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Influences of energy management strategy on stress state of near real geometry of turbine disk

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ABSTRACT

From the point of view of the physical essence, using cooling technology in turbine systems is a process of energy management and the developed cooling structure in the last forty years is aimed at carrying out a different energy management strategy. Based on this idea, in this paper the energy management strategy for each cooling structure was abstracted first and reflected by parameters of heating energy Q_e in the outer surface, exchanged energy Q_{in} in the inner surface and wall heat transfer coefficient h of the disk. Then, the influences of energy management strategy on stress state of near real geometry of the turbine disk were investigated. That is, the equation correlating different energy management strategies with stress states for disks was built by theoretical analysis and the computational fluid dynamics and finite element simulations were applied to validate the theoretical analysis. Results showed that the stress state could be effectively controlled through actively adjusting the energy management strategy. And under a constant cooling structure and equal consumption of cooling air and heating energy conditions, the heating energy of disks could be rearranged (reflected by allocation ratio of heating energy ϕ) in outer (Q_e) and inner (Q_{in}) surface to achieve the actively heated hub of the disk, and the resulting decline ratio of maximum equivalent stress level in hub could be arrived 45.52% at $\phi = 0.20$ to compare with the conventional energy management strategy ($\phi = 0$), even in 3981 rpm. The reason for the preceding effect was explained by an artificial V-shaped temperature distribution that was established in the disk through actively rearranging the heating energy and correspondingly, the reverse temperature gradient between the hub and web produced a pulling effect and counteracted parts of the stress from rotating. In general, the simulation data were in strong agreement with the above results.

1. Introduction

As one of the core parts of gas turbines, the turbine disk operates under extremely severe and complex conditions of centrifugal and thermal loading [1]. The result is that a progressive deterioration of material is generated due to the accumulation of fatigue and thermal creep damage [2,3] and consequently jeopardizes the safety of gas turbine.

In general, several cooling technologies have been developed on the turbine disk to decrease the thermal loading [4]. However, cooling technology is restricted by the amount of cooling air from the compressor. The excessive consumption of cooling air will directly cause the decline in the efficiency of the gas turbine. Thus, in the last four decades, most of the studies in the field of disk cooling technology primarily concentrate on the cooling structure to enhance the cooling efficiency under the limited cooling air consumption condition [5–7]. For the disk cavity, the typical cooling structure includes centric air inflow configuration, high positioned air inflow configuration and prewhirl inlet configuration [8–10]. For the disk, some novel disk configurations are developed, such as the twin web disk [11–13], which has a high cooling efficiency because the air enters the inside of the disk directly.

Nevertheless, it seems that the potentials for using pure cooling technology to control thermal loading have been nearly exhausted. However, it should be pointed out that from the physical mechanism's point of view, the essence of using cooling technology is a process of energy management for the turbine system. And the essence of developed structures of disk cavity and disks mentioned above is to carry out the different energy management strategy. That is, for an energy management strategy, the position of heat sources and the organization of cooling flow are concrete

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Nomenclature

C	coefficients of thickness function
$C_{1,2,3,4,5}$	coefficients of centrifugal stress equation
$D_{1,2}$	coefficient of stress equation
E	Young's modulus of elasticity
F	radial force
h	convective heat transfer coefficient
$\bar{h}$	average convective heat transfer coefficient
I_n	n-order Bessel function
k	coefficient of thickness function
K_n	n-order Bessel function
$M_{1,2}$	substitution variable
n	number of annular disks
$N_{1,2}$	substitution variable
q	heat flux
Q_e	heating energy in outer surface of disk
Q_{in}	heating energy in inner surface of disk
$Q_{\text{interface}}$	exported energy between disk and cooling air
Q_{total}	total heating energy of disk
r	radius
$[R_{D_{1,2}}]$	coefficient matrix of Eq. (16)
$[R_F]$	coefficient matrix of Eq. (22)
$[R_Q]$	coefficient matrix of Eq. (5)
$[R_T]$	coefficient matrix of Eq. (7)
$[R_V]$	coefficient matrix of Eq. (22)
t	temperature of disk
t_{ref}	reference temperature
$V_{1,2}$	substitution variable
W	substitution variable $W = (\bar{h}/\lambda\delta)^{0.5}$
α	coefficient of thermal expansion
δ	width of disk $\delta = Cr^k$
ε_θ	thermal strain
ϕ	allocation ratio of heating energy
λ	heat conductivity
μ	Poisson's ratio
ρ	density of disk
σ_r	radial stress
σ_θ	circumferential stress
σ_e	equivalent stress (von-Mises)
ω	angular velocity of rotating disk

