International Journal of Heat and Mass Transfer 73 (2014) 170–176

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Steady dynamical behaviors of novel viscous pump with groove under the rotor

Lu Jianfeng [a,*], Ding Jing [a], Yang Jianping [b], Yang Xiaoxi [a]

[a] School of Engineering, Sun Yat-Sen University, Guangzhou 510006, China
[b] Key Laboratory of Enhanced Heat Transfer and Energy Conservation of Ministry of Education, South China University of Technology, Guangzhou 510640, China

ARTICLE INFO

Article history:
Received 22 August 2011
Received in revised form 9 October 2012
Accepted 28 January 2014
Available online 3 March 2014

Keywords:
Viscous pump
Micro system
Vortex
Groove
Driving power

ABSTRACT

A novel viscous pump with groove under the rotor in straight channel is first analyzed, and associated flow dynamic behaviors and characteristics are numerically investigated by 2-D laminar model. As Reynolds number rises, the vortices near the rotor become asymmetrical and larger, and then the dimensionless flow flux drops, while the dimensionless driving power rises. The groove height can also play an important role in the dynamical performance of the viscous pump. As the groove height increases, the dimensionless flow flux will first increase and then decrease, and it reaches maximum with optimal groove height. For small groove height, the flow passage with positive x-velocity is extended near the rotor, so the flow flux increases with groove height. For large groove height, the vortices in the upstream and downstream regions can combine into one large vortex, and the flow flux is obviously reduced. The driving power also affects the dynamic performance of viscous pump, and it is dependent upon the wall shear stresses at the rotor interface. In the narrow gap between the groove and rotor, thin film flow exists, so the wall shear stresses adjacent to the groove are much larger than those away from the groove, and the shear stresses will reach maximum near the groove edge. As a result, the dimensionless driving power of rotor will increase with the groove height but decrease with the gap width.

1. Introduction

Fluid transport [1] is recently an important task for kinds of NEMS and MEMS applications including biochips, chemical analyses, space technology, and so on. Since fluid transfer becomes an urgent and challenging research topic for microscale system, kinds of novel pumping mechanism have been developed based on the interfacial phenomena [2], electrochemical process [3], and mechanical technology [4]. In microscale system, the effects of inertial force and centrifugal force are normally limited, and the viscous force can become the dominant driving force in fluid transport. Odell and Kovasznay [5] first considered the viscous-driven pump to generate the density stratified flow. In general, the viscous pump can be driven by rotating cylinder, rotating disk [6], screw [7], etc.

The viscous pump driven by rotating cylinder is easy to be fabricated, and associated experiments and numerical computations have been carried out in many literature. Sen et al. [8] proposed viscous pump based on the rotation of a cylinder placed asymmetrically in a narrow channel, and indicated that a net flow was induced by the differential viscous resistance between the small and large gaps. They further tested the fluid transfer performance of the pump with the effects of the channel height, rotor eccentricity and angular velocity, and visually illustrated the flow field using tracer particles. Sharatchandra et al. [9] used a finite-volume approach to simulate the viscous pump at low Reynolds numbers by Navier–Stokes equation, and calculated the critical geometric parameters for optimum performance. Furthermore, Sharatchandra et al. [10] numerically described the thermal aspects of the viscous pump, and considered the effects of temperature-dependent viscosity and viscous dissipation. Courtye et al. [11] numerically analyzed the three dimensional flow in the viscous pump, and found a gradual decrease of bulk velocity and pump energy efficiency for the increase of viscous resistance on the two side walls. Bataineh and Nimr [12] studied the microscale viscous pump with slip flow by 2D Navier–Stokes simulations, and stated that pump head decreased with slip factor increasing.

Different viscous pump configurations were further reported to optimize the pumping performance. Maeng et al. [13] proposed the viscous-driven micropump with tandem rotating cylinders, and calculated the pumping performance. Abdelgawad et al. [14] studied the performance of the viscous micropumps with multiple

* Corresponding author. Tel.: +86 20 39332320; fax: +86 20 39332319.
E-mail addresses: lujfeng@mail.sysu.edu.cn (J. Lu), dingjing@mail.sysu.edu.cn (J. Ding).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.02.004
0017-9310/

Nomenclature

b	groove height (m)
D	channel width (m)
d	diameter of the rotor (m)
h	gap width between the rotor and groove (m)
P	driving power (W)
p	pressure (Pa)
Q	dimensionless flow flux (–)
q	flow flux ($m^2\ s^{-1}$)
Re	Reynolds number (–)
U	characteristic velocity (ms^{-1})
u	x-velocity ($m\ s^{-1}$)
v	y-velocity ($m\ s^{-1}$)
Greek symbols	
μ	viscosity ($kg\ m^{-1}\ s^{-1}$)
τ	wall shear stress (Pa)
θ	angle (–)
ω	angular velocity (s^{-1})

rotors as the dual-horizontal rotor and symmetrical dual-vertical rotor. Silva et al. [15,16] reported three different viscous pump configurations including a straight housed pump and two curved housed pumps, and found that the curved housed pumps provided larger mass flow rate and required less shaft power. Lu et al. [17] numerically studied the flow dynamical behaviors and characteristics of the aligned and staggered viscous pumps, and found the pump type and rotor spacing can play an important role in flow dynamics of the viscous pumps. The flow flux of the staggered pump was usually higher than that of aligned pump, and it can reach maximum flow flux at optimal rotor spacing. Choi et al. [18] optimized the design of a viscous micropump with two rotating cylinders for maximizing efficiency. Till now, few researchers have investigated the dynamical performances of the viscous pump with groove under the rotor, and the groove can increase the flow rate of viscous pump by enlarging the flow passage near the rotor under certain conditions.

