlgussverfahren'. Because of this process only simple surface structures can be realized. More complicated geometries are more expensive and therefore not economical. The different kinds of surface geometries are burled by LBE, pointed by WS and corrugated by IBS, NOXMAT and WS. As well as in steel design there are plain ceramic recuperators. (The ceramic material of the recuperators consists of about 88% SiC and 12 % free silicon. The ceramic material is characterized by the following properties: Consistently mechanical strength up to 1380 °C, excellent thermal shock resistance, high thermal conductivity of about 28W/mK at 1100°C, corrosion resistant to aggressive combustion components, no tinder formation, with a density of about 3.1 g/cm³ significantly lighter than steel, gastight and no shrinkage of the ceramic during the manufacturing process.)

T3200, T3600, T3700 Heat Exchanger design and designing of the prototype burner, integration and testing

A new recuperator with a new heat exchanger geometry had to be integrated in a reference burner. This burner prototype should be based on an existing burner of NOXMAT K-RHGB Series. The main requirements were to define the burner size and to analyse the burner components. It had to be figured out which parts can be reused, modified slightly or developed newly. The next step was to check which geometry is possible for the development of the new heat exchanger element.

The product range of NOXMAT was analysed by using characteristic numbers of burner dimensions. The main focus laid on the gap-width between the burner tube and the recuperator and accordingly between the recuperator and the radiant tube or insulation of the waste gas chamber. This examination showed that the gap-widths between the tubes were too small for all burner lines. For this reason a burner should be combined with a burner tube of a smaller one. The decision was to combine the burner housing of a K-RHGB 160 burner with a burner tube of a K-RHGB 80 burner. A lot of different concepts of the new burner design were developed and compared. These Concepts included burners with a recuperator element with a loop radius of 5 mm, 8 mm and 10 mm with different outer diameters of the recuperator element. The burner design with a recuperator component with a loop radius of 8 mm assembled in a radiant tube K type 200 with an outer diameter of 200 mm were developed further.

Because of the combination of the two burners it was necessary to modify existing and to design new burner components. The burner unit with the burner tube with its fixing, gas lance, gas part and electrode of a K-RHGB 80 was used. The waste gas part, the recuperator fixing and the air part are parts of K-RHGB 160. With the help of different steel adapters the assembly of the prototype burner was like that of a serial burner of NOXMAT-Series. For the new recuperator element a commercial ceramic plain tube with loops with a radius of 8 mm inside and outside was used. The geometry of the recuperator element differs from the serial recuperator of K-RHGB 80. The recuperator head is equal to that of the serial recuperator of the K-RHGB 80. The end of the recuperator where the recuperator is fixed in the waste gas part has the same geometry as the recuperator of K-RHGB 160. The middle part which is covered with loops on both sides has a new geometry and its outer diameter is bigger than the recuperator of K-RHGB 80 and smaller than the recuperator of K-RHGB 160.

The first prototype of the recuperator component was not exactly like the drawing. The loops were very different. The radius of the loops was not really 8 mm, they partly laid on the surface. This was recognized inside as well as outside of the new recuperator.

Because of that and the narrow tolerances between the tubes there were problems at the assembly of the burner tube into the burner or into the recuperator. That's why some loops were removed to assembly the burner tube. With the help of the adapter parts the assembly of the prototype burner was possible without problems.

The next work was to test the burner with the new recuperator element. A test bench and a measuring concept were designed and assembled. Two different burners were tested: a burner with a plain recuperator and with the loop recuperator. The following criterions were measured quantities and calculated performance indicators were determined: efficiency, air preheating, waste gas temperature, NOx-emissions and pressure drop. Both burners operated in indirect heating in a radiant tube K type 200 of NOXMAT, because all the waste gas returns via the recuperator. Three different power capacities 40 kW, 60 kW and 80 kW were tested.

