

Designing a power plant with highest efficiency: results from SFB 561

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Abstract: The goal of Collaborative Research Centre (SFB) 561 “thermally highly loaded, porous and cooled multi layer systems for combined cycle power plants” is to expand the current technological and scientific knowledge on power plants in order to achieve total efficiencies of 65% in a combined cycle power plant in the year 2025. Therefore, the aerothermomechanical, structural mechanical, materials’ scientific and production fundamentals for the development of steam and gas turbine components that are able to withstand highest thermal loads are being worked out within this SFB.

This means for the gas turbine that combustion chamber outlet temperatures of 1520 °C at 1.7 MPa are to be attained. In order to control these high temperatures, it is not only required to develop new materials’ solutions, including thermal barrier coatings, but also to apply improved cooling techniques, as for example effusion cooling. This novel cooling concept is to be realised through open porous structures. These structures can consist of drilled open porous multi layer systems or open porous metallic foams. The development of graded multi layer systems is also extremely important, as the grading will enable the use of coolant in dependence of the requirements. The live steam parameters in the high pressure turbine are expected to be increased up to approximately 700 °C with pressure of 30 MPa. These elevated steam parameters can be encountered with Ni base alloys, but this is a costly alternative, associated with many manufacturing difficulties. Therefore, the SFB proposes cooling the highly loaded turbines instead, as this would necessitate the application of far less Ni base alloys.

To protect the thermally highly loaded casing, a sandwich material consisting of two thin face sheets with a core of a woven wire mesh is used to cover the walls of the steam turbine casing.

The current state of the research shows that by utilising innovative cooling technologies a total efficiency of 65% can be reached without exceeding the maximum allowable material temperature, thereby prolonging the life span.

Key words: gas turbine; steam turbine; cooling; novel materials; process calculation

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Introduction

The preservation of natural (fuel) resources and the reduction of gases that are harmful to the environment are presently the driving forces behind the improvement of the thermal efficiency of power plants. Modern combined cycle power

plants reach total efficiencies of over 58% and steam turbine power plants can reach up to 46% net efficiency, although the temperatures required to reach this efficiency lead to the load limits of the currently used materials being reached. Therefore, the economic and environmentally-friendly production of electrical energy

will be one of the fundamental challenges for the power plant industry of the 21st century.

The world market is, at present, determined by an increasing demand for combined cycle power plants and, in countries with large coal reserves, by a demand for modern steam turbine plants with highest efficiencies. There will be a significant demand for additional power plants with increased power output in Europe in the next decades, as a replacement for the plants from the 1960's and 1970's that are being currently decommissioned. In the foreseeable future, though, emerging markets like China and India will dominate the demand for power plants on a global level. The challenge for the power plant industry in the near future will be to cope with the demand for higher efficiencies and to fulfil the increasingly severe environmental laws while simultaneously guaranteeing the availability of the plant at reduced operating costs. Therefore, applied fundamental research at universities, as conducted within the framework of Collaborative Research Centre (SFB) 561, is required.

1 Challenges

Increasing the efficiency of both single power plant components and their interaction can make a substantial contribution to the preservation of natural resources and the reduction of emissions. Gas turbine inlet temperatures in modern combined cycle power plants attain 1230 °C (ISO) and live steam temperatures in modern steam turbine power plants reach levels over 600 °C, which means that the load limits for currently applied materials are being reached. A secure and long-lasting operation at high availability rates can only be achieved by using complex cooling techniques, sophisticated constructions and exact revision schedules.

The goal of SFB 561 "thermally highly loaded, porous and cooled multi-layer systems for combined cycle power plants" at RWTH Aachen University is to expand the currently available technical and scientific knowledge and to

establish the scientific basis for achieving a total efficiency of 65% in future power plants built after the year 2025. This means that within the SFB the aerothermomechanical, the structural-mechanical, materials' scientific and production fundamentals for highly loaded components of these combined cycle power plants are being worked out. The results from the SFB show that the operating parameters, like temperatures and pressures, have to be raised further^[1].

In order to achieve a total efficiency of 65% it will be necessary to realise gas turbines with combustion chamber outlet temperatures of 1520 °C at 1.7 MPa and steam turbines with live steam temperatures of 691 °C at 30 MPa. On the gas turbine side these high process temperatures can only be controlled by the development of new materials' solutions, including thermal barrier coatings (TBC), in combination with improved cooling concepts. The rise in temperature cannot be countered by developments in the field of structural materials alone, even when applying 9% – 12% Cr steels or single crystal Nickel alloys, because physically determined boundaries are being reached. Because of the rise in the live steam temperature those components with the highest thermal load on the steam turbine side have to be cooled as well, since the prohibitive costs and production difficulties mean that applying Nickel base alloys in these areas can be problematic. At the same time, the efficiency and the life span of the low pressure steam turbines can be increased by improved water extraction mechanisms. These improvements will only reach their full potential if the components in the gas and steam turbine cycles are tuned optimally onto each other^[2].

