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Research Paper

Application of heat and mass transfer analogy on hot gas ingestion through rim seal

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HIGHLIGHTS

- Mass and heat transfer analogy is applied on ingress of transfer theoretically and experimentally.
- A formula relating two kinds sealing efficiencies is derived from the Chilton–Colburn analogy.
- Experiments of heat and mass transfer in ingress are conducted separately to obtain these two sealing efficiencies.
- The experiment result shows two kinds sealing efficiencies have similar but different distribution inside cavity.

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ABSTRACT

This paper presents a theoretical and experimental investigation on developing the relation of concentration-based sealing efficiency and temperature-based sealing efficiency on ingress of transfer by applying the mass and heat transfer analogy. A formula connected these two sealing efficiencies is derived from the Chilton–Colburn analogy. Experiments of heat and mass transfer in ingress are conducted separately to obtain the concentration-based sealing efficiency and temperature-based sealing efficiency respectively, and get a suitable value for the variable "n" originated from the formula derivation. In experiment, annulus Reynolds number is set at 3.25×10^5, rotating Reynolds number is changed from 6.26×10^5 to 8.34×10^5 while the dimensionless sealing air flow rate ranges from 1252 to 5512. The experiment result shows temperature-based sealing efficiency has similar but different distribution inside cavity compared with concentration-based sealing efficiency as Lewis Number is greater than 1 in the experiment. By setting $n = 0.105$, the experiment data and predicted data from derived formula matches well. In the further discussion of the derived formula, it shows that the difference of concentration-based sealing efficiency and temperature-based sealing efficiency enlarges with the increase of air temperature.

1. Introduction

It's of great interest for gas turbine designer to obtain the minimum flow rate of sealing air that purges into turbine cavity to prevent hot annulus gas ingestion through rim seal into cavity as it is related with the safety and efficiency of gas turbine.

Therefore, many researchers utilized various methods to gain the minimum sealing air flow rate. The pressure method was first proposed and used by Owen [1] to obtain minimum sealing air flow rate. A turbine cavity with axial rim seal but annulus was utilized in experiment. The pressure inside cavity was measured and compared with the pressure in atmosphere to determine whether the ingress was prevented or not. With this method, the widely used formula to predict minimum sealing air flow rate was obtained.

$$c_w = 0.61 G_c Re_\phi \tag{1}$$

Based on this formula, Phadke [2] conducted experiment to explore sealing character of seven kinds of rim seals and proposed a modified formula that could be applied for different rim seals as shown below.

$$c_w = C_{i,j} G_c^{m_{i,j}} Re_\phi^{n_{i,j}} \tag{2}$$

where different values of $C_{i,j}$, $m_{i,j}$ and $n_{i,j}$ would be chosen for different rim seals. However, as research continues, annulus flow was found to have a significant effect on ingress and then it was taken

