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CFD Analysis of the Heat Transfer and Fluid Flow Around a Low Pressure Turbine Blade

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The present work is focused on the investigation of heat transfer around a low pressure T106 turbine blade. The investigation was performed with the CFD computations which were validated against isothermal experimental measurements from literature. Detailed CFD computations were also performed for conditions including heat transfer for varying values of Reynolds number and turbulence intensity in order to assess their effect on average and local heat transfer coefficient on the low pressure turbine blade. The CFD analysis resulted in the development of new heat transfer correlations for the calculation of the average heat transfer coefficients taking into account the effect of Reynolds number and turbulence intensity. A comparison of these correlations in relation to literature available correlations for flat plate was performed in order to assess their deviation. The comparison indicated that for some cases a significant underestimation, of more than 10 %, of the average heat transfer coefficient can be presented resulting to an overestimation of the cooling air mass flow for turbine blade cooling applications and to a subsequent work loss and thermal efficiency decrease. Finally, the effect of this heat transfer coefficient underestimation on the efficiency and fuel consumption of a two-spool turbofan aero engine was calculated with Gas Turb11 performance analysis software. The results showed that through the use of more accurate heat transfer correlations an increase in core efficiency and a decrease in specific fuel consumption can be achieved.

1. Introduction

The optimization of gas turbine performance is one of the most intense areas of engineering research activities for both environmental and economic reasons. Currently, gas turbine components already operate with noticeable high efficiency, i.e. approaching ~90 % isentropic efficiency for compressors and turbines, Salpingidou (2017a), leaving a limited optimization margin for the achievement of further optimization of the gas turbine thermodynamic performance through optimization of components efficiency alone.

From a strict thermodynamic point of view, the performance of a gas turbine is strongly affected by the turbine inlet temperature value with higher turbine inlet temperature leading to increased gas turbine performance. Since there is always a limit to the maximum temperature that can be sustained by the turbine blades material, cooling techniques are applied on the most sensitive gas turbine parts, such as the turbine blades in order to achieve gas turbine materials endurance and longevity. This cooling is usually achieved through the utilization of a part of the compressor discharge air, which is relatively much colder than the combustion chamber outlet hot gas. The compressor discharge air bypasses the combustion chamber and provides cooling by its circulation, typically, in internal channels in the turbine blades, even though various other cooling concepts can be applied as presented in the work of Bunker (2017). Since the cooling air is not heated and not participating in the turbine expansion the turbine work potential is reduced. As it is evident, the amount of required cooling

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air should not be overestimated and be just enough to offer the right amount of thermal protection to the turbine blades. For the proper selection of the amount of turbine cooling air, the accurate and reliable estimation of the heat transfer coefficient development on the turbine blade surface is of primary importance.
In this respect, open-literature correlations for flat plate under constant heat flux conditions or constant temperature are currently used, usually with some correction factors taking into consideration geometrical characteristics of the turbine blade geometry, in order to calculate the hot-gas side heat transfer and to facilitate the evaluation of the necessary cooing air mass flow. However, since the turbine blade geometry deviates strongly from the flat plate geometry, it is expected that a significant overestimation (or even underestimation in case no safety factors are used) of the cooling air amount can be calculated resulting in degradation of the gas turbine performance. As a result, the derivation of new more appropriate, conditions sensitized, heat transfer correlations for the estimation of the heat transfer coefficients on the turbine blade surface can provide useful contributions in engineering efforts targeting the optimization of gas turbine performance. The use of validated CFD computations can strongly support these efforts since they can provide a detailed inside look in the direct vicinity of the turbine blade surface, in regions which otherwise cannot be cost-efficiently or time-efficiently approached in conventional experimental measurements.
Such an effort is presented in this work where the investigation of the heat transfer around a low pressure T106 turbine blade is attempted with the use of CFD computations. The CFD computations were performed with the use of OpenFoam open source CFD software while for the turbulence modeling the low-Reynolds Shear Stress Transport model, Menter (1994), was applied. The CFD model results were validated in relation to experimental measurements for isothermal conditions which were carried out in the Laboratory of Fluid Mechanics and Turbomachinery of Aristotle University of Thessaloniki and are presented in Sideridis et al. (2011). At the final part of this work, CFD computations were performed for conditions including heat transfer for varying values of Reynolds number and varying turbulence intensity values so as to calculate their effect on the heat transfer coefficient on the low pressure turbine blade. The results analysis provided the identification of regions operating with favorable heat transfer conditions and regions where decreased heat transfer was presented. Additionally, new dedicated heat transfer correlations for the calculation of the average heat transfer coefficients were derived taking into account the effect of the inlet Reynolds number and turbulence intensity. These new heat transfer correlations can be used for a more accurate determination of the cooling air mass flow requirements, resulting in a more productive trade-off in the utilization of the gas turbine compressor air resulting in gas turbine efficiency increase, reduction of fuel consumption and subsequent decrease of fuel pollutants emissions.