2 Solutions

The challenges arising from the formulation of the fundamentals for the innovative design of the thermally and mechanically highly loaded components in combination with an optimal process configuration can only be mastered by the joint efforts of fluid flow experts, structural

engineers, materials' scientists and production engineers (cf. Fig. 1).

From a thermodynamic point-of-view, the increase in efficiency for a complete power plant process can be achieved by increasing the difference between the maximum and minimum temperature within the process. This means that an increase in the steam and gas turbine inlet temperatures is pursued as a contribution to the efficiency increase, but also that the cold end should not be neglected either.

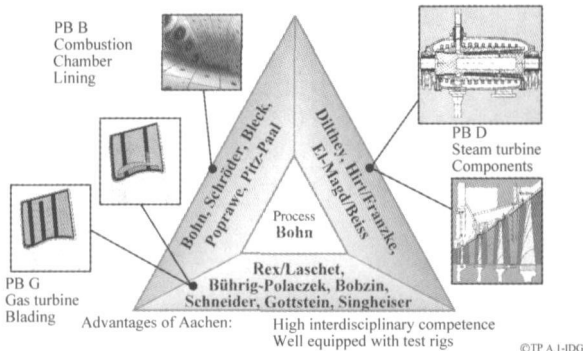


Fig. 1 Project partners within SFB 561

2.1 Gas turbine technology

With the gas turbine in particular, it shows that the amelioration of the structural materials by itself will not suffice to handle the high temperatures prevailing in the working fluid.

Only by intensively cooling the thermally highly loaded components, like the vanes and blades in the first stage of the gas turbine, temperatures close to or even above the melting point of super alloys become possible. Over the last decades cooling has evolved from convection over impingement to film cooling. The next step in this chain is a cooling system that brings the advantages of an open cooling system while minimising its main disadvantage, i. e. the “loss” of compressor air to the cooling system (Figure 2).

With open cooling systems, like current state-of-the-art film cooling, the interaction between coolant and hot gas can lead to an increased level of turbulence and locally overheated surfaces, significantly reducing the life-span of turbine blades. Moreover, the discrete nature of the cooling holes leads to an excessive amount of coolant being introduced into the system in order

to guarantee a closed cooling film. Therefore, effusion cooling in the gas turbine, as the first step in the realisation of transpiration cooling using open porous structures, is one of the main foci of the SFB. Effusion cooling can provide full-coverage cooling using much lower amounts of coolant than film cooling, due to the much smaller holes that are being used here. The effectiveness of this cooling can be raised by distributing the cooling holes on the surface according to the local demand. It can be increased even further by contouring the holes (Figure 3). These holes are manufactured using laser-drilling through the three layer system of TBC, bondcoat and substrate.

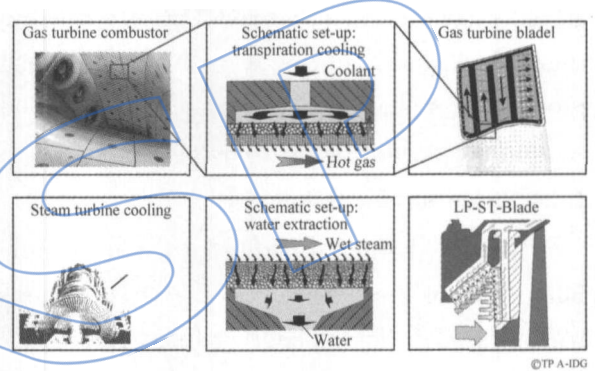


Fig. 2 Application of open porous structures in gas and steam turbines

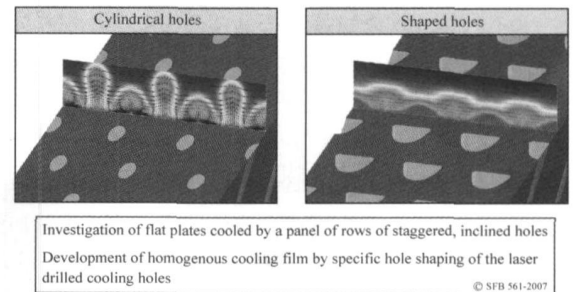


Fig. 3 Homogeneous cooling film due to hole contouring

The coolant is fed through the structural material to a cavity underneath a porous inter-layer. This layer is protected against a direct contact with the hot gas by a permeable TBC, through which the coolant leaves the component as full-coverage cooling. The outer layer of a future gas turbine blade could be conceived similarly to the combustion chamber lining.