A comparison of these two burners led to the following results. A considerable increase of firing efficiency could be achieved by using the loop recuperator. In the normal operating range of a ceramic burner (800 - 1300 °C) the increase in efficiency is about 4 to 8 %. In the same temperature range the decrease of the waste gas outlet temperature is between 130 and 170 K of a burner with a loop recuperator compared to a plain recuperator. At the same conditions a burner with a loop recuperator has a 135 up to 150 K higher air preheating than the same burner with a plain recuperator. The increase of the NOx-emissions is almost constant on the whole temperature range and is about 50 mg/m³. At lower capacities the rise of the emissions is higher (about 10 to 110 mg/m³) and depends on the waste gas inlet temperature. The difference of the pressure drop with a loop recuperator compared to a plain recuperator is 4-5 mbar per side. On the waste gas side the pressure drop was 5 mbar without and 9 mbar with loops. And the pressure drop on the air side was 15 mbar with and 11 mbar without loops on the recuperator.

Only a limited comparison of the new recuperator was possible with the state of the art. A comparable and serial burner of the NOXMAT product range was the K-RHGB 80 with a corrugated recuperator. Both burners had a fitting length of 535 mm. The differences between the two burners were: the waste gas part, the air part, the waste gas guiding tube and the outer diameter of the recuperator component. The firing efficiency with the loop recuperator is 3 to 5.5% higher than with a corrugated recuperator. By using a loop recuperator the waste gas outlet temperature falls by 60 to 90 K depending on the waste gas inlet temperature. The NOx-emissions were similar because of the other geometry of the recuperator component and as a consequence of that another division of the combustion air into primary and secondary air. The handling or assembling of the burner with the loop recuperator was difficult. A lot of loops were damaged or broken during the mounting and dismounting of the burner. Further disadvantage was the high price because of the expensive production process. For the future a production process in one step, a better approach and reproducibility of the planned geometry and better assembly tools are required.

WP 4000 Alternative designs.

For the work package 4000 alternative designs the work of NOXMAT was to develop a concept of an application and to test them. The application was to cover a serial flame tube of a radiant tube with foams. The influences on heat transfer on the furnace and on the thermal homogenisation to the radiant tube were determined with and without foams. With the help of the surface temperatures, pictures of an infrared camera and the waste gas inlet temperature at the recuperator a several quantity of foams were tested and compared. Only tests with 9 and 13 foams were realized. No significant improvements in heat transfer and thermal homogenisation to the radiant tube have been achieved with these configurations. It is possible that with other arrangements, like different diameters or numbers of foams better results can be obtained. But this will require further tests and new foams.

WS: Second gas burner application

During the first half of the CEREXPRO project the efforts of WS were focused on the enhancement of the heat transfer performances of ceramic regenerative heat exchangers. In order to achieve this objective numerical and experimental investigations were carried out at TUBAF.

The basic unit of the regenerative heat exchanger, integrated in the state-of-the-art self-regenerative burner, is a cylindrical cartridge filled with a pile of ceramic honeycomb structures. The combustion air and the exhaust gas alternatively stream through this cartridge mainly in the axial direction.

The aim of the proposed innovative design for this basic regenerative unit was to induce a significant radial component in the flow although the overall direction would remain along the axis of the cylindrical honeycomb structure. At the same time, the idea was that of limiting the heat loss through radiation in the axial direction and this was realized by means of shields interposed between two regenerative elements. The presence of the shields also helped redirecting the flow towards the axis and the tube walls, alternatively from on element to the next. By doing so the desired radial direction of the flow could also be generated.

The numerical investigation of such geometrical configuration revealed the opportunity of using ceramic foam structures as heat storage elements for the regenerator and at the same time no significant improvement was indicated when using structures made out of textiles instead.

Therefore such Si-SiC foam structures were manufactured at ERBICOL and were subsequently integrated within the existing housing of the industrial WS self-regenerative gas burner Regemat® M350.

An important design parameter for the new heat exchanger is the spacing between two flow redirection plates. Since the overall length of the regenerator unit was kept constant (constraint deriving from the requirements on the furnace wall thickness and from the current design of the burner) the spacing between the redirection plates would affect the length of the single Si-SiC foam elements and most importantly the shape of the flow through the regenerator and subsequently the heat transfer performance of the heat exchanger.

The computational investigation at TUBAF demonstrated the strong correlation between the 'density' of the flow redirection plates and the heat transfer enhancement: approx. 3 percentage points could be gained in the burner efficiency while going from 10 to 20 redirection plates. At the same time the calculated pressure drop through the regenerator unit would increase from about 40 to 120 mbar.