2. CFD computations

The investigation of heat transfer around a low pressure T106 turbine blade was performed with the use of CFD computations. For the pre-processing stage the freely accessible Salome platform (2016) was used for the creation of the computational grids. Regarding the CFD solver, the CFD computations were performed with the use of OpenFoam version 4.0 (2016) open source CFD software, as implemented by CFD Support (2018) with the use of the compressible solver rhosimpleFoam, while for the turbulence modeling the low Reynolds Shear Stress Transport model, Menter (1994), was applied. The post-processing of the CFD results was performed with Paraview (2016) software. The selected roadmap for the CFD computations, pre-processing, CFD solver and post-processing, with open source tools, is similar to the one presented in the work of Medina et al. (2015).

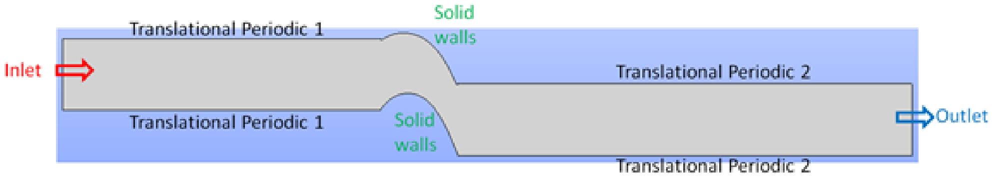


Figure 1: The computational domain with the applied boundary conditions

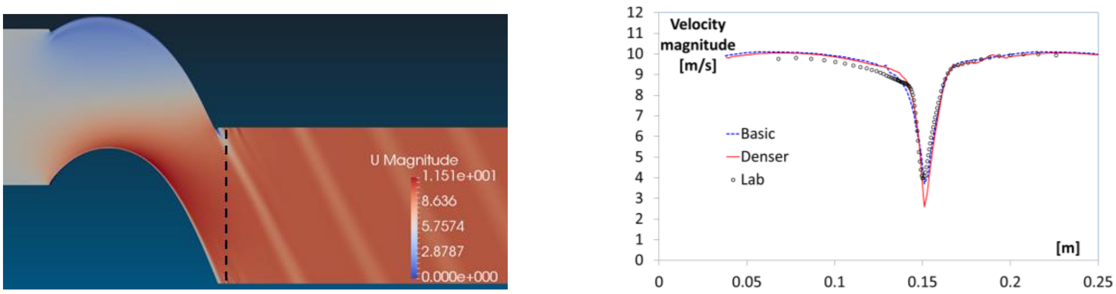
The 2D computational domain, the boundary conditions and the computational grid are shown in Figures 1 and 2. In the first part of the analysis CFD computations were performed for two computational grids in order to assess the grid independency of the CFD results. The basic grid was consisting of ~100 K computational points and the denser computational grid was consisting of~300 K computational points which was the one finally used for the CFD analysis. The CFD results were grid independent as shown in Figure 3b where a comparison with the experimental data of Sideridis et al. (2011) is shown.

a) b)

Figure 2: Typical views of the 2D computational grid (~300,000 computational nodes) a) general view, b) enlarged view on the turbine blade suction side

