



Optimization of the heat transfer coefficient and pressure drop of Taylor-Couette-Poiseuille flows between an inner rotating cylinder and an outer grooved stationary cylinder

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ABSTRACT

The aim of this study is to find optimum values of design parameters of annular flow with outer grooved cylinder and rotating inner cylinder in the presence of axial flow by using Response surface Method (RSM). This configuration is popular in cooling of electric generators and rotating machineries. Groove aspect ratio ($0 < b/c < 1.5$), number of grooves ($0 < N_g < 20$), Taylor number ($0 < Ta < 2.24 \times 10^6$) and axial Reynolds number ($4437 < Re_a < 14,297$) are selected as design parameters while the Nusselt number (Nu) and pressure drop (ΔP) are selected as responses. Firstly, the effect of b/c and N_g on pressure drop, friction factor and heat transfer enhancement inside grooved channel is investigated. In the next step, RSM has been employed to construct correlations required in optimization. The accuracy of correlations is proved experimentally. Finally optimization based on heat transfer to pressure drop ratio has been employed to determine optimum values of design parameters to maximize heat transfer and minimize pressure drop of Couette-Taylor-Poiseuille flow inside the grooved channels. Heat transfer to pressure drop ratio is maximum at $b/c = 1.42$ and $N_g = 19$. This optimization gives a lot of freedom to designers to choose the optimal geometric parameters of electric motors.

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1. Introduction

Heat transfer enhancement inside electric motors and power generators is very important to prevent insulation damage from overheating due to heat generation inside stator and rotor of electric motors. The mechanical designers take into account heat transfer and pressure drop factors and pay attention to geometrical parameters to increase heat transfer and to reduce pressure drop inside annular channels. Fluid flow between two coaxial cylinders in the presence of rotation is called Taylor-Couette flow. If an axial flow is superimposed on the rotation inside an annular channel, it is named Taylor-Couette-Poiseuille flow. Presence of axial flow in the air gap between two coaxial cylinders significantly enhances heat transfer and pressure drop. Maximizing the ratio of heat transfer to pressure drop plays a dominant role in design of the rotating machines and enhances the system efficiency and cooling.

Mounting axial grooves on one or both cylinders is an effective method to enhance the heat transfer inside the annular channels. Lee and Minkowycz [1] experimentally investigated the heat transfer and the pressure drop in four different grooved channels for a

range of Taylor numbers (Ta) between 10^3 and 2×10^7 and the axial Reynolds numbers (Re_a) ranging between 50 and 1000. They concluded that the Nusselt number increases with increasing the axial Reynolds and Taylor numbers. They also found that the presence of grooves on one or both cylinders significantly increases the Nusselt number and the pressure drop inside the annulus. The groove geometries of their experimental work were 10.3×10.3 mm, 10.3×7.8 mm and 10.3×5.3 mm. Hayase et al. [2] conducted a numerical study on heat transfer of annular flow with 12 grooves on rotor and stator. They showed that heat transfer can be enhanced by a factor of 1.2 in the case of inner grooved cylinder and by a factor of 1.1 in the case of outer grooved cylinder. F  not et al. [3] conducted an experimental study on the effect of axial flow on heat transfer enhancement inside a four-pole synchronous motor. Heat transfer decreased from the entrance for both rotor and stator in their study. They also presented two different correlations for the average Nusselt number on stator and rotor. According to Sommerer and Lauriat [4] who developed a numerical modeling of heat transfer in an annulus with rectangular grooves embedded in the outer cylinder, increasing the number of grooves from 0 up to 25 will increase the mean Nusselt number. They also examined the effect of groove aspect ratio on heat transfer at very low Taylor numbers ($Ta < 1700$). The effect of axial

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Nomenclature

A	surface area, mm ²
a	groove pitch, mm
b	groove depth, mm
c	groove width, mm
D	diameter, mm
e	air gap between two cylinders, mm
g	gravitational acceleration, m/s ²
h	heat transfer coefficient, W/m ² K
L	length, mm
N	number
Nu	Nusselt number
p	pressure, N/m ²
Pr	Prandtl number
Q	heat transfer rate, W
r	r-direction
R	cylinder radius, mm
Re	Reynolds number
T	temperature, °C
Ta	Taylor number
U	axial velocity component, m/s
V	peripheral velocity component, m/s