Based on the numerical results, different sets of ceramic foam elements with different lengths were manufactured at ERBICOL so that different configurations (from 10 to 14 elements and related flow redirection shields) could be tested and compared with the honeycomb ceramic structures.

The new heat exchanger prototype was extensively tested and the results of the experimental campaigns showed that it was possible to reach burner efficiencies in the same range of those achieved with the existing regenerator design. Nevertheless, this was obtained at the cost of significantly higher pressure drops through the heat exchanger at constant burner capacity (for instance the measured pressure drop results more than doubled at a simulated burner capacity of 160 kW, i.e. from approx. 25 to 60 mbar). Additionally, the economic analysis showed a relevant increase in the manufacturing costs of the ceramic foam structures compared to the honeycomb structures currently adopted in the self-regenerative burner.

It is acknowledged that self-regenerative burners at the current state of the art already represent a technology able to offer the highest heating efficiencies among industrial burners, in a range between 80 and 90% depending on the design and type of application. At this point, according to the results and considerations reported above, the decision was made to focus on the investigation of possible alternative designs for recuperative applications.

The aim was to create a design which would increase the heat exchange compared to current state-of-the-art ceramic recuperators, by using a more simple ceramic structure than the ceramic loops structures developed within the main activity on the first recuperative application.

Therefore, the basic idea remained that of enhancing the heat transfer of a tubular ceramic heat exchanger by means of structures that would have modified the flow regime and characteristics both on the combustion air side and the exhaust gas side.

In order to validate this approach experimentally as a proof-of-concept a first set of tests were carried out on a standard recuperator with corrugated surface. A heat resistant metallic mesh was wrapped onto the inner and outer surface of the recuperator and the concavities on both sides were also filled up with the same metallic structures.

The results of these preliminary tests with metallic structures showed some 3-4 percentage points increase in the burner efficiency while the pressure drops were only slightly affected by the presence of the mesh (tests were performed with exhaust gas inlet temperatures from 600 up to 1050°C). This became the base for the following investigation and development of a fully ceramic heat exchanger prototype.

The experience gained with ceramic foams during the study of the regenerative application led to the trial of these structures as additional elements on the ceramic recuperator: the advantage with respect to the regenerative case is that for this application ceramic foams would only represent additional elements on the monolithic recuperator piece therefore limiting the additional costs and also making this idea suitable for refurbishment plans.

The final solution considered the use of Si-SiC foam rings with a porosity of 10 ppi (pores per inch) as additional structures to be fixed on a ceramic bare-tube heat exchanger with the aim of generating an additional level of turbulence by interrupting and re-mixing the flow streamlines. These structures were manufactured at ERBICOL according to the geometrical specifications provided by WS.

The dimensions of the rings were defined on the base of the existing state-of-the-art WS burner (reference burner: Rekumat® C150) which was selected for the comparison with the prototype burner.

The distance between the different rings was defined according to a preliminary experimental study by TUBAF aimed at identifying the minimum distance between two neighbouring rings that would have prevented a significant re-stabilization of the flow before the following ring. These preliminary results were showing that the distance between two rings should be kept under 30 mm.

In the final recuperator prototype a distance of approximately 27 mm between two neighbouring rings was chosen.

During the burner assembling most of the components (gas lance and nozzle, air head, gas and air trains, valves, etc.) were acquired or adapted from existing WS burners with the aim of a final geometrical similarity (recuperator length and diameter) with the state-of-the-art burner. Therefore the main efforts were made to produce the new heat exchanger.

Some ingenuity had to be used to assemble the prototype burner in a quick and reliable fashion in order to be able to proceed with the testing activities. Particularly critical was the fixation of the foam rings to the ceramic bare-tube: a high temperature ceramic-based glue was used to fix spacing elements between the foam rings on the outer side of the ceramic bare-tube. By doing so, the distance between two rings was maintained approx. constant at the desired value of 27 mm and the rings were kept free from thermally induced stresses during operation.