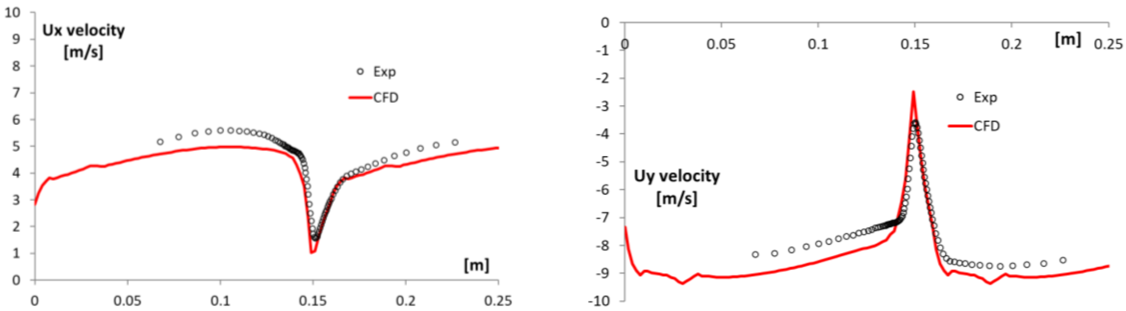
3. Results and Discussion

The CFD results were validated in relation to experimental measurements for isothermal conditions presented in the work of Sideridis et al. (2011) which are summarized in Table 1. Typical view of the velocity field from the CFD results is shown in Figure 3 where the region of the T106 low pressure turbine wake is clearly presented. The comparison is presented in more detail in Figures 4a and 4b, where a close agreement between the numerical results and the experimental measurements of Sideridis et al. (2011) is shown.



a) b)

Figure 3: Velocity magnitude results isothermal case) a) distribution around the turbine blade and b) comparison with experimental data for the two grids (basic and denser right after trailing edge) along dashed line



a) b)

Figure 4: Comparison between CFD computations and experimental results a) Ux velocity and b) Uy velocity

After the comparison with the isothermal experimental measurements, CFD computations were performed for flow conditions including heat transfer. The selected conditions are presented in Table 2, and are based on the suggestions and conclusions presented in the works of Choi et al. (2004) on turbulence and Salpingidou et al. (2017b) on blade cooling.

Table 1: Boundary conditions for the isothermal CFD computations (same as Sideridis et al. (2011))

Boundary condition	Details
Inlet	Ux=4.312 m/s, Uy=3.333 m/s, Turbulence intensity level=1.8 %, Length scale selected equal to 0.025 m, Static temperature set at laboratory conditions
Outlet	Static pressure set at laboratory conditions
Solid walls	Adiabatic stationary walls

Table 2: Boundary conditions for the heat transfer CFD computations

Boundary condition	Details
Inlet	Mass flow modified to achieve Reynolds number from ~10,000 to ~90,000 Turbulence intensity equal to 5% and 15%, length scale selected equal to 0.025 m Static temperature set at 1,250 K
Outlet	Static pressure set at constant value
Solid walls	Fixed temperature gradient equal to -50,000 W/m^2

Regarding the selection of blade walls heat transfer conditions there are two basic possibilities; to apply fixed temperature or constant heat flux (fixed temperature gradient) conditions. In reality, neither of the two conditions can capture 100 % the operational heat transfer conditions due to differences in the internal cooling flow heat transfer, Misirlis et al. (2019). Since the turbine blade temperature is expected to vary strongly in real operational conditional conditions the fixed temperature gradient assumption was selected as more appropriate. In order to assess the effect of Reynolds number and turbulence intensity on heat transfer, the local heat transfer coefficient was calculated using Eq(1). Typical results of the heat transfer distribution on the blade suction and pressure sides are shown in Figure 5, which are corresponding to turbulence intensity value equal to 5 %. The results of Figure 5 were then used to calculate the average heat transfer coefficient on the turbine blade suction and pressure sides and are presented in Figure 6. From the values of Figure 6, new correlations in the form of Eq(2) have been derived for the heat transfer coefficient for the turbine blade suction and pressure sides.

