Chinese Journal of Aeronautics, (2018), xxx(xx): xxx–xxx

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

Development of secondary flow field under rotating condition in a straight channel with square cross-section

Ruquan YOU [a,b], **Kuan WEI** [c], **Zhi TAO** [a,b], **Haiwang LI** [a,b,*], **Guoqiang XU** [a,b]

[a] *National Key Laboratory of Science and Technology on Aero-Engines Aero-Thermodynamics, Beihang University, Beijing 100083, China*
[b] *Collaborative Innovation Center for Advanced Aero-Engine, Beihang University, Beijing 100083, China*
[c] *Aero Engine Academy of China, Aero Engine (Group) Corporation of China, Beijing 101304, China*

Received 18 July 2017; revised 16 November 2017; accepted 25 December 2017

KEYWORDS

Circulation analysis;
Entrance section;
Field Programmable Gata Array (FPGA);
Particle Image Velocimetry (PIV);
Rotating channel;
Secondary flow

Abstract The developing secondary flow fields in the entrance section of a rotating straight channel were experimentally investigated using Particle Image Velocimetry (PIV). The effects of streamwise position, Reynolds number and rotation number on the development of the secondary flow fields were revealed. The results show that the absolute values of vorticity flux of the trailing side roll cells increase with increasing radius of the measured plane and rotation number. When the absolute value of vorticity flux exceeds a critical value, the merging of the trailing side roll cells appears. Moreover, when the number of the trailing side vortex pairs is even, the absolute values of vorticity flux of the leading side vortices increase along streamwise direction. Otherwise, the absolute values decrease along the streamwise direction. By the circulation analysis, this phenomenon was found to have relationship with the merging of the trailing side roll cells, and further concluded that the secondary flow field in a rotating channel has to be treated as a whole. At last, the increase of the Reynolds number was found to be able to induce the merging position moves upstream.

1. Introduction

To improve the thermal efficiency of modern gas turbine engine, the turbine blade has to be operated in the environments with extremely high temperature (> 1900 K) which is far beyond the suitable working temperature, even the melting point of the turbine blade material. To resolve this conflict, lots of cooling techniques were applied to protect the turbine blade. Internal cooling technique is one of the most classical and pop-

---

* Corresponding author at: National Key Laboratory of Science and Technology on Aero-Engines Aero-Thermodynamics, Beihang University, Beijing 100083, China.
E-mail address: 09620@buaa.edu.cn (H. LI).

Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER **Production and hosting by Elsevier**

https://doi.org/10.1016/j.cja.2018.06.008

Please cite this article in press as: YOU R et al. Development of secondary flow field under rotating condition in a straight channel with square cross-section, *Chin J Aeronaut* (2018), https://doi.org/10.1016/j.cja.2018.06.008

Nomenclature

AR	aspect ratio
d	hydraulic diameter (m)
f	force (N/m^2)
g	acceleration of gravity (m/s^2)
Ro	rotation number
Re	Reynolds number
Ri	Richardson number
r	radius (m)
$\boldsymbol{r}$	radius vector
t	time (s)
U	velocity (m/s)
$\boldsymbol{U}$	velocity vector
x	streamwise direction
y	spanwise direction
z	rotating axis
Γ	circulation
$\boldsymbol{\Gamma}$	circulation vector
ν	kinematic viscosity (m^2/s)
μ	dynamic viscosity (Pa·s)
ρ	density of the coolant (kg/m^3)
σ	change of relative density
Ω	rotating speed (r/min)
$\boldsymbol{\Omega}$	vector of rotating speed

Subscripts

e	exterior
w	wall
center	center position
Ekman	Ekman layer
Non	Not
m	mean

ular methods used to protect the turbine blade. As an effective method, serpentine passage in the middle section of a turbine blade was developed.[1,2] Most of the previous work was focused on the heat transfer in the serpentine passages because the heat transfer is the intuitive phenomenon and is easier to be measured than the flow field. However, sometimes the heat transfer phenomenon was not able to be explained reasonably because of a lack of the knowledge about the flow behavior under rotating condition. In order to enrich the knowledge in this field, some previous work focused on the primary flow fields in rotating channels. In these work, a variety of experimental techniques were utilized. For instance, Bons and Kerrebrock[3] measured the velocity profiles of the primary flow in a square cross-section rotating channel with PIV; Macfarlane and Joubert[4] investigated the developing boundary layers in three rotating channels with different aspect ratio using hot wire. The current work also investigated the flow fields in a rotating channel. However not the primary flow fields, the secondary flow fields are the main concern of the present work.

Why the secondary flow fields? Because the secondary flow fields deeply affect the primary flow and the heat transfer in the rotation channel.[4] Macfarlane et al.[5] defined the secondary flow strength and claimed that if this secondary flow strength exceeded a critical number, the secondary flow would influence the boundary layer development in a rotating channel.

The history of studies on the secondary flow field in a rotating channel can be stretched back to 1971. Lian et al.[6] investigated the stability of the secondary flow vortex structures in a rotating channel with AR = 8:1.15 by both the flow visualization experiment and the theoretical analysis, where AR means aspect ratio. The experimental results demonstrated the existence of three secondary flow regimes in a rotating channel. That is, when the rotation number is smaller than a critical value, there was only a slightly straightening of the dye lines in the boundary layer. On the contrary, when the rotation number is larger than this critical value, a waviness of the dye lines was observed. If the rotation number increased further and the flow passed into the Taylor-Proudman regime, the most essential characteristic of the Taylor-Proudman regime flow was detected, the dye lines in the core region were parallel to the axial direction. Furthermore, Hart carried out a linear stability analysis about the onset of the waviness for the dye lines, namely the roll cells instability. Lezius and Johnston[7] also conducted a linear stability analysis about the instability of the onset for the roll cells.

Speziale and Thangam[8] numerically studied the same problem with Hart, and gave some secondary flow streamlines in detail. The results show that, for a given Reynolds number, when the rotation number Ro was smaller than a critical value, there is a symmetric vortex couple in the cross section plane. Meanwhile, when the rotation number is larger than this critical value, a series of small vortices appear near the trailing side. As the rotation number increased furthermore and exceeded another critical value, the flow passed into the Taylor-Proudman type regime. In this regime, the small scale vortices disappear, and the symmetric vortex couple reappeared. Moreover, the stability boundary for the appearance of small vortices was obtained.

Speziale[9] repeated Hart's experiments but changed the aspect ratio of the channel from 8:1.15 to 2:1. The similar transition process of the secondary flow revealed by Hart was also discovered by Speziale.

Besides the three stages, some other complicated transition phenomena were also found in the secondary flow transition process.

Smirnov and Yurkin[10] conducted a flow visualization experiment in a rotating channel with the aspect ratio equaling to 1. The experiments were carried out with water, and the flows were visualized by hydrogen bubbles and dye lines. By analyzing the results, nine flow regime boundaries were discovered; there was the stability boundary for the onset of the small vortices near the trailing side among them.

Kheshgi and Scriven[11] numerically studied fully developed laminar flow in a rotating channel with the aspect ratio equaling to 1. The three stages of the secondary flow transition process were also discovered. It is notable that an analysis of the secondary flow transition process from the intermediate rotation number regime to the high rotation number regime was given. In the phase chart, the four-vortex solution branch was found to be connected with the two-vortex solution

Please cite this article in press as: YOU R et al. Development of secondary flow field under rotating condition in a straight channel with square cross-section, *Chin J Aeronaut* (2018), https://doi.org/10.1016/j.cja.2018.06.008