Superscripts

(i)	ith annual element

Subscripts

combination	combination surface between neighbor annular elements
e	outer radius
i	inner radius

implementation methods in the disk cavity, the temperature level and temperature gradient of the disk are reflected phenomena, and the stress level and distribution of the disk are acquired results or assessment criteria to guarantee the permissible strength of the disk in a harsh working environment. In other words, the study of cooling technology should rise to the height of energy management. Therefore, it is not enough to concentrate only on cooling efficiency and its limits in order to explore the potentiality of cooling technology in currently technical conditions because from the point of energy management, it is possible that the strength demand of the disk can be more easily satisfied by actively reorganizing and managing the energy of the disk under existing cooling technology and material conditions. To this end, some researches have made some efforts in this region and the implementation method may be focused in two directions. One of the directions is to adjust the structure of disk cavity and reorganize the flow of cooling air. The other direction is to use new types of disk.

1.1. Adjustment of turbine system

Fig. 1 presents a scheme of turbine system in SNECMA and the essence of this structure is actively managed the energy distribution of disk. That is, in this turbine system [14], parts of cooling air of the combustion are imported to actively heat the inner surface of the disk through an additional channel. Also, three structures of the disk hub are given to strengthen the heating effect by active construct, the jet impingement, or extensive area of inner surface. Obviously, here, it can be believed that the thermal loading is managed in this turbine system, and consequently a reverse temperature gradient (compared with conventional temperature distribution of disk) is built between web and hub and the pulling effect from produced thermal stress can be used to control stress level of the disk.

In addition, for rotating cavity with an axial fringe inlet and a radial outlet, the influences of rotating Reynolds number, cooling air Reynolds number and Grashoff number on the local heat transfer and flow characteristics are investigated experimentally in Ding and Tao's study [15]. The results indicate that the local heat transfer coefficient on the edge of main disk rapidly increases with the increase of cooling air Reynolds number and rotating Reynolds number. Most important, the local heat transfer coefficient becomes negative near the center of the disk at large cooling air Reynolds number and Grashoff number conditions as shown in Fig. 2. It means that the temperature of lower part of disk is increased and this phenomenon will not appear in rotating cavity with centric air inflow configuration. That is, from the energy management point of view, the development of cooling structure of disk cavity from centric air inflow to axial fringe inlet reflects the change of energy management of strategy.

1.2. Heat pipe disk

A disk called the adiabatic heat pipe disk (AHPD) as shown in Fig. 3, using radially rotating high-temperature heat pipes, has been proposed to control the stress state [16]. Here, the effect of heat pipes is to build beneficial temperature gradient based on energy management. That is, the analogous V-shaped temperature distribution is achieved (Fig. 4) and the results show that, compared with the disk without heat pipes, the maximal circumferential stress in the hub of the proposed disk can be reduced by more than 100 MPa under 10,000 rpm (Fig. 5).

All research work previously mentioned has shown effort to actively manage energy of in actual application. However, although the turbine system of SNECMA obtained patents in 1994 and the obvious effect of stress control in the disk is confirmed by the heat pipe disk, the mechanism research, especially the relationship between different energy management strategies and stress states of near real geometry of the turbine disk, is limited in this field. Thus, based on the above background, and using the theoretical and simulation analysis method, this research studies the