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Heat transfer and vortical structures around a rotating cylinder with a spanwise disk and low-velocity crossflow

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ABSTRACT

In this paper, we study the flow field characteristics and heat transfer of a rotating cylinder with a spanwise disk attached and subjected to low-velocity crossflow with a disk-cylinder diameter ratio, $D_d/D_c = 3.06$. Reynolds Averaged Navier–Stokes (RANS) simulations using the k-ϵ realizable turbulence model with enhanced wall treatment were performed for various crossflow and rotational velocities. We were particularly interested in the case of a rotating cylinder, with a spanwise disk attached, in an air stream with a crossflow Reynolds number, $Re_U = 23{,}560$, and rotational Reynolds numbers, Re_Ω, ranging from 5500 to 109,800. Large-eddy simulations (LES) using the dynamic kinetic energy subgrid-scale model were performed for $Re_\Omega = 54{,}900$ and 109,800. Heat transfer results from the RANS simulations were compared to results from previous studies. Flow statistics computed from the LES calculations were compared to results measured by particle image velocimetry experiments. Unsteady flow patterns and thermal behaviours are discussed with reference to the instantaneous LES results.

1. Introduction

Systems composed of a rotating cylinder with attached fins or disks are commonly used as standard heat exchangers and are important in many engineering applications, such as electrical devices, automobile vehicles, and turbomachinery. Study of heat transfer of the rotating finned cylinder with no crossflow is relevant to magnetic disk storage systems in the computer industry, and to the cooling systems of electrical machinery. Rotors in such rotating systems are often attached with fins or disks to improve the cooling process by increasing the exposed area for heat dissipation. However, in studies on the thermal behaviour of the smooth rotating brake disk [54,55], the rotating heat-pipe brake disk [49,50] or on the cooling processes of rotating systems of electrical devices equipped with fans, the presence of a superposed air crossflow must be considered. Cooling these rotating systems has become a challenge because there are not only many heat sources, such as motors, bearings, and electrical chips, which substantially increase the system temperature, but there are also complex, three-dimensional flow patterns that occur and either enhance or diminish heat transfer in the system.

Various researchers have studied the flow characteristics of an enclosed co-rotating disk pair, which is a simplified model of disk storage. Abrahamson et al. [1] experimentally investigated the flow between shrouded co-rotating disks. The authors observed a solid body inner region near the hub, an outer region dominated by large counter-rotating vortices, and a boundary layer region on the shroud. The inner and outer regions were two dimensional, whereas the shroud boundary layer was three dimensional and displayed a pair of toroidal vortices. Humphrey et al. [17] performed two- and three-dimensional simulations to study unsteady laminar flow between a pair of disks co-rotating in a fixed, cylindrical enclosure. Their results showed that the flow was steady for $Re_U < 22{,}200$ and was characterised by a symmetrical pair of counter-rotating toroidal vortices in the cross-stream plane. At higher Reynolds numbers, the flow became unsteady and periodic, and the symmetry near the middle plane was broken. The flow instability was generated by the interaction between the outward fluid in the Ekman layer of the disk and the fluid flowing inward in the return core flow.

A rotating cylinder with one or multiple spanwise disks attached is a simple model of a disk brake system, which is often used in vehicles such as motorbikes, cars and trains. aus der Wiesche [53–55] has intensively performed numerical simulations to investigate the heat transfer in disk brakes used for motorbikes modelled by a thin rotating disk (ratio of disk thickness and disk radius is $e/R_d = 0.02$) subjected to an additional outer parallel flow. Wiesche [53] estimated the mean Nusselt numbers on the disk surface using Reynolds Averaged Navier–Stokes (RANS) simulations and the classical k-ϵ model of turbulence. In that study, the heat transfer augmentation due to the rotation did not start until a

