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Aerothermodynamics of tight rotor tip clearance flows in high-speed unshrouded turbines☆

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HIGHLIGHTS

- Publication on the thermal effects of tight gaps in rotating fluid machinery.
- Tight clearances (0.1% of the airfoil height) revealed novel reversed flow topology.
- Heavily altered thermal field due to increased importance of the viscous effects.
- Identified optimal clearance height for suction side heat load.
- Accurate prediction of the adiabatic efficiency through isothermal simulations.

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ABSTRACT

The inevitable clearance between stationary and rotating parts in any fluid machinery gives rise to leakage flows, which strongly affect the overall performance of the machine. In modern gas turbine engines, the existing gap between the rotor airfoil tip and the shroud is responsible for about one third of the total aerodynamic losses. Additionally, this leakage flow induces fierce unsteady heat loads onto the rotor casing and provokes significant thermal stresses at the airfoil tip. One can attempt to curtail these detrimental effects by running tight clearances; however, the meager number of publications on this topic presents an obstacle to exploiting the design opportunities.

This paper presents the outcome of an extensive numerical investigation of a high pressure turbine stage operating at engine-representative non-dimensional parameters (Reynolds and Mach number, temperature ratios). RANS calculations were performed using the Numeca FINE/Turbo suite, adopting the $k-\omega$ SST turbulence model to investigate the aerodynamic and heat transfer characteristics in the tip region. Five clearances, ranging from 0.1% to 1.9% of the rotor channel height, were simulated at adiabatic and isothermal ($T_{total,in}/T_w = 1.57$) conditions. The detailed flow analysis revealed an unexpected aerodynamic flow topology at tight clearances ($h/H < 0.5\%$), characterized by a reverse flow over a significant part of the tip gap region. The heat transfer on the airfoil tip, shroud and near-tip regions was examined in detail, with emphasis on the different driving phenomena. This elaborate numerical study provides a deeper insight into the complex aerothermal physics of leakage flows occurring for tight clearances in a high-speed environment relevant to any fluid machinery design and analysis.

1. Introduction

The tight clearance in between two mechanical components offers various aerodynamic advantages to regulate mass flows (such as control valves) or to enhance the mixing effects (e.g. atomizers). In turn, heat transfer aspects within such narrow passages are vital to develop novel miniaturized heat sinks or to assess the thermal phenomena inside slotted coaxial rotating shafts [1,2]. Leakage flows, encountered in many mechanical machines, are the prime source of aerodynamic losses with a consequent performance drop (e.g. reciprocating engines [3]) and may provoke severe

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thermal loads onto the side surfaces [4]. The abatement of the detrimental effects demands for enhanced sealing methods and compels to run at tighter gap sizes without deteriorating the mechanical integrity and reliability of the machine.

In gas turbines, the pressure difference between both sides of the rotor blade forces a portion of the flow to travel over the tip through the clearance gap, giving rise to a leakage jet and a leakage vortex. The cross flow inside the tip gap generates fierce unsteady heat loads onto the rotor casing and severe thermal stresses in the blade tip; consequently, the aerothermal issues have been the subject of many noteworthy experimental and numerical investigations in the past [5]. Several tip design approaches have been proposed [6] to mitigate tip leakage effects at the behest of the turbine durability [7] and aerothermal performance improvement. Squealer tips adopting rims are proven to enhance the aerodynamic performance [8] and reduce the average heat loads [9] compared to a plain tip. To further increase the efficiency, a winglet shaped tip [10] can be considered as a suitable alternative. Due to the mechanical simplicity, robustness, ease of cooling and machinability, tight running flat tips are desirable solutions to turbine manufacturers. Bunker [11] presented an extensive review of the research, mainly performed in low-speed environments, on the aerothermal performance of the plain turbine tips in a high pressure environment. Subsonic tip gap flows are characterized by the formation of a recirculation bubble followed by a flow reattachment onto the blade tip. Creating thereafter a mixing zone up to the suction side of the blade, this leakage flow is mainly dominated by the pressure loading across the tip and the maximum channel flow contraction over the bubble.