$$h_{local} = \frac{\dot{q}}{T_{inlet\ mean} - T_{local\ wall}} \tag{1}$$

where

h_{local} the local heat transfer coefficient [W/ (m^{2}K)], $\dot{q}$ the local heat flux [W/m^2]

$T_{local\ wall}$ the local wall temperature [K], $T_{inlet\ mean}$ the inlet temperature [K]

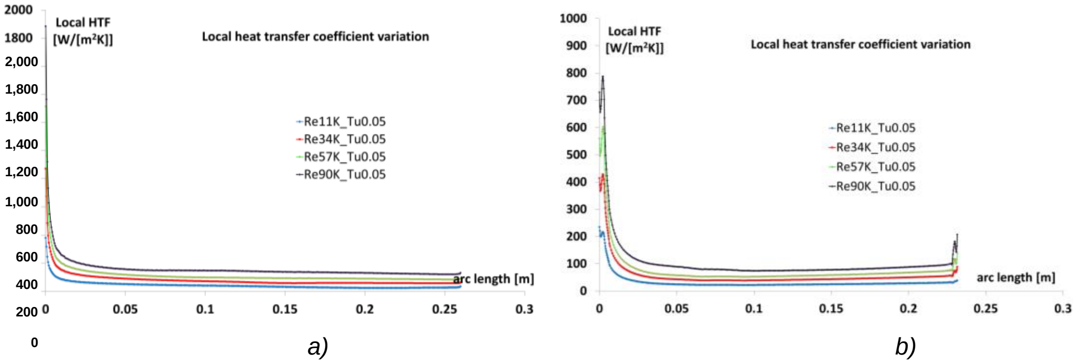


Figure 5: Local heat transfer coefficient for turbulence intensity equal to 5 %, a) suction side, b) pressure side

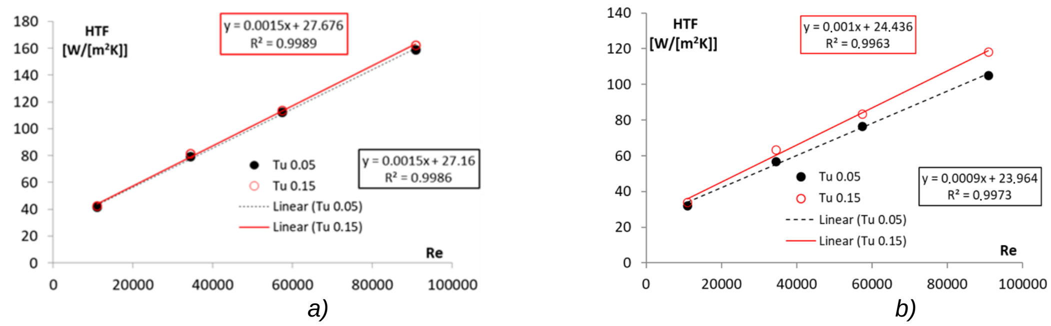


Figure 6: Average heat transfer coefficient (HTF) in relation to Reynolds number and turbulence intensity a) suction side, b) pressure side

$$h_{average} = \mathrm{a\ Re + b} \tag{2}$$

where

a, b calibration coefficients depending on turbulence intensity and blade side from Figures 6a and 6b
Re Reynolds number based on inlet flow conditions and blade length
As a next step, the average heat transfer coefficients on the overall T106 blade geometry CFD results were compared with open literature correlation regarding heat transfer on flat plates for fully turbulent flow conditions following the suggestions of Cunha (2020). The comparative results are presented in Figure 7. As can be seen, in Figure 7a, the CFD results follow a similar trend to the results of the flat plate correlation. The deviation, which is presented in Figure 7b as a function of Reynolds number, can be incorporated in an adapted form of the flat plate correlation by the adoption of a shape factor parameter, similar to the approach presented in the work of Misirlis et al. (2019). The deviation is more important for lower Reynolds number conditions, where a significant underestimation of the heat transfer coefficient is presented which can be as high as 50 %.