After the assembling phase the burner prototype was extensively tested in a test furnace at the WS laboratory. It was decided to investigate the performance of the test burner in comparison with the bare-tube design (without the foam rings) and the WS self-recuperative burner in a ceramic radiant tube application.

The experimental rig set up at the WS laboratories was equipped with combustion air and gas flow measurements, furnace temperature, radiant tube temperature, exhaust inlet and outlet temperature measurements as well as exhaust gas analysis for the control on combustion.

The conventional, the prototype and the bare-tube recuperators were tested at different burner capacities (36, 40 and 44 kW) and different temperatures levels (900, 1000, 1100 and 1200°C). Only the case with the bare-tube recuperator was tested at furnace temperatures up to 1000 °C since the exhaust temperatures at the recuperator outlet already reached too high values for the available exhaust gas system (about 850°C and higher).

The measured values were collected once a constant operation of the burners was reached (no significant variations in the relevant variables: furnace and exhaust gas temperature, exhaust gas composition, etc.). Finally, the stoichiometry of the combustion was kept constant during the different tests at the typical targeted values for industrial heat treatment applications with natural gas combustion.

Though with the Rekumat® C150 burner always the lowest exhaust outlet temperatures were obtained in comparison with the other two configurations (while maintaining the same conditions in terms of power input, stoichiometry and furnace temperature), it became evident that a substantial reduction in the exhaust outlet temperature could be observed when passing from the ceramic bare-tube design to the bare-tube equipped with Si-SiC foam rings.

For instance, at 1000°C reference test furnace temperature (corresponding to exhaust gas inlet temperatures in the range of 1100°C) the measured exhaust outlet temperatures were 615°C on the Rekumat® C150, 640°C on the recuperator prototype with ceramic foams and 858°C on the bare-tube recuperator. This leading to burner efficiencies of 71,2%, 69,7% and 58,0%, respectively.

Then, based on the experimental results, at 1200°C reference furnace temperature the efficiency of the Rekumat® C150 burner and the prototype burner were 70% and 68%, respectively. An analogous behaviour was observed at the other temperature levels (in average the new burner was showing efficiencies of about 2,5% lower than the current WS burner).

Thus, the state-of-the-art recuperator always displayed slightly better performances than the burner prototype, as far as the burner efficiency is regarded. At the same time, it is worth noticing that a large improvement was possible with the new design in comparison with the bare-tube design, this confirming the heat transfer enhancement potential of the Si-SiC foam rings on the bare-tube surface.

Furthermore, the improvement of the heat transfer characteristics with the new recuperator design did not affect significantly the pressure drops of the system which only increased of few mbar in comparison with the simple ceramic tube and remained slightly lower than those measured when using the Rekumat® C150 burner.

Finally, in terms of NOx emissions no significant comparison could be drawn since the fuel and air nozzles designs were by chance completely different in the two cases and the burners were only tested in flame operation. However, on principle the application of the FLOX® technology (flameless oxidation regime) would allow for extremely low NOx emissions in both cases.

Potential Impact:

The successful market introduction of new technologies is always related to the associated investment costs. For the case of the CEREXPRO target products (recuperative or regenerative industrial burners and additionally further future innovative alternative application schemes) a reference comparison to nowadays most advanced burner technology with integrated waste heat recovery is adequate. Intensive market studies on industrial heating technology and energy costs are performed. On the basis of recent economical data the improvement in efficiency due to the application of the new heat exchanger is significant. The calculated pay back times are below 2 years. The calculations are performed for new installations as well as for refurbishment of existing industrial furnaces. Especially the replacement of older burners is a great market in Europe. Depending on the degree of preheating of combustion air the energy consumption and therefore the CO_2 emissions could be reduced drastically.

TUBAF:

During elaboration of the project many numerical and physical experiments are performed. The results allow a deeper understanding of the behavior of fluid flows around and behind disturbing elements. The formation of vortexes behind the elements is studied. Understanding the physical behavior behind the phenomenon helps to improve the design of surfaces of heat exchangers. The first applications are elaborated during the CEREXPRO project. The knowledge can be transferred easily to further designs of heat exchangers for very different applications.

The cooperation with partners from different European countries is very good. Further projects in research and development are expected. The project is also incorporated in scientific education. A number of students was working within the projects frame and preparing 9 student theses. The results of research work at TUBAF will be the core of one doctoral thesis. All results will be introduced into scientific education.

