ABSTRACT

Rapid civilisation development in the last century was driven by the massive consumption of fossil fuels. Very cheap energy sources such as coal or oil have improved the life quality globally, but at the cost of unprecedented greenhouse gasses emission. Taking into account that fossil fuels resources are limited, it should be acknowledged that they need to be replaced at some point with renewable energy sources. This is a very expensive process, but crucial to avoid abrupt shortage of energy supply in the peak of civilization development.

Research presented in this thesis is a part of the project "nCO2PP - Negative CO2 emission gas power plant", which is aimed at sewage sludge gasification and synthetic gas utilization inside the wet combustion chamber (WCC) powering gas turbine. The advantages of such cycle is utilisation of toxic wastes, power generation and carbon dioxide storage, which was initially trapped in the sewage.

Efficiency improvement of heat engines is equally important as sustainable management of energy sources. Based on the thermodynamic description of gas turbine operation (Brayton cycle), inlet temperature increase improves engine efficiency leading to the fuel savings. On the other side, outlet temperature is restricted by the strength of turbine components. Thermal FSI (Fluid-Solid Interaction) method is a proper choice for the analysis of actively cooled gas turbine components, as it offers precise prediction of structural temperature. In contrast to that, separate CFD and CSD analyses are less accurate, which introduces the necessity of wider safety margins and reduction of nominal temperature of heat engines.

The research hypothesis is formulated as follows: "It is possible to describe relationships between thermo-mechanical parameters and changes in composite structure of highly loaded components of gas turbines such as combustion liner. This will take into account the occurrence of such complex phenomena as the transpiration of the coolant through the micropores of the ceramics and evaporation at the inner wall of the combustion chamber. It is also possible to predict the process of damage evolution of ceramic matrix composite (component durability) with known load parameters. Description of such physical mechanisms and phenomenon is necessary to control deterioration effects".

The task formulated in this thesis is original and forms an important step in the design process improvement. The research hypothesis was confirmed using the Thermal FSI method, which enables heat transfer modelling between fluid and solid within one model operating on consistent mesh at interfaces. As a consequence, boundary layer temperature variation influences solid temperature and vice versa. The other element of the research hypothesis confirmation was application of GRI-Mech 3.0 combustion model and DPM (Discrete Phase Modelling) model, which links droplet evaporation (discrete phase) with continuous phase. From the solid side, it was crucial to model composite structure of liner, as it enabled application of Tsai-Wu failure criterion at the later stage.

Presented Thermal FSI approach is of a greater importance when modelling actively cooled components such as combustion chamber, where solid wall is washed simultaneously with cold and hot flow. On top of that, it was proved that consistent mesh at fluid/solid interferences improves considerably analysis convergence, so it should be always used instead of coarse and non-consistent mesh.

Especially important step in the model build was determination of thermal expansion coefficient of CMC (Ceramic Matrix Composite) material in an experimental way. This is a key parameter enabling the proper prediction of thermal stresses, which dominates in structures heavily heated and cooled at the same time. Due to the complex internal structure of CMC liner, measured thermal expansion coefficient is non-linear. It is caused

by the fact, that heat it conducted better along the fibres than through the porous matrix. Additionally, weak contact between fibres and matrix can be easily broken, which adds additional non-linearity into thermal expansion behaviour.

The final result of Thermal FSI analysis is the distribution of Tsai-Wu inverse reserve factor within the domain of CMC liner. Region located at the proximity of flame has Tsai-Wu inverse reserve factor exceeding one. It means that some regions of liner are expected to be cracked, which does not disqualifies the experiment. It should be noted, that presented results refer to the prototype, so project assumptions will be verified at the later stage of the design process. Combustion chamber analysis at the highly loaded conditions is a key requirement from the thermodynamic and economic point of view.