Two different concepts for realising this

cooling concept are pursued within the SFB: both laser drilled multi-layer systems and coated open porous metallic foams can be applied, depending on the prevailing boundary conditions. These will be discussed in turn in the section devoted to the results of the SFB.

A further rise of the gas turbine inlet temperature with almost $150\text{ }^{\circ}\text{C}$ would be possible by applying thermal barrier coatings on the basis of ZrO_2 , but this potential can currently not be unlocked completely because the life span of these coatings cannot be predicted with certainty. This means that the coolant has to compensate for a possible failing of the TBC. Within the SFB a novel approach to this problem, whereby a graded layer of bondcoat and TBC is applied to the blade surface, is being tested. This approach promises to reduce the spalling of the TBC and to improve its life span considerably.

2.2 Steam turbine technology

Cooling thermally highly loaded steam turbine components using grid sheets structures with a throughflow is another focus of the SFB (Figure 4). These cooling structures consist of two sheets and one woven wire mesh interlayer and facilitate using live steam at 30 MPa and $690\text{ }^{\circ}\text{C}$ without the need to manufacture the casing from Nickel base alloys. The woven wire mesh boosts the turbulence in the coolant and therewith the heat transfer in the grid sheets. At the same time, the wire mesh ensures the mechanical integrity of the cooling structure because it takes on the forces that result from operation. This sandwich material is manufactured using capacitor discharge welding. Because of the limited size of the capacitors, single grid sheets have to be combined to larger structures by laser beam welding when applied to steam turbines. After welding, the grid sheets have to be bent into curved shapes, which remains a topic for further research due to the layered nature of the grid sheets, which includes many welds. The grid sheets have to be vigorously tested, not only with regard to their low cycle fatigue, but also

with regard to their tensile strength. Critical is a possible spot weld failure in the grid sheets, which is therefore investigated vigorously within the SFB.

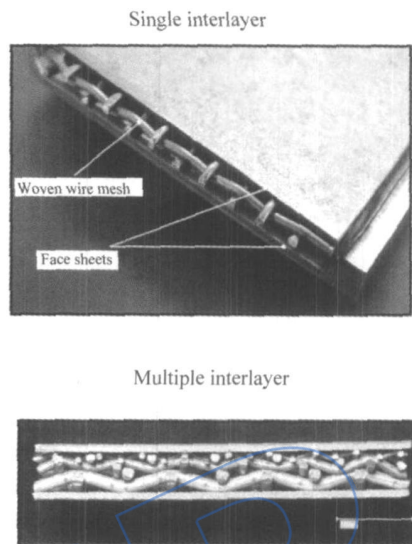


Fig. 4 Grid sheets with single and multiple interlayer

2.3 Project coordination

The phases in the development of the technologies in a joint research project of this size have to be projected in advance (Figure 5). In the first phase, the theoretical possibility of manufacturing open porous structures for power plant applications could be proven. In the second phase, the manufacturing of these structures was started, with an emphasis on real component geometries. The third phase focused on the next step towards application, i. e. more complex models for a more detailed depiction of the porous structures in numerical simulations, capable of making more precise predictions on the cooling effectiveness of the structures. The experimental investigation of first test specimens for the novel cooling techniques was started and demonstrator parts were manufactured. The fourth phase, which is currently under way, will see the manufacturing and testing of graded structures. This testing will happen under or close to real engine conditions. It is planned to start several transfer projects in which the results from the SFB will be shared with industrial partners during this phase as well.

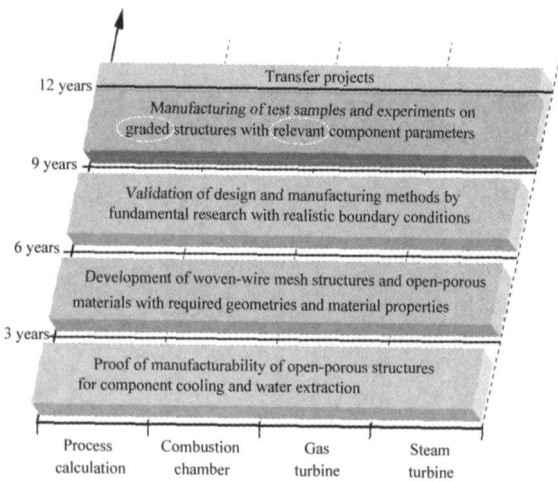


Fig. 5 The "road map" of SFB 561

3 Results

3.1 Gas turbine technology

Although a considerable amount of work remains to be done before the set goals are reached, the following results have been attained so far:

1) The ReactionSlipFoamSintering(RSFS)-process has been developed for the manufacturing of open porous structures for combustion chamber linings, (stator) blades and the removal of water from the low-pressure turbine. The goal is to influence the pore structure and

distribution by controlling the process parameters, especially with regard to the sintering process, as well as to provide a model depicting the foam. Several test specimens for experiments on the heat transfer properties have been manufactured. Laser welding the foams onto the structural material remains a challenge for the current phase of the project. The difficulties with manufacturing a weld that can withstand a continuous thermal load of 1000 °C over a period of 10, 000 operating hours are mainly due to the porous structure of the foam. This leads, depending on the pore distribution, to a locally different heat flux into the material (Figure 6) ^[3].

2) Laser drilling is used for manufacturing the cooling holes in the coated multi-layer system. The procedure chosen succeeds in driving the molten substance from the drilled hole ^[4]. Depending on the diameter of the hole and the thickness of the material, either a single pulse laser, percussion drilling or trepanning is used.

3) A manufacturing process for incorporating Al₂O₃-fibres in the NiAl matrix of the load bearing core of a future gas turbine blade has been developed. The fibres receive a coating of hexagonal Boron Nitrite in order to maximise the adhesion between the fibres and the matrix.

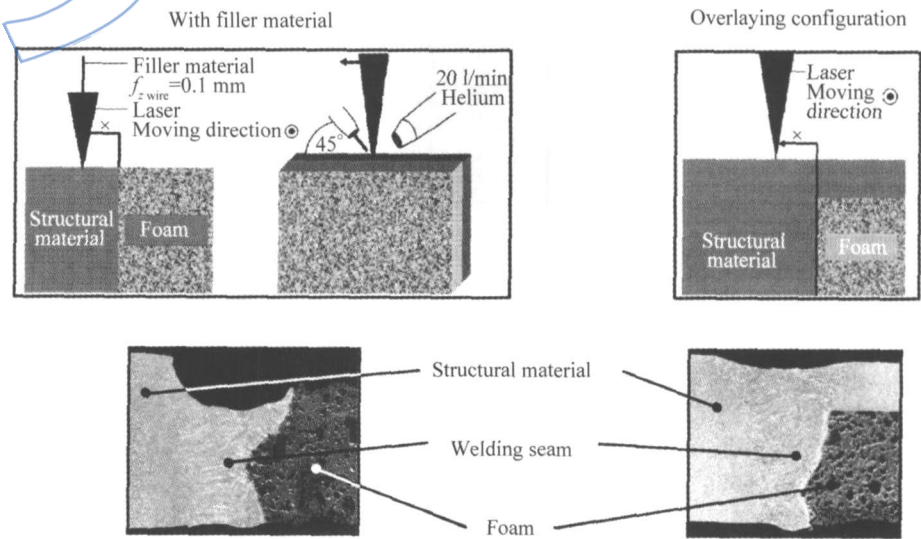


Fig. 6 Application of open porous structures in gas and steam turbines

4) Comprehensive approaches in the development of new ceramic casing moulds and adequate core materials could be pursued in the area of investment casting. This resulted in the production of a manufacturing demonstrator at the end of the third project phase in 2007.

The components that have been manufactured have to be tested extensively before they can be applied to real machines. Although the complete testing will be beyond the scope of the SFB, the theoretical applicability can be proven by tests with boundary conditions (e. g. temperature) close to real engine conditions. These tests also provide valuable results for the validation and refinement of the numerical models of the porous structures. With the help of these models

1) stationary and transient operating conditions

2) the interaction of hot gas and coolant

3) the combined aerothermal calculation of flow and solid body

4) the equivalent material properties of porous structures can be described in great detail. The parameters for the manufacturing of the novel structures are determined on the basis of these models.

By using trepanning for drilling the inclined

cooling holes, precise contours can be achieved in the TBC while keeping a cylindrical inlet geometry in the substrate. To avoid under cutting the TBC while drilling the inclined cooling holes, a process for applying a TBC to already drilled structures has been developed. These holes are kept open by emitting Argon through them during the application of the TBC. This means, unfortunately, that the contour of the holes cannot be controlled as precisely as when drilling directly through the three layer system. Therefore a processing step has to be added, in which the hole contour is improved in accordance with the requirements resulting from the aerothermal calculations of the flow field using ps-radiation (Figure 7) [4-5].