IFTH:

The knowledge created enlarges the use of polymeric fibers in textile technology. These fabrics open the opportunity for the textile industry to enlarge its range of applications in trans-sectorial activities. The development of woven, knitted or nonwoven structures often needs the temporary stopping of industrial lines, so loss of production. By making available its pilot development lines, IFTH is committed to the development of textile prototypes for non conventional sectors, which do not exist in Europe. This process will allow developing its expertise in melt spinning of innovative polymers, new fibres' processing and 3D textile developments. This gives the opportunity to open further activities for utilizing textile technologies in other industrial sectors.

Potential impact

The CEREXPRO project has required the implication of RTD personnel in IFTH, but also of industrial partners who will be able to provide the right structures to make heat exchanger. This can complete their volume of production (it can occupy one to two weeks of a loom per year).

Dissemination

IFTH has organised a conference followed with a work shop with textile industrialists on October 13th, 2011 in Villeneuve d'Ascq, France. This conference has drained Belgium and French professionals.

IFTH has participated to the final project workshop in Frankfurt on March 22d, 2013

Exploitation of results

The expertise acquired by IFTH during CEREXPRO project will be useful for other independent developments:

In melt spinning, for blends' development, regarding in particular the integration and good dispersion of powder in a polymer matrix,

In weaving process, with new possibilities of 3D weaving prototyping,

The drawing developed for knitting process can be exploited in other skills such as clothing.

The interdisciplinary approach of CEREXPRO has opened the opportunity for the textile industry to develop a high technical textile for a non-conventional sector. CEREXPRO project has allowed to develop this textile on pilot looms without stopping production in an industrial facility. IFTH has identified potential partners who will be able to produce on ask this type of textile structure. IFTH mission is now to transfer the production of this textile in a common textile facility.

ERBICOL:

The knowledge and know-how produced during this project has a potential impact on the company and its future operations. Following items are of great value for the company, also in other application fields:

Processing of complex shapes products

Joining technique

Processing of textile template materials

Considering the direct impact of the project, i.e. the impact related to the recuperative burner tube with enhanced heat exchange product, this depends on further effort to optimize and industrialize the product. Market entry is not foreseen for the moment, but if it will be the case, the result would be a consistent increase in personnel and turnover.

Moreover, considering the indirect impact, the knowledge and experience collected during the four years project are useful also for the manufacturing of products for the aerospace and chemical industry. In particular the joining technique and the processing of textile structures allow the company to increase the product portfolio and to add value to already marketed products, increasing sales and consequently personnel.

SUPSI:

After the patent submission SUPSI started the dissemination activities in collaboration with the project partners. These activates culminated with the preparation of a paper on the most reputed journal in the field of applied ceramics (Int. J. Appl. Ceram. Technol.) whose details are given below. The main goal is to trigger the interest of Ceramic manufacturers in order to adopt this solution in new application fields by integrating the manufacturing procedure of the loop structure with that of their monolithic sub structures.

With this aim Prof. Ortona held a speech entitled “Si-SiC heat exchangers with highly structured surface elements for recuperative gas burners” at the annual congress of the American Ceramic Society in Daytona Beach USA (see details below) there was a great interest on the subject and preliminary talks were initiated in view of a possible cooperation with the two biggest Si-SiC manufactures (Schunk (Germany), and Saint Gobain (France).

The manufacturing technology which allows to produce regular and repeatable ceramic structure from engineered textiles can be easily transferred to other technological field dealing with heat transfer, especially those working at very high temperatures such as: concentrated solar power, Aero-engines and aerospace.

NOXMAT (AICHELIN)

-Potential partners for further projects in the future

-New manufacturing processes for new heat exchangers with different and efficient geometries.

-Insights and learning about other industries, companies and activities.

-New networks and contact persons for questions or problems

-Institutions, universities and companies for possible services

-Learning about foreign countries, companies, people, customs and their ways of working.

-A further step to efficient burner technology and associated to that a conservation of energy resources.