Current turbine designs tend to adopt higher stage loadings and rotational speeds which result in a supersonic overtip leakage flow. Oblique shock waves originate at the reattachment point and are reflected between the rotor tip and casing [12], setting an effective limiter on the leakage mass flow [13]. Enhanced heat transfer levels are observed at the reattachment line on the tip pressure side [14] and on the rotor shroud, just above the pressure side edge of the airfoil [15]. Zhang et al. [16] observed parallel lines of high heat transfer due to the shock impingement. Additionally, an increase in clearance height was found to give rise to increased leakage flow velocities in the overtip region, resulting in an enhanced gap mass flow and a leakage vortex core further detached from the airfoil suction side.

To the authors' knowledge, there are no publications addressing the physics of overtip gap flows for clearances below 0.5% of the turbine passage height. The current paper presents the results of an elaborate numerical study of a high-speed turbine covering tight tip clearances as low as 0.1% of the channel height. The aerothermal field investigation revealed remarkable changes between tight and large running clearances. This research thus yields insight into the complex flow phenomena occurring in the overtip region. The description of the physics, needed for the future design of tight running fluid machinery, will contribute to reducing the machine performance loss and therefore the engine's impact on the environment will be minimized.

2. Numerical methodology

2.1. Computational domain and mesh

Fig. 1(a) presents the cross section of the investigated turbine stage, containing 42 stator vanes and 64 rotor blades. Such geometry was selected as to be representative of modern gas turbine technology for aero-engines and power generation. In order to allow a sufficient development of the flow, the outlet of the computational domain was placed 2 chord lengths downstream of the trailing edge of the rotor blade. The stationary stator passage and rotating rotor domain are connected through a mixing plane. Only one periodic section of the turbine stage is modeled (i.e. 1/42 of the stator annulus and 1/64 of the rotor annulus). A flat rotor tip geometry was considered along with five different clearances, h, between the rotor tip and the stationary shroud, ranging from 0.1% to 1.9% of the rotor channel height, H. The relevant geometrical parameters are summarized in Table 1.

Fig. 1 additionally displays the structured grids created with Numeca AutoGrid5, dividing radially the stator vane and rotor blade computational domain into 61 and 80 flow paths respectively. In order to be able to resolve the detailed gap flow characteristics, the clearance height was further divided radially into 33

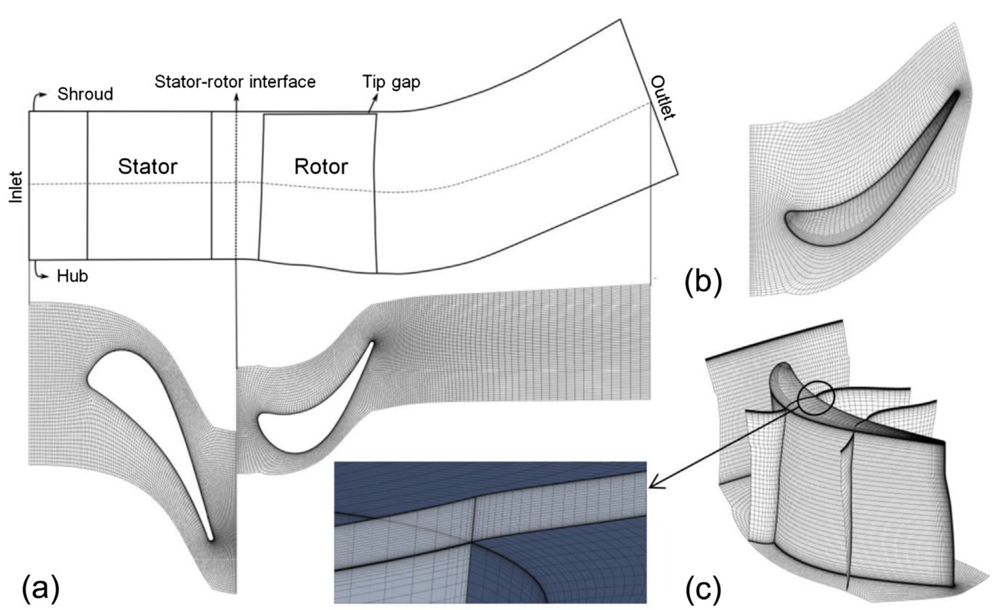

Fig. 1. Turbine stage geometry and computational mesh: (a) meridional view and mesh at the mid-height meridional surface; (b) rotor shroud mesh; (c) rotor blade mesh, including detail of the tip gap mesh.