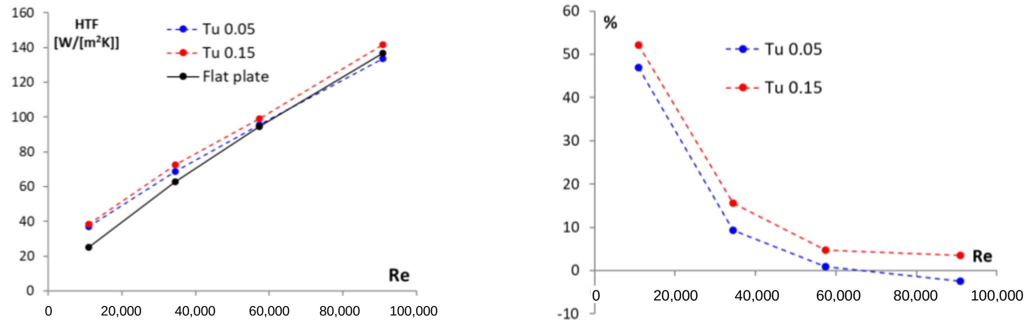


Figure 7: Heat transfer coefficient vs flat plate correlation comparison, a) average value, b) deviation percentage

At the next step, in order to assess the effect of the deviation of the heat transfer coefficient in the turbine blade heat transfer calculation, in relation to flat plate correlation, the previously developed surrogate model for turbine blade cooling calculations for aero engine applications, presented in the work of Misirlis et al. (2019), was used. In this surrogate model, a conservative deviation value of -10 % was considered for the turbine blade external side heat transfer coefficient, indicating that the flat plate correlation was underestimating the heat transfer coefficient by 10 % in relation to the T106 correlation. The results showed that a 10 % underestimation of the heat transfer coefficient on the external T106 side results in a ~7 % overestimation of the required cooling mass flow (by assuming all other turbine blade cooling technology parameters and conditions are constant). The effect of the required cooling mass flow overestimation was assessed in GasTurb 11 (Kurzke, 2011) gas turbine analysis software, for a two-spool turbofan aero engine (pressure ratio=~17, maximum cycle temperature = 1,450K) which resulted to an increase of core efficiency of ~0.2 % and a decrease of specific fuel consumption of ~0.1 % by considering the 7 % decrease of the required mass flow on the high pressure turbine.
From the CFD results the following observations are derived:

- The increase of Reynolds number results to significant increase of local and average heat transfer coefficients. Turbulence intensity increase results to a much more limited increase of both local and average heat transfer coefficients. This increase is more intense in the pressure side.
- At the suction side, in all cases, significantly higher heat transfer coefficients are presented near the T106 leading edge where the velocity and thermal boundary layers are not yet fully developed and are still limited in height. Low thermal resistance values and favorable heat transfer conditions are presented. These increased heat transfer coefficients are reduced after the T106 leading edge and are approaching an almost constant value (per case) near the T106 trailing edge as the boundary layers are developed, reducing the heat transfer coefficient. A similar pattern is also developed in the pressure side for all cases.
- The T106 suction side develops higher local and average heat transfer coefficients than the ones of the pressure side. The developed local heat transfer coefficient patterns are similar qualitatively to the ones shown in the work of Choi et al. (2004) for similar conditions.

4. Conclusions

New correlations have been derived through which the average heat transfer coefficient on both suction and pressure sides can be calculated as a function of Reynolds number and turbulence intensity.
The comparison of average heat transfer coefficients on the T106 blade shows a significant underestimation of the average heat transfer coefficient for low Reynolds number values when flat plate correlations are used. The deviation percentage is significantly affected by turbulence intensity values.

The underestimation of the heat transfer coefficient can result to an overestimation of the cooling air mass flow for turbine blade cooling applications. As a result, an unnecessarily higher than required cooling mass flow might be used for covering the turbine blade cooling needs resulting in a subsequent work loss and a thermal efficiency decrease.
Further investigations are planned to be performed in future research activities which will include the effect of flow angle and the use of more advanced turbulence models targeting the derivation of more accurate dedicated correlations for heat transfer coefficients. These correlations will provide a more accurate heat transfer calculation resulting in a more refined and conditions-sensitive calculation of turbine blade cooling demands and a more productive utilization of the cooling air targeting gas turbine efficiency increase.

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