The application of these laser-drilled holes for effusion cooling leads to a full-coverage cooling of the parts. Figure 8 shows the results from Reynolds-averaged Navier Stokes (RANS) calculations of the flow over plane, convex and concave plates [6]. Holes with two differently shaped contours in the TBC have been investigated. The ratio of coolant to hot gas, the blowing ratio, was varied in order to determine the cooling effectiveness of the different configurations. The diagram shows the minimum cooling effectiveness in metallic substrate of the three-layer

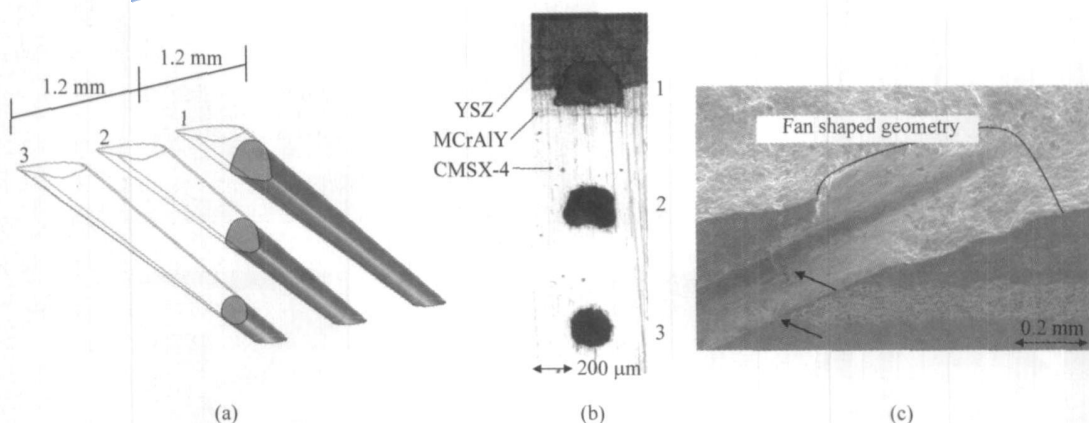


Fig. 7 Laser drilling of effusion cooling holes through multilayer systems

(a) Schematic cross section of 3 shaped holes;

(b) Trepanned shaped holes (light microscopy), process gas oxygen $p_t = 1.2$ MPa, pulse duration $t_p = 0.5$ ms, pulse energy $E_p = 0.64$ J, pulse frequency $f_p = 20$ Hz;

(c) Longitudinal section of the hole entrance with schematic illustration of the fan shape geometry (YSZ, MCrAlY, CMSX-4, sample chemically etched, SEM), same process parameters as (b)).

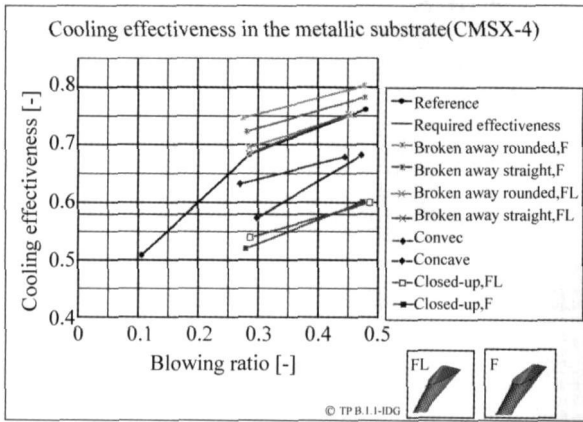


Fig. 8 Cooling effectiveness in the substrate layer

system. This follows from process calculations discussed later on (innovative process calculation). The cooling effectiveness depends on whether the plates are plane or curved: for both the convexly and concavely curved plate the effectiveness diminishes significantly. The convexly curved plate suffers from the lift-off of the cooling film from the surface. The effectiveness of the cooling on the concavely curved plate decreases because the hot gas is pressed against the plate due to the pressure profile in the main flow. In the open literature, the main focus is on perfectly shaped holes have been discussed, but the effect on the cooling effectiveness due to deviations from this geometry that occur during either manufacturing or operation have to be quantified as well. Prior to application of the cooling technique in real engines, the possible breaking away of the TBC caused by undercutting and the closure of a cooling hole through dust particles are to be investigated^[7].

The RANS models can perform the calculations quickly and are, as yet, the only ones capable of calculating both the fluid and the solid in a conjugate calculation, but the model of the flow, especially the turbulence, is not very refined. Above all, the choice of turbulence model may influence the outcome of the calculations. Therefore it has to be proven that the applied model depicts the physical phenomena behind the interaction of coolant and hot gas with sufficient accuracy. The hot gas ingestion in the cooling

hole is a particularly important issue in this respect.