-A stimulation of ideas for future products and projects

-Strengthening of the market presence and the competitive ability

-Advertising and presentation of the company NOXMAT at various articles, fairs, symposiums and conferences.

-Raising the awareness of the company NOXMAT for energy-saving technologies.

-Further training of employees

-Growing image as an innovative company

-Development of Know-how for processing of further or higher cooperation projects.

-Bundling of innovation capacity

-Variety of helpful personal contacts

-Functioning prototype

WS:

At present self-recuperative burners using ceramic heat exchangers are commonly operating in a power range from 10 to 100 kW with maximum temperatures of the hot flue gases up to 1300°C. Although a higher power output is considerable, there are still problems concerning the manufacturing of larger monolithic ceramic parts. Yet most heat exchangers made of steel are offering a larger surface for the heat transfer than their ceramic counterparts because of limitations while machining ceramic pieces.

When industrial burners are installed in high temperature processes (in the range between 1200 to 1300°C), an increase in the relative air preheating (defined as the ratio between the combustion air preheating temperature and the exhaust gas temperature before the heat recovery) by improving the heat exchanger design, results in major benefits in terms of combustion efficiency which translates into fuel savings potential.

Innovative manufacturing processes for the production of ceramic components in a wide range of shape and structure offer the opportunity of re-designing the heat exchanger concept for existing self-recuperative and self-regenerative burners.

The CEREXPRO project within the study of the second recuperative application proved the feasibility of the integration of Si-SiC foam rings with tubular ceramic recuperators showing at the same time positive results as far as the efficiency enhancement is taken into account. Moreover, positive results in terms of burner efficiency could obtained without drawbacks on the related pressure drops throughout the heating system. Therefore, it could be technically and economically worthwhile to carry on with further development activity on this type of recuperator design.

On one hand, further development activity would be required in order to technically improve the manufacturing process of the complete heat exchanger and make it adequate for industrialization and commercialization (for instance regarding the connection between the foam structures and the ceramic tube) as well as in the fundamental investigation for the optimization of the heat exchanger design (optimal porosity and if required anisotropic structure of the foams, optimized spacing between the ceramic foams, integration between ceramic and metallic structures working at different temperature levels throughout the heat exchanger, etc.).

On the other hand, the costs associated with such manufacturing processes are also an issue to be assessed in order to allow for economical feasibility of new technical solutions and have to be taken into account as for any design process.

The application of the new design concept for self-recuperative industrial gas burners might become of particular interest in specific cases where the use of recuperators with corrugated or bulged ceramic surfaces would be impracticable and too expensive (large counter-flow heat exchangers for high temperature applications).

During the course of the project a great number of dissemination activities are performed. The first activity is the launch of a project web site. The public part is used to introduce the project, its context and objectives. All partners are briefly introduced, the role in the project is described and links to their web sites are given. Another folder contains publications and oral presentation of the project in a free accessible copy.

The project was presented worldwide at 9 trade fairs. Oral presentations were given at 8 scientific conferences and meetings of engineer associations. Furthermore the European Committee of industrial furnace and heating equipment associations CECOF has already co-operation agreements and established co-operation with several non-European associations in the process-heating sector like the US Industrial Heating Equipment Association (IHEA) and the Japan Industrial Furnace Manufacturers Association (JIFMA). A bilateral participation as a guest at the respective annual delegate assemblies established, providing an overview of the last year activities to the foreign associations. On these occasions CECOF regularly reported on the progress of CEREXPRO.

In March 2013 a dissemination work shop was held in Frankfurt/Main. Referents from all beneficiaries explained their contribution to the project and the main results gained. The invitation was sent to companies active in the branch of thermal processing, in ceramic technology and heat exchanger production. The companies are mostly situated in Europe. Also engineer associations and associations of companies representing different industrial branches were invited. The participants of the workshop were - as planned and expected - employees of manufacturers of thermo process plants and burners and their components from Europe, with a focus on Germany. The participants were either head of research and development departments or project managers.

The future applications were from particular interest for the participants. A main part of the workshop was dedicated to an open discussion between the participants from the different customer industries. The work shop was held in an open atmosphere. The response from the audience was very positive and encouraging. The aim of the work shop was fully achieved.

List of Websites:

http://www.cerexpro.org