Greek symbols

α	thermal diffusivity, m ² /s
β	thermal expansion coefficient, 1/K
η	performance ratio
ν	kinematic viscosity, m ² /s
ρ	density, kg/m ³
Ω	rotational speed rad/s or rpm

Subscripts

1	inner
2	outer
a	axial, ambient
c	convective heat transfer
eff	effective
g	groove
h	hydraulic
l	lost
s	smooth
t	total
w	wall

grooves on pressure drop was not included in their work. Jeng et al. [5] investigated the heat transfer and pressure drop enhancement of Taylor–Couette–Poiseuille flow in a grooved annulus. The heat transfer was increased by mounting 10×3 mm longitudinal ribs on the rotating inner cylinder, especially at $Re_a = 300$ and 600. They also presented a relationship between the Nusselt number and the rotational Reynolds number. The effect of radial temperature gradient on the Taylor–Couette flow in the presence of grooves on stator was experimentally investigated by Liu et al. [6]. In their work, the number of grooves varied from 0 up to 18. They concluded that the transition process for a larger number of grooves can be accelerated due to perturbation of fluid flow. Both rotor and stator remained at constant temperature in their study. The effect of differentially heated cylinders on heat transfer and the onset of turbulence in annular channel with rotating inner cylinder was numerically investigated by Lopez et al. [7]. They found a new correlation for the critical Rayleigh number in the grooved annulus. They also observed that heat transfer enhances significantly with increasing temperature difference between cylinders. Abou-Ziyan et al. [8] performed an experimental investigation on heat transfer and pressure drop inside annulus by mounting helical fins on the rotating inner cylinder in Taylor–Couette–Poiseuille flow. They showed that heat transfer enhances by a factor of 7.5 in the presence of helical fins at $Re_a = 1.5 \times 10^5$ and $\Omega = 400$ rpm. Further studies about heat transfer and pressure drop inside the grooved annulus can be found in the following references [9–11].

Thermal optimization is an effective method to determine the optimal geometrical parameters in many engineering systems [12–14]. Subasi et al. [15] worked on optimization of a honeycomb heat sink. They employed the response surface methodology (RSM) with the face centered central composite design (FCCCD) to construct correlations for heat transfer and friction factor required in optimization problem. They also proposed semi-analytical equations to find the relationship between objective functions (heat transfer rate and pressure drop) and five independent geometrical and physical parameters. Nouri-Borujerdi et al. [16] used the response surface methodology to optimize geometric parameters and cooling performance of vortex tubes. It is concluded by Jeng

et al. [5] that axial grooves increases both heat transfer and pressure drop inside the grooved cylindrical gap. Therefore, an optimal number of grooves on outer cylinder exists that can be determined by maximizing the heat transfer to pressure drop ratio of Taylor–Couette–Poiseuille flow in grooved channels.

To the authors' knowledge, there is no experimental investigation dealing with the optimization of design parameters (such as number of grooves mounted on stator and groove geometry) of electric motors with rotational and axial fluid flows. The main objective of this study is to optimize the heat transfer to pressure drop ratio inside grooved channels influenced by different geometrical and physical parameters. The effect of grooves geometry on heat transfer and pressure drop in grooved cylindrical gaps is also investigated.

2. Experimental apparatus

Fig. 1 shows the schematic diagram of the experimental setup. The blower supplies the air through a reducer to provide fairly uniform flow with minimum turbulence intensity in the test section inlet. The test section consists of two parts: the rotor which is mounted on a shaft and the stator. The rotor is made of aluminum without any heat loss from its surface with $R_1 = 44.1$ mm and $L = 19.1$ cm. Its temperature reaches a fixed value at the steady state conditions. The stator is made of copper sheet with 0.2 mm thickness with radius $R_2 = 47.5$ mm. Pressure drop across the test section is measured with an inclined manometer. 20 thermocouples are connected to the surface of outer cylinder to measure the surface temperature. Ambient temperature is also measured with high precision k-type thermocouples in the inlet and the outlet of grooved channel. All these thermocouples are connected to a data recorder. The surface of grooved stator is maintained in constant temperature by pumping water from a constant temperature water tank to the stator which is located inside an acrylic container. Water flow rate is controlled by two ball valves and the outer surface of acrylic container is insulated to prevent heat loss to the environment. TT-T-30SLE high precision thermocouples (± 0.1 °C) are used to measure the water temperature at the inlet and outlet of the test section. The volumetric flow rate of water

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