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Thermal analysis of gas turbine disk integrated with rotating heat pipes

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ABSTRACT

The combination of the rotating heat pipe with conventional air cooling technique can be considered as an emerging and effective cooling technique for gas turbine disk. Accordingly, the thermal steady and transient analysis of a simplified turbine disk integrated with heat pipes have been numerically investigated. The steady and transient temperature variations in the presence and absence of heat pipes were investigated for various parameter, such as the thermal conductivity of the disk, the convective heat transfer coefficient for both the air and heat pipes, the dimension of the disk, and the number of heat pipes. The thermal analysis were performed by using finite element (FE) modeling software ANSYS-17.2. The extensive numerical simulations showed that when the number of heat pipes equal to 32, the maximum temperatures at the disk edge can be decreased by more than 100 degree. Additionally, increasing the convective heat transfer coefficient of the working fluid inside the heat pipes up to 10,000 W/m^2.°C, the maximum temperature at the disk rim can further be reduced by more than 280 degree. It has also been observed that the time required to achieve the minimum steady-state temperature was more sensitive to the air convective heat transfer coefficient.

1. Introduction

Temperature is one of the most significant factors affecting the gas turbine cycle efficiency. Increasing the turbine inlet temperature improves both thrust to weight ratio and decreases the specific air consumption [1,2]. However, the desirability of high turbine inlet temperature is often overlapping with the capacity of the material to resist this rise of heat. Moreover, the outer disk edge in a modern gas turbine engine (i.e rim) is always close to a high temperature working fluid, and may approach 1300 K. Thus, these critical locations require higher material performance than others which improved the creep resistance of disk structure. Therefore, turbine blades, vanes and disk cooling technique are crucial for a safe operation and heat flow improvement. In the past decades, many researches associated with turbine disk cooling have confirmed that the local heat-transfer coefficient at the disk edge is relatively low. Impinging liquid jet onto rotating turbine disk is often used to supply high local heat transfer coefficient, but the high cost of implementation and utilization is an important limiting factor [3–7]. In more advanced aero-engines and gas turbines, a small percentage of high pressurized air is extracted from various locations in the compressor for sealing and cooling purposes. Some of the air is employed for cooling the turbine blades, nozzle guide vanes, and the turbine disks. Steam has been used as alternative coolant for the gas turbine blade cooling. Steam cooling as applied to gas turbine blades has many advantages over traditional air cooling such as high cooling efficiency, fast cooling speed, and simple structure. However, it is not adequate for operation and is not practical for an aircraft gas-turbine engine. It is well known that higher gas turbine power density can be achieved as a result of engine size reduction. Thus, the area available for the cooling process at the disk edges will be minimized, and the upper temperature

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limits incorporated the aircraft engine will be more significant. Furthermore, what makes the temperature along the disk rim very high is the fact that disk material is poor in thermal conductivity. In addition, the traditional methods of cooling are woefully inefficient. The needed heat transfer surface area for the cooling purpose is limited. Such extraordinary gas turbine working conditions and size constraints require a new and more efficient cooling technique. Based on this understanding, the most features of the common practice methods for the enhancement of cooling is to employ the radially rotating heat pipes [8–14].

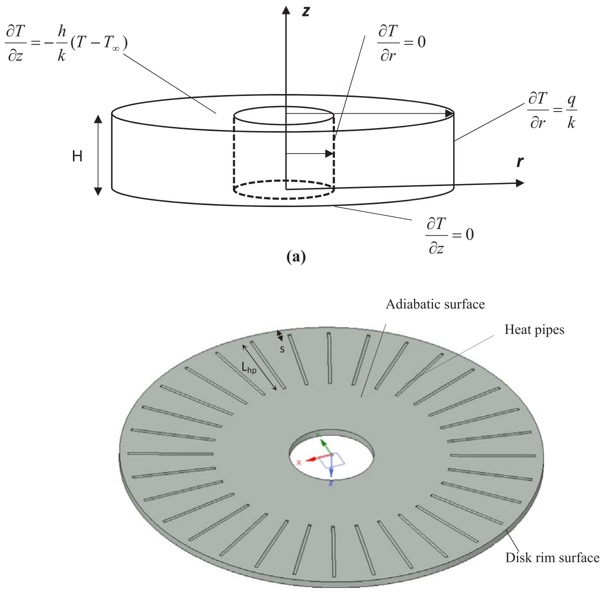
Generally, heat pipe is passive heat transfer-device that merges the principles of both thermal conductance and phase mutation to convey the heat between two materials. The working fluid inside the heat pipe comes into contact with the hot interface and convert it into a vapor by soaking up heat from that surface. The heated working fluid then moves over the heat pipe to the cold region and subsequently condensing the vapor by releasing the heat there. The working fluid then comes back to the hot region to repeat the cycle by many mechanisms such as centrifugal force or capillary motion. A heat pipes are extremely high effective thermal conductors because of their high boiling and condensation heat transfer coefficients. The advantage of heat pipes over many other conventional mechanisms is in their great efficiency in conveying heat. Moreover, simplicity in design, manufacturing, and the ability to dominate the amount of heat at high temperature scales make them distinctive and unlike any other methods [15–18].

The impact of the low-temperature heat pipes on the temperature decrease on the periphery of the disk was numerically estimated by Ling et al. [19]. The numerical analysis was based on the comparison between disks in the presence and absence of the heat pipes. The analysis of their results showed that heat pipes are highly efficient in the cooling process, which can decrease the temperature of the disk edge to over 100 °C under similar working conditions. This analyses was only performed on the disk, while the effect of the heat pipes cooling on the blades were neglected. They found that the use of miniature heat pipes with a liquid metal as an ideal coolant in disk cooling are effective, because they have a high heat transfer capacity compared to heat pipes working on water as an ideal coolant. Based on the results of Cao (1997), the effective thermal conductance of heat pipe working on liquid metal were evaluated to be about 500–1000 times that of copper. This in turn means that thermal conductivity is more than 5000 times higher than the common materials used in manufacturing the disk itself.

In this paper, the transient and steady state thermal analysis were performed for a typical turbine disk integrated with and without heat pipes by exploiting the numerical model of Ling et al. (2004). Moreover, the numerical analysis is based on three-dimensional model to improve the accuracy of the analysis. Various factors that affect the cooling effectiveness of heat pipes on the gas turbine disk such as the thermal conductivity, the heat transfer coefficient of the disk and heat pipes, the dimension of the disk, and the number of heat pipes required have been analyzed and evaluated.

2. Governing equations and numerical procedure

The equation governing the rotating disk exposed to a heat input at the disk edge and cooled at the disk lateral surface through convection are the heat conduction equation in cylindrical coordinates (see Fig. 1). Fig. 1 shows the schematic diagram of a simplified turbine disk model integrated with heat pipe and subjected thermal boundary conditions. As a result of high disk rotation speed, the two lateral surfaces of the disk are subjected to heavy thermal convection and so the two surfaces dissipate the heat. It is noted that the two sides surface of the disk are assumed to expose to the same cooling conditions, so due to the presence of symmetry one half of



(a)

(b)

Fig. 1. Schematic of a turbine disk (a) without heat pipes (b) with heat pipes.