Detailed description of Thermal FSI model geometry, boundary conditions and results was supplemented by deep and wide study of mathematical models. From the CFD (Computational Fluid Dynamics) side this is the turbulence, combustion, water evaporation and porous medium model. From the CSD (Computational Solid Dynamics) side this is the elastic model of isotropic and orthotropic materials (composite). Thermal FSI method integrates CFD and CSD analyses into one numerical model.

It should be highlighted, that CMC material was developed by research institutions as a response to the necessity of having material able to withstand high temperatures like monolithic ceramic, but non-brittle at the same time. CMC material is employed mainly in aerospace and space industry, but it can be found in other sectors as well. Due to the fact that CMC manufacturing methods is a modern technology developed by only few companies worldwide, the experimental data is not easily accessible in the public domain. WHIPOX is a commercial name of CMC material developed by the German Institute of Aviation. Its porous structure was designed to reduce brittleness in the extremely high temperatures, so available publications ignore WHIPOX behaviour in the wet condition. The key innovative element of presented research is the WHIPOX ability to enable transpiration cooling of liners. This application is present in the literature, but it is much less common than mixing enhancement and flame stability methods. Another important subject widely explored in the literature are active cooling systems based on the cooling films application.

The literature review was made inside the appropriate chapters. Presented thesis is based on nine main steps, which were taken to confirm research hypothesis. They are listed below.

1. Verification of research methods is based on Thermal FSI model generation and cross-check of numerical results against experimental data. The first model contains 3D Tay combustion chamber geometry with cold air flow. It was successfully verified based on the axial and circumferential velocity plots at the control section. The second model calculates temperature and pressure distribution at the midspan of internally cooled NASA C3X vane. After the comparison of several turbulence models, it was found that k–ω *SST* model generates most accurate results. For that reason it was employed in the further Thermal FSI modelling (Chapter 3).

2. 3D steady CFD analysis of wet combustion chamber taking into account oxi-fuel combustion of methane, water droplet evaporation inside the flame and transpiration cooling. Based on the cyclic symmetry assumption, geometry was reduced to the 120 sector. The decision about the geometry selection was based on the several parametric models, aimed at mixing intensity maximization and flattening of outlet temperature profile (Chapters 5.7).

3. Liner 3D CSD model generation using CMC material is a key enabler of further component durability analysis. Steady and transient assessments supported the fibres winding angle optimisation and proved that model was built in a robust way (Chapter 5.2-5.4).
4. Experimental assessment of heat expansion coefficient of CMC material in the laboratory of Institute of Fluid-Flow Machinery at Polish Academy of Sciences. This parameter has a key role in the prediction of stress distribution inside the liner, which is heavily heated and cooled at the same time. Measurements revealed, that mon-linear heat transfer coefficient can be interpolated with two constants - one below and one above 100 C (Chapter 5.1).
5. Build and analysis of steady and transient CSD models of wet combustion chamber assembly. In these cases temperature boundary conditions were applied arbitrarily to test model before conversion into Thermal FSI analysis (Chapter 5.5-5.6).
6. Build and analysis of Thermal FSI model consisting both solid and fluid domains is the key element of presented thesis. Thanks to this approach all physical phenomena are coupled with each other, so all of them are taken into consideration in every iteration of numerical solution (Chapter 5.8).
7. Liner temperature comparison between CFD and Thermal FSI models reveals noticeable differences. This is driven by the boundary layer behaviour, which exchanges heat with the wall in the Thermal FSI method (Chapter 5.9).
8. CMC liner durability analysis was performed using Tsai-Wu failure criterion. These results are directly applicable to the prototype durability. However, the more complex model the higher uncertainty of obtained results (Chapter 5.8).
9. Proposal of analysis' method improvement to take into account material properties modification when pores are filled with non-compressible fluid. In such a case liner became stiffer when loaded rapidly, because fluid will not be able to outflow the pore in a very short period of time. As a consequence of that, trapped liquid is able to carry hydrostatic load applied to the pore (Chapter 5.10).