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ORIGINAL ARTICLE

Non-adiabatic flow characteristics of micro impeller

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Abstract Non-adiabatic working condition is one of the major causes of performance deterioration in micro gas turbine engines. Complex micro scale geometry, low Reynolds number operating condition and high surface to volume ratio all lead to severe heat transfer. This paper first established a simple heat transfer model to determine appropriate non-adiabatic boundary condition for computational fluid dynamics (CFD) simulations. Isothermal wall temperature is identified as a heat transfer boundary based on model analysis in combination with material selection for pre-design of the engine and verified by the experiment carried out on directed structure applied in the model. A series of numerical simulations with adiabatic and non-adiabatic boundary conditions is then carried out to study the flow characteristics of high speed, low Reynolds number micro impeller. The physical nature for significant performance degradation related to flow behavior changes due to heat transfer effect is revealed by detailed analysis of typical flow features extracted from the comparative investigation. The result established the basis for heat transfer modeling of micro impeller purposing implications for design modification in order to attain high efficiency and better performance.

1. Introduction

For millimeter-scale gas turbine engines, it is proposed by Epstein [1] that not only is there more heat transfer to or from the structure but thermal conductance within the structure is much higher due to the considerable short length scale. Therefore, it is difficult to achieve a completely adiabatic working condition for the compression

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Nomenclature

A	area (unit: m^2)
c	specific heat capacity (unit: J/(kg · K))
E	thermodynamic energy (unit: J)
h	enthalpy (unit: J/kg)
L	length (unit: m)
m	mass flow rate (unit: kg/s)
Q	heat transfer rate (unit: W)
QH	heat addition parameter
r	radius (unit: m)
T	temperature (unit: K)

Greek letters

ρ	density (unit: kg/m^3)
λ	thermal conductivity (unit: W/(m · K))
η	efficiency
π	Pi or total pressure ratio

Subscripts

0	bottom surface of the shaft
1	shaft
2	impeller disk
ex	heat exported from the system
gen	heat generated by internal heat source
im	heat imported to the system
inlet	impeller inlet
t	total quantity

system so that there will be heat flux from the hot turbine to the cold compressor resulting heat addition through conduction leading to reductions in mass flow rate, pressure rise, and efficiency. This makes heat transfer a highly important aspect of fluid mechanics in micro turbine engines as micro devices operate in a whole different design space than large-scale machines on the entire performance map.

The impact of internal heat transfer between the turbine and compressor of a micro gas turbine rotor on component efficiency, power output and gas turbine cycle efficiency is thoroughly analyzed by Van den Braembussche [2]. A diabatic flow model is established as a function of heat flux for the calculation of performance deterioration. However, the evaluation of the decrease of gas turbine power output and cycle efficiency requires a correct estimation of heat flux.

The Heat transfer impact on micro turbomachinery performance has been discussed by Ribaud [3]. A thermodynamic model taking into account heat transfer in an ultra micro turbine was developed and applied in different cases, confirming that the dramatic penalties in performances of turbomachines are attributed to the non-adiabatic operation. An estimation of the external radiative heat loss which is about 10% of the nominal power for the 2 cm diameter microturbine is reported by the model and a thermal shield of 2 mm thickness is suggested for performance enhancement. In addition, the research proposed that better knowledge of the heat transfer coefficients at low Reynolds numbers in different components should be obtained to refine the model.

Sirakov [4] implemented a set of numerical experiments to identify dominant performance-limiting mechanisms in micro-impellers in order to quantify and characterize their effect on performance. The results on the effect of heat transfer revealed severe performance deterioration with a 25% decrease in efficiency indicating that heat addition is one of the dominant performance limiting mechanisms.

Gong [5] studied the drop in performance of micro impeller on the non-adiabatic working conditions and proposed a thermodynamic model to evaluate the effect of heat transfer. The model is established based on the assumption that the actual non-adiabatic compression process can be considered as two separate processes which are flow being heated under constant pressure and preheated flow being compressed adiabatically respectively. A heat addition parameter is defined so that the effect of heat transfer on total pressure ratio, efficiency and mass flow rate can be quantified for a given working condition with an estimated total heat added to the system.

It can be concluded from the review of previous study that most researches mainly focused on the general estimation of performance deterioration affected by heat transfer without exploring the changes of flow behaviors for loss analysis. Therefore, the purpose of this research is to provide an insight into the detailed flow features in micro impellers considering the heat transfer effect. A computational fluid dynamics (CFD) based comparison study of adiabatic and non-adiabatic flow characteristics is carried out to examine the flow phenomenon and to explain the relevant physical mechanisms owing to heat transfer effect in micro impellers. The influence of heat transfer on micro impeller design is also briefly discussed to provide corresponding modifications for better performances.

2. Diabatic boundary condition modeling

The heat transfer model is carried out based on a simplified structure composed of just the shaft and the impeller disk as shown in Figure 1. As the bottom surface of the shaft is connected to the turbine disk, it is supposed that there is constant heat flux transferred to the shaft and impeller disk from the turbine through this surface, meanwhile the temperature is uniform at that end of the shaft.

In order to obtain mathematical expression for the temperature distribution of thermal objects, partial differential equation of heat conduction is built on cylindrical