Applied Thermal Engineering 133 (2018) 33–38

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Experimental investigation on the air-liquid two-phase flow inside a grooved rotating-disk system: Flow pattern maps

Wei Wu[a,b,*], Bingqing Xiao[a], Jibin Hu[a], Shihua Yuan[a], Chenhui Hu[a]

[a] National Key Laboratory of Vehicular Transmission, Beijing Institute of Technology, Beijing 100081, PR China
[b] State Key Laboratory of Fluid Power and Mechatronic System, Hang Zhou 310027, PR China

HIGHLIGHTS

- Three different flow patterns appear with different flow rates and disk gaps.
- Flow patterns include stratified flow, full liquid flow, and bubble flow.
- The flow pattern transition can be confirmed by two sets of parameters.
- The dimensionless flow rate and the gap Reynolds number are one set parameter.
- The Weber number and the gap Reynolds number are another set parameter.

ARTICLE INFO

Keywords:
Rotating disk
Flow pattern
Two-phase flow
Stratified flow
Full liquid flow
Bubble flow

ABSTRACT

An experimental system has been built up for the flow pattern analysis inside an open grooved rotating-disk system. The geometric construction and the governing parameters of the open grooved rotating-disk are presented. The measured results indicate that three different flow patterns appear in the flow field with the change of liquid flow rates and disk gaps. The flow patterns include the stratified flow, the full liquid flow, and the bubble flow. The transition of the air-liquid stratified flow to the full liquid flow is caused by an insufficient flow supply. The dimensionless liquid flow rate and the gap Reynolds number determine the transition boundary between the stratified flow and the full liquid flow. The shear force and the surface tension force of the liquid play a leading role when the full liquid flow transfers to the bubble flow. The Weber number and the gap Reynolds number can be applied in the boundary calculation for the full liquid to bubble flow transition. The two-phase flow pattern maps can be used for identifying the transition from one flow pattern to another inside the grooved rotating-disk system.

1. Introduction

The flow inside the rotating-disk system has drawn attention in the fields of fluid disk machines, such as the wet clutch [1] and the turbomachinery [2]. The earlier theoretical study of the rotating-disk flow should be traced back to Von Karman's investigation [3]. The fundamental flow structures of both rotor-stator disks and counter-rotating disks have been proposed by Batchelor [4] and Stewartson [5].

Most of the studies on the flow behaviour of the two-disk system are focused on shrouded disk systems [6]. It is the theoretical foundation of the turbomachinery [7]. On the other hand, open disk systems are essentials and fundamentals in theoretical studies for many applications [8,9]. The flow field for an open disk system is recognized as a Stewartson flow [10]. The flow presents annular or spiral rolls and Ekman layer on rotor disk [11]. Lopez and co-researchers [12] have revealed that the self-similar solution is able to describe the fluid flow near the rotating disk. In many applications of the open disk systems, the disks always have complicated surface texture to realize better operating performance. The single-phase flows inside an open grooved disk system used for mechanical seals and thrust bearings have been investigated a lot [13–16]. The multiphase flow inside open grooved two-disk systems constitutes the simplified theoretical model of wet clutches [17,18]. The flow would exert an extensive effect on the heat transfer with different flow behaviour [19,20]. Jang and co-researchers investigated the geometric effects of the radial and waffle-shape grooves on the thermal and torque response of the wet clutch during engagement [21]. Many other models have been proposed to analyse the flow effects on the heat dissipation characteristics of the wet clutch during

* Corresponding author at: Room 412, Building 9, Beijing Institute of Technology, Beijing 100081, PR China.
E-mail address: wuweijing@bit.edu.cn (W. Wu).

https://doi.org/10.1016/j.applthermaleng.2018.01.031
Received 28 March 2017; Received in revised form 17 December 2017; Accepted 9 January 2018
Available online 10 January 2018
1359-4311/

Nomenclature

h	depth of the groove, mm
H	disk gap, mm
N_g	groove number, -
Q	liquid flow rate, l/min
Q^*	dimensionless liquid flow rate, -
Re_H	Reynolds number, –
r	radial coordinates, mm
$r1$	internal radius, mm
$r2$	external radius, mm
r_m	nominal radius, mm
We	Weber number, -
z	axial coordinate, mm

Greek symbols

α	groove circumferential angle, °
θ	azimuthal coordinate, °
μ	dynamic viscosity, N·s/m^2
σ	surface tension coefficient, N/m
ρ	liquid density, kg/m^3
υ	velocity, m/s
ω	angular velocity, rad/s

engagement [22,23]. However, the transitioning flow patterns and the groove effects from disengagement to engagement are yet not revealed, which makes the mechanism between disk configuration and flow field unclear. Further, the heat dissipation characteristics are largely determined by the flow behaviour [24]. Some measured results of the flow behaviour have been presented based on the practical clutch friction plate [25,26] and the quantitative investigation of the drag torque is presented.