The RANS calculations were verified using the results from advanced large eddy simulations (LES) of a single cooling hole. These simulations were in turn validated by particle image velocimetry (PIV)-measurements. The limitation to one cooling hole was determined by the fact that the LES simulations are much more accurate than the RANS calculations, but at the same time take much more computational time to converge. The predicted interaction phenomena for one hole are virtually the same for RANS and LES (Figure 9). The final validation of the RANS calculations will take place in the current, concluding phase, when the interaction between several cooling holes will be investigated using LES as well^[8,9].

The calculation of hundreds or even thousands of cooling holes will not be feasible in the foreseeable future. Therefore the SFB tries to develop a methodology for determining the equivalent material properties of porous materials using the homogenisation technique^[10-11]. These equivalent properties are implemented in a conjugate flow solver that simulates large arrays of effusion cooling holes.

The open porous metallic foams for combustion chamber linings are manufactured with the Reaction Slip Foam Sintering process. By systematically investigating the variations in dispersant, solvents and expanding agent proportions as well as the sintering temperature, parameter combinations leading to a certain, well-defined porosity can be found. The RSFS process leads to foams with large primary pores that are connected by smaller, secondary, pores. Computer tomographic images show that cell walls form a coherent, interconnected structure, providing strength to the foam (Figure 10). The distribution of the pores is relatively homogeneous. Numerical models describing the permeability and pore distribution have been developed. These models can provide a detailed information on the foam properties, including their heat conductiv-

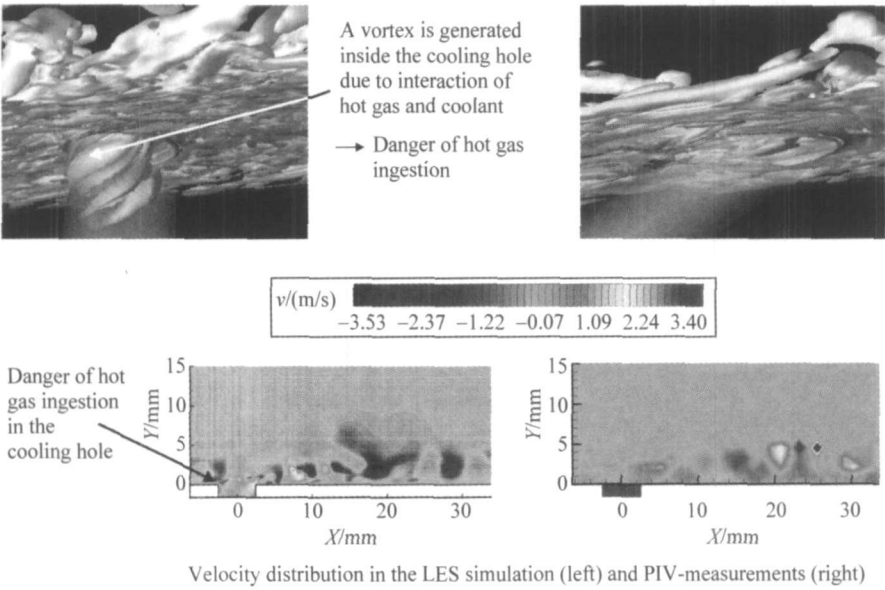


Fig.9 Visualisation of the vortex structures at the cooling hole exit

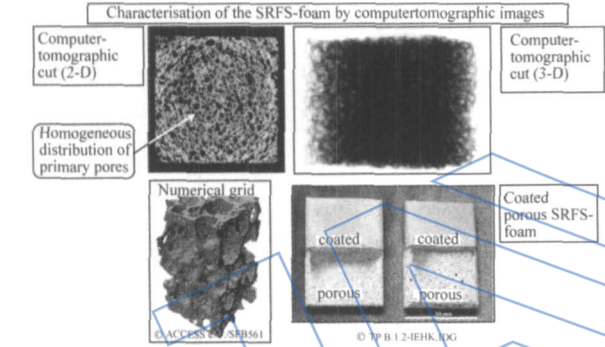


Fig. 10 Characterisation of the metallic RSFS foam
 ty and the pressure loss over the foam^[12-13].

It has been proven that the application of a TBC on the metallic foams is possible. The ZrO_2 -TBC is deposited on an MCrAlY-bondcoat with atmospheric plasma spraying (APS). The porous sublayer will provide a homogeneous distribution of the coolant before it is emitted through the opened TBC into the hot gas flow. The permeability of the closed thermal barrier coating will be ensured by drilling cooling holes through the covering layers into the porous foam [4, 14-15].