This paper numerically investigated the steady flow pattern and dynamical performance of a novel viscous pump with groove under the rotor in microchannels. The viscous pump with groove under the rotor was first designed, and was then simulated using a 2-D laminar model. Based on the simulation results, the flow flux and driving power of the viscous pump were further analyzed with the effects of Reynolds number, the gap width and groove height.

2. Physical and mathematical description

2.1. Pump configurations

Viscous pump with an arc groove under the cylinder rotor, whose center coincides with that of the rotor, is schematically shown in Fig. 1. When the rotor rotates at angular speed of ω, a net flow is driven by the unequal shear stresses on the upper and lower surfaces of the rotor. Important structural parameters of the viscous pump include: the channel width D, the channel length L, the rotor diameter d, the gap width between the rotor and groove h, and the groove height b.

2.2. Governing equations

For the flow dynamical process in viscous pump, the Reynolds number is normally less than 500, so the laminar model can be adopted to simulate this problem. In present article, all the calculations are reported in dimensionless quantities, so the prediction of the viscous pump performance can be used regardless of the dimensions or the fluid. For an incompressible steady flow, the dimensionless governing equations can be written as:

$$\frac{\partial \bar{u}}{\partial \bar{x}} + \frac{\partial \bar{v}}{\partial \bar{y}} = 0 \tag{1a}$$

$$\bar{u}\frac{\partial \bar{u}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{u}}{\partial \bar{y}} = -\frac{\partial \bar{p}}{\partial \bar{x}} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 \bar{u}}{\partial \bar{x}^2} + \frac{\partial^2 \bar{u}}{\partial \bar{y}^2}\right) \tag{1b}$$

$$\bar{u}\frac{\partial \bar{v}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{v}}{\partial \bar{y}} = -\frac{\partial \bar{p}}{\partial \bar{y}} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 \bar{v}}{\partial \bar{x}^2} + \frac{\partial^2 \bar{v}}{\partial \bar{y}^2}\right) \tag{1c}$$

where $\bar{x} = \frac{x}{D}$, $\bar{y} = \frac{y}{D}$, $\bar{u} = \frac{u}{U}$, $\bar{v} = \frac{v}{U}$, $\bar{p} = \frac{p}{\rho U^2}$, and the characteristic velocity and Reynolds number are described as:

$$U = \frac{\omega d}{2} \tag{2a}$$

$$\mathrm{Re} = \frac{\rho U d}{\mu} \tag{2b}$$

The pump structure can be mainly described by four dimensionless geometry parameters, or

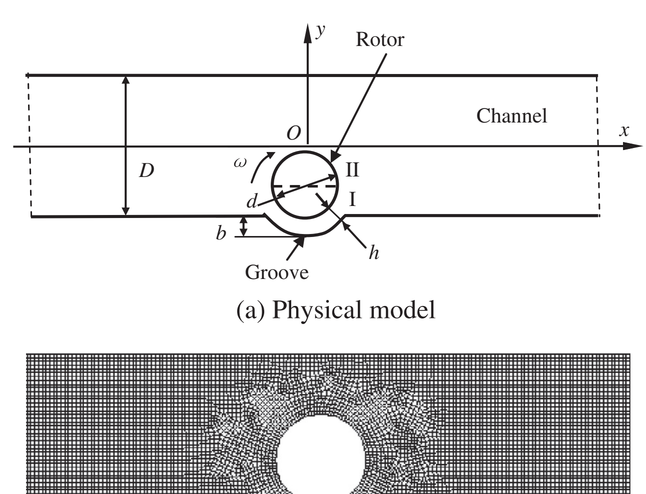
$$\bar{d} = \frac{d}{D}, \quad \bar{h} = \frac{h}{D}, \quad \bar{b} = \frac{b}{D}, \quad \bar{L} = \frac{L}{D} \tag{3a}$$

In present article, $\bar{b}$ and $\bar{h}$ will be investigated in detail, while $\bar{d}$, $\bar{L}$ are respectively assumed to be 0.60 and 12.0.

In order to analyze the viscous pump performances only by the differential viscous resistance at rotor surface, the inlet and outlet pressures are assumed to be zero, or

$$\bar{p}_{in} = \bar{p}_{out} = 0 \tag{4}$$

The channel walls are assumed as non-slip conditions, or



(a) Physical model

(b) Mesh model

Fig. 1. The viscous pump with groove under the cylinder rotor.