An experimental system has been built up for the viscous flow field analysis inside an open grooved rotating disk system. The geometric construction and the governing parameters of the open grooved rotating disk system are presented. The flow patterns inside the open grooved rotating-disk system are investigated by the experimental results. It is aimed to propose the two-phase flow pattern maps for identifying the flow behaviour variation inside the grooved rotating-disk system. The results are also fundamental in the design of advanced cooling mechanism for clutch disks.

2. Experimental system

Fig. 1 presents the grooved rotating disk system. A gap H is set between the disks. The stationary disk is smooth and ungrooved. The grooved disk rotates axially with an angular velocity ω. The groove depth of the grooved disk is h. The groove is radial. The groove area is defined by the groove number N_g and the groove circumferential angle α. The viscous flow field inside the disk system is described by a cylindrical coordinate system (r, θ and z), denoting the radial, azimuthal and axial coordinates, respectively. r_1 and r_2 represent the internal and external radius of the grooved disk, respectively. The inlet is supplied with a liquid flow rate Q. The ambient outlet pressure is atmospheric.

As shown in Fig. 2, an experimental system is designed to investigate the flow pattern. The test rig is comprised of a rotating grooved disk, a stationary disk, a pump, an image acquisition system and a control system. The stationary and rotating disks are coaxial in the test. The rotating disk is driven by an electric motor. The error of the angular speed controlling is within ± 1 r/min in the steady state. To visualize the flow structures in the flow field, the smooth stationary disk is made of transparent plexiglass. The gap between the stationary disk and the rotating disk can be adjusted continuously within ± 10 μm. The pump supplies a liquid flow rate from 10 to 1000 ml/min continuously. Basic technical data of the tested open grooved disk system is provided in Table 1. In the experiment, the temperature of the liquid is measured. Meanwhile, the liquid temperature rising is controlled to be no more than 2 °C so that the liquid dynamic viscosity is assumed to be constant in the test process.

3. Results and discussion

3.1. Visualization and interpretation of two-phase flow patterns

In this section, visualization results of different flow patterns inside the grooved rotating-disk system will be presented. Based on the visualization results, flow regimes will be analysed in detail. The flow behaviours in each flow regime will be discussed as well.

The flow structures formed in the experiments can be divided into three typical flow patterns. The representative measured results under the following operation parameters have been presented as an example. The rotating speed of the grooved disk is 180 r/min and the liquid flow rate is 20 ml/min. The disk gap varies from 0.15 mm to 2.0 mm. In the experiment, the flow picture was taken by the digital SLR camera. The different flow structures are captured after 2 min upon the observation of the certain flow structure. It guarantees a clear and steady visual reflection of the flow structure. Further, different shutter speeds are also needed to get a clear flow field image with the changing of the rotating speed. The corresponding shutter speed is chosen according to the linear velocity of the outer diameter of the rotating disk. At the same time, the aperture and the lighting should also be adjusted appropriately to obtain a clear flow field image.

3.1.1. Stratified flow regime

The visualization results of the air-liquid two-phase flow are presented in Fig. 3. Under the given operation parameters, the viscous flow field appears to be stratified air–liquid flows in the grooved rotating disk system when the disk gap is between 1.5 mm and 2.0 mm. The pure liquid region is formed around the internal radius of the disk. The air enters the disk clearance from the outlet and forms the pure air region. Between the pure liquid region and the pure air region, an obvious two-phase interface appears in the radial direction. Further, the two-phase interface of the stratified air–liquid flow is steady. The disk shearing effect is strengthened with the decreasing of the gap at the interface. The centrifugal force of the liquid at the interface will be increased to maintain the balance of the fluid forces. It results in the expansion of the pure liquid region. The two-phase interface also shrinks. In the stratified flow regime, the liquid mainly discharges through the

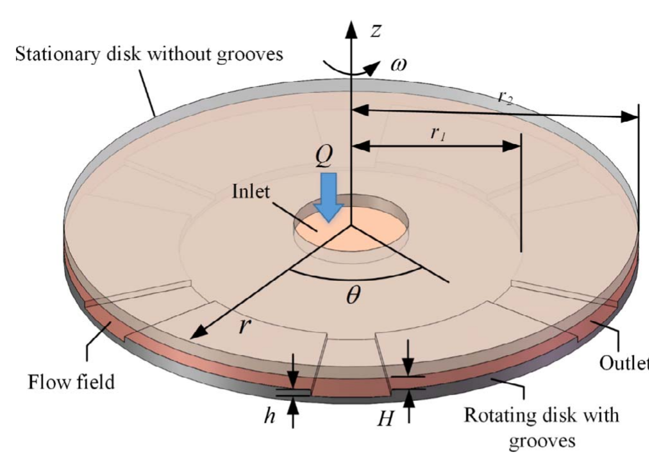

Fig. 1. Configuration of the grooved rotating disk system.