When using only open porous materials, though, the creep resistance of the gas turbine blade cannot be guaranteed. Therefore, a new concept is pursued, in which a load bearing core made of NiAl with inlaid ceramic fibres supports a thin outer contour. The core with Al_2O_3 -fibres

is manufactured with diffusion welding. At low temperatures, the NiAl is extremely brittle, necessitating a weak connection between the ceramic fibres and the NiAl, because otherwise the NiAl may crack. At high temperatures, the NiAl is ductile, but needs to be supported by the Al_2O_3 -fibres. Therefore the fibres are coated with a MAX-phase (hBN) prior to the welding and then with NiAl-FG75.

MAX phases are compositions of metal, a intermediate material and carbon. This lends the composite strength and ductility, but also the temperature stability normally associated with ceramics. The chemical composition of the MAX-phase interlayer is of crucial importance for the mechanical connection of the fibres and the NiAl-matrix. An optimisation of the composition of the chemical systems is at present still necessary, although significant improvements have been made in the first three project phases^[16-17]. At present, the cores are welded at 1300–1350 °C and pressures of up to 30–40 MPa for over 2 hours^[18-21] in order to achieve a pore free composite.

The outer contour will be provided with laser-drilled fields of cooling holes and a TBC. The cooling hole distribution will vary over the blade surface, depending on the temperature and

pressure level as well as the flow field over the blade. With this concept, the temperatures inside the blade can be increased substantially, and the required cooling fluid decreased proportionally, compared to current materials.

All of the developments mentioned above serve to realise the vision of the SFB as depicted in Fig. 11.

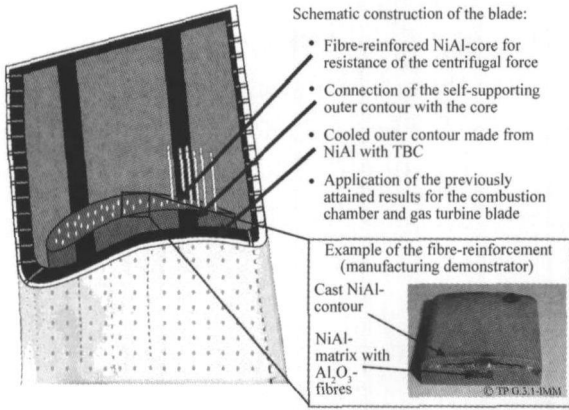


Fig. 11 Vision of a future gas turbine blade

3.2 Steam turbine technology

The grid-sheet structures for convective cooling of the thermally highly loaded casing of the high and intermediate pressure steam turbines are manufactured using capacitor discharge welding. First, segments consisting of sheets and woven wire meshes are joined. The connection between the wire meshes and the sheets has to be of excellent quality, because this structure has to withstand the forces resulting from the prevailing pressure difference between cooling and live steam under an operating temperature of ca. 700 °C as well as the different loads resulting from start-up, shut-down and load changes (low-cycle fatigue). The grid sheets serve to boost the turbulence in the coolant flow and thereby the heat transfer from the structure into the flow. In order to influence the heat transfer and the pressure losses in a controlled manner, graded structures are being manufactured during the final project phase, see Fig. 5^[22-23].

The size and the geometric complexity of the grid-sheets structures manufactured by capacitor-discharge welding is limited due to causes

arising from production technology (limited size of the capacitors) and practical considerations. The segments are joined by laser welding to ensure that sufficiently large grid sheets for the cooling of turbine parts can be provided. The welded structures are then adjusted to the contour of the structure using rolling and deep drawing. The spring back of the grid-sheets has to be taken into account here and remains a topic for further research due to the layered nature of the grid-sheets, which includes many welds^[24].

As steam turbines are operation for decades, the mechanical strength of the applied grid-sheet structures has to be proven. On the one hand the quality of the welds is checked with thermographic, non-destructive methods, on the other hand the creep resistance has to be proven and weld failure due to LCF has to be investigated. But also with regard to their tensile strength is a topic that is investigated with great care. The characterisation of the deformation and failure of the grid-sheets is an important last step towards the proof of mechanical strength (Figure 12)^[25-26]. Therefore, experiments over a temperature range from room temperature up to operating temperature and with loads transverse and along the wire mesh are conducted using several material combinations.

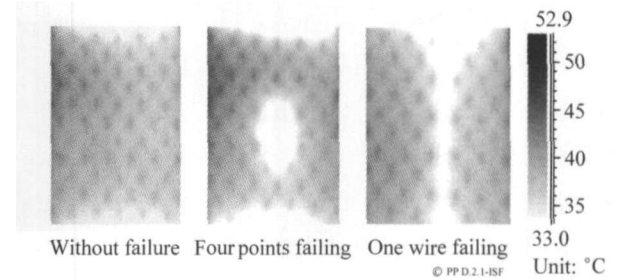


Fig. 12 Thermographic investigation of grid sheets

The cooling effectiveness of these grid-sheets is also investigated numerically, first results can be found in Ref. [27].