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Nomenclature

A	area
a	thermal diffusivity
b	radius of disk, mathematic variable
c	carbon dioxide concentration
c_0	the carbon dioxide concentration of sealing air
c_{ave}	concentration of cavity
$C_{A\infty}$	the concentration of main flow
C_{AS}	the concentration on wall
$C_{i,j}$	mathematic variable
C_P	specific heat at constant pressure
C_w	non-dimensional flow rate [$= \dot{m}_c/\mu b$]
c_∞	the carbon dioxide concentration of annulus flow
D	mass transfer coefficient
D_{AB}	mass transfer coefficient of CO_2 in air
G_c	seal clearance ratio ($= s_c/b$)
h	heat transfer coefficient
j_H	Colburn heat transfer factor
j_D	Colburn mass transfer factor
k	overall heat transfer coefficient
k_c	mass transfer coefficient
Le	Lewis Number [$= a/D$]
$\dot{m}$	mass flow rate
$\dot{m}_o$	mass flow rate of sealing air
$m_{i,j}, n_{i,j}$	mathematic variable
m_{c0}, m_{c1}	mathematic variable
m_{T0}, m_{T1}	mathematic variable
N_{Ay}	mass flux
Pr	Prandtl number
Q	heat flux
r	radius
R	radius of sealing air inlet
r_1	radius of sealing air inlet
Re_W	annulus Reynolds number [$= \rho W b/\mu$]
Re_ϕ	rotational Reynolds number [$= \rho \Omega b^2/\mu$]
s	axial clearance between rotor and stator
Sc	Schmidt number [$= \nu/D$]
s_c	seal clearance
T	temperature
T_a	temperature of annulus flow
T_{ave}	temperature of cavity
T_{cav}	cavity temperature inside turbine cavity under adiabatic condition
T_{ci}	temperature of core flow
$T_{c,loss}$	temperature reduction of core flow caused by heat loss
$T_{i,wj}$	static wall temperature in insulation cavity
ΔT_{cav}	uncertainty of T_{cav}
T_f	temperature in main flow or sealing air
T_{r1}	average temperature on left side of rotor
T_{r2}	average temperature on the right side of rotor
T_s	temperature of sealing air
T_W	temperature on wall or in annulus flow
T_{Wi}	temperature on static wall
ΔT	the temperature difference on two sides of the walls
W	axial velocity in external annulus
z	axial coordinate
β	swirl ratio ($= V_\phi/\Omega r$)
δ_i	thickness of one kind of material
ε	sealing effectiveness ($= 1 - C_{w,i}/C_{w,e}$)
ε_c	concentration-based sealing efficiency [$= (c_s - c_a)/(c_o - c_a)$]
$\varepsilon_{c,ave}$	averaged concentration-based sealing efficiency
ε_T	temperature-based sealing efficiency [$= (T_a - T)/(T_a - T_s)$]
$\varepsilon_{T,ave}$	averaged temperature-based sealing efficiency
$\Delta\varepsilon_T$	uncertainty of temperature-based sealing efficiency
λ_i	thermal conductivity of one kind of material
θ	angular coordinate between vanes
μ	dynamic viscosity
υ	kinematic coefficient of viscosity
ρ	density
Ω	rotating velocity of disk

Subscripts

a	annulus
ave	average
cav	cavity
i	insulation
o	sealing flow
s	static disk
1–10	location in cavity and annulus, mathematic variable

into consideration in the study of ingress. From that time forth, other methods were proposed to indicate sealing efficiency in experiment.

Flow visualization method is the most directly way to identify whether ingress happens or not. Tracer particle is added into annulus, while a window is set on cavity to monitor whether the tracer particle from annulus gets into cavity. When the tracer particle can't be found in cavity, ingress is prevented. This method was utilized by Phadke [3,4] to obtain the minimum sealing air flow rate. But the degree of ingress couldn't be indicated with this method.

The most widely used method is the concentration method. In gas turbine, hot gas ingestion is an issue of heat transfer with hot annulus flow and cooling purged air of cavity. But adiabatic wall is difficult to measure in experiment. Therefore, analogy of mass transfer and heat transfer, which was widely used for researches [5–10] in many areas, was applied in experiment of ingress. In 1987, Graber [11] proposed the concentration method to indicate sealing efficiency. The specific way is to add certain amount of tracer particle, such as carbon dioxide, into sealing air but none into annulus. The concentration of the annulus flow (c_∞), sealing air (c_0) and test position inside cavity (c) are measured in corresponding positions to obtain the concentration-based sealing efficiency (ε_c). The concentration-based sealing efficiency can be calculated by:

$$\varepsilon_c = \frac{c - c_\infty}{c_0 - c_\infty} \tag{3}$$

With the application of concentration method, Sangan [12–14] conducted series of experiments on hot gas ingestion, and gained the sealing efficiencies for different rim seal geometries. It was founded the experiment data fitted well with the theoretical result proposed by Owen [15,16].

The temperature method is the one that tallies with the actual situation of hot gas ingestion of gas turbine. In experiment, the annulus flow or cavity flow is heated to certain temperature to simulate the temperature difference of annulus flow and sealing air. Then, the temperature of annulus (T_a), sealing air inlet (T_s) and monitor inside cavity (T) are measured to obtain the temperature-based sealing efficiency. The temperature-based sealing efficiency (ε_T) can be expressed as below:

$$\varepsilon_T = \frac{T_a - T}{T_a - T_s} \tag{4}$$