The foams for the water extraction in steam turbines are manufactured using the same ReactionSlipFoamSintering (RSFS)-process as those applied for gas turbine cooling. The challenges for joining these foams to the structural material

are therefore the same. Because the thermal load on these foams is negligible, no thermal barrier coating is applied, but at the same time this increases the requirements on the surface quality of the weld.

In order to optimise the extraction, the location of the saturation line in the last stages of low pressure steam turbines has to be determined as accurately as possible. With this information, as well as information on the thermodynamic and kinematic losses, the foams can be graded to maximise the amount of water extracted from the turbine and minimise the amount of extracted steam. Results from both the numerical and the experimental research of the Institute of Steam and Gas Turbines in this area are therefore applied in the SFB.

3.3 Innovative process calculation

The contributions of the different project partners towards the goal of achieving a total efficiency of 65% is monitored using an advanced process analysis tool^[28]. The efficiency increase due to the novel cooling technologies and the innovative materials' solutions is calculated using a reference combined cycle power plant in Tapada do Outeiro, Portugal. This plant was built only a decade ago and it has the same features as currently build combined cycle power plants: a three-pressure heat recovery steam generator with single reheat and a single-shaft configuration of the gas and steam turbine. The total efficiency is just short of 58%. The depiction of this plant in the process analysis tool is detailed enough to allow for an evaluation of the advances on both the gas and the steam turbine side, to analyse the strengths and weaknesses of the pursued solutions and to give feedback to the project partners with regard to future goals. These goals are also discussed with several experienced counsellors from industry and the emphasis for further work can be specified on the basis of these analyses and discussions.

After three project phases, an increase in total efficiency of a combined cycle power plant to 64.2% has been achieved. Figure 13 shows

the contributions made by effusion cooling in the gas turbine, the rise in the live steam parameters, the water extraction and the material development. The size of the contributions was calculation using the aforementioned process simulation tool that also contributes to determining the thermal and mechanical loads resulting from the operating concept.

Because of a further improvement in the technologies, especially the introduction of graded structures, additional potential within the new concepts can be unlocked. A reduction in cooling fluid demand and a rise in the permissible material temperatures will lead to total efficiencies of 65% in power plants from the year 2025.

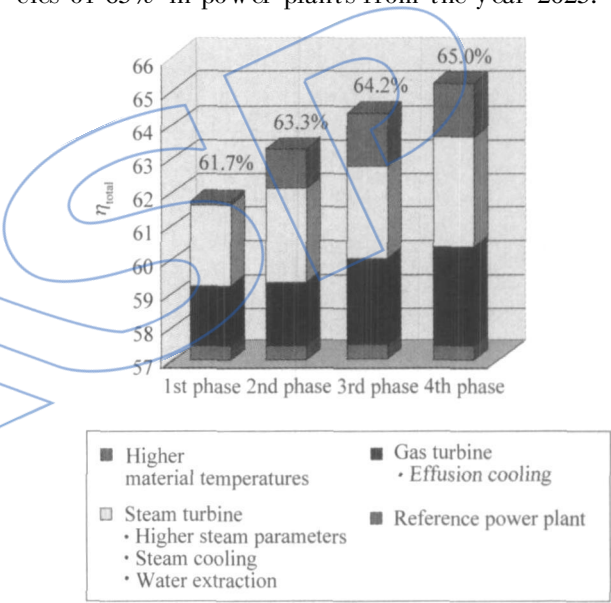


Fig. 13 Contributions of the different developments towards a total efficiency of 65%

4 Summary and conclusion

By the founding of Collaborative Research Centre 561 “thermally highly loaded, porous and cooled multilayer systems for combined cycle power plants” at RWTH Aachen University, the basis was laid for the development of new technologies with which a total efficiency of 65% in combined cycle power plants can be reached in power plants built from the year 2025. Considerable advances towards the development of thermally highly loaded open porous components have been made in fluid dynamics, materials’

science and production technology. In the current, concluding project phase, graded structures will be tested under conditions close to those in the real operating point of advanced turbines.

An efficiency potential of 12% and a CO₂-reduction potential of 15% are possible by the application of the results from the SFB. The potential for future power plants does by no means end with that, because the SFB focuses on the improvement of component technologies and flow technology to decrease the required cooling fluid. This means that, for example through innovative operating concepts, additional potential can be unlocked, which will enable the total efficiency of combined cycle power plants to reach 70%.

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