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Nomenclature

$\langle . \rangle$	time-averaged operator
ϵ	turbulent dissipation rate (m^2/s^3)
λ	thermal conductivity (W/m/K)
μ	dynamic viscosity of air (kg/m/s)
ν	kinematic viscosity of air (m^2/s)
Ω	rotational speed (rad/s)
ω	vorticity magnitude (s^{-1})
ρ	density of air (kg/m^3)
θ	azimuth angle
Nu_m	mean Nusselt number
Pr	Prandtl number
Re_U	$=U_m R_d/\nu$, crossflow Reynolds number
Re_Ω	$= \Omega R_d^2/\nu$, rotational Reynolds number
α	$=U_c/U_m$, spinning ratio
Δt_{LES}	LES time step (s)
Δt_{PIV}	PIV sampling interval (s)
$\dot{q}'$	fluctuating heat flux (W/m^2)
$\dot{q}$	heat flux (W/m^2)
$\dot{q}_m$	surface-averaged heat flux (W/m^2)
$\Omega_{i,j}$	rate of rotation tensor (s^{-1})
c_p	specific heat (J/kg/K)
e	thickness of the spanwise disk (m)
k	turbulent kinetic energy (m^2/s^2)
p	pressure (Pascal)
r	radius (m)
R_c,D_c	radius and diameter of cylinder (m)
R_d,D_d	radius and diameter of spanwise disk (m)
$S_{i,j}$	rate of strain tensor (s^{-1})
T_d,T_∞	temperature of disk and crossflow (°C,°K)
u',v',w'	horizontal, vertical and axial fluctuating velocities (m/s)
U_c	$=\Omega R_c$, cylinder circumferential velocity (m/s)
U_m	mean crossflow velocity (m/s)
u_r,u_θ	radial and tangential velocities (m/s)
$u_{i,j}$	velocity gradient (s^{-1})
x,y,z	horizontal, vertical and axial directions

critical value of rotational velocity was reached. Wiesche [54,55] determined the heat transfer coefficients and various correlations for heat transfer in crossflow and rotational velocity fields by means of large-eddy simulations (LES) using the Smagorinsky subgrid-scale model. The crossflow Reynolds numbers in these studies varied from 10^3 to 10^6, and the maximum ratio between the rotational Reynolds number, Re_Ω, and the crossflow Reynolds number, Re_U, was approximately 10. The results of these studies showed the existence of a critical ratio of the rotational and crossflow Reynolds numbers, above which the rotational heat transfer augmentation set on in the case of the laminar crossflow Reynolds number. However, all of these studies were performed on a thin rotating disk without a rotating cylinder, which serves as a rotating shaft in a practical brake disk system.

The aerodynamic characteristics of a rotating cylinder with endplates have recently been investigated by Badalamenti and Prince [3] and Thouault et al. [47]. The latter authors performed unsteady RANS simulations, comparing their results with the experiment of Badalamenti and Prince [3]. They studied flows with the crossflow Reynolds numbers ranging from 2.9×10^4 to 9.6×10^4, a disk-cylinder diameter ratio, D_d/D_c, ranging from 1.1 to 3, and a spinning ratio, α (the ratio of the cylinder circumferential velocity, U_c, to the crossflow velocity, U_m), varying from 1.9 to 3.4 for $Re_U = 2.9 \times 10^4$, and from 0 to 1.5 for $Re_U = 9.6 \times 10^4$. The results from their unsteady RANS simulations showed the appearance of flow separation on the endplate edges that formed two tip vortices and strongly influenced the flow topology.

The convective heat exchange from a rotating cylinder mounted with spanwise disks can be applied to the cooling system of electrical devices, whose rotors often have fins. This configuration is also suitable for cooling a disk brake connected to a rotating shaft via a heat-pipe, using a finned cylinder for the condenser. For instance, the braking of a high-speed train (TGV) reduces the speed from 320 km/h to 0 km/h, and the friction involved in braking provokes a high temperature on the disk. Without an efficient cooling system, such thermal extremes cause thermal fatigue on the disk, causing disk wear. An experimental setup of a rotating cylinder with a spanwise disk attached has recently been studied in the primary author's research group, allowing researchers to consider the influence of the cylinder's presence on thermal behaviour at various rotational speeds. Watel et al. [50,51] compared the convective heat exchange between cooling a rotating TGV brake disk by air crossflow and cooling a rotating heat pipe disk in still air. The results showed that it was more efficient to cool the disk using the rotating heat pipe. Then, Siroux et al. [44] performed experiments using a thermally heated thick disk and an infrared thermal camera to identify the local and mean Nusselt numbers on a rotating TGV brake disk exposed to air crossflow. The heat transfer experiments were reinforced by Latour et al. [23–25]. The authors have proposed a transient method to identify heat transfer using infrared thermography. These works identified the mean convective heat transfer coefficient by solving the inverse heat transfer problem during the cooling process. Various correlations showing the influence of the crossflow Reynolds number and rotational Reynolds number on the mean Nusselt number were presented in Latour et al. [25]. In these studies, the crossflow Reynolds number based on the cylinder diameter was between 0 and 3.9×10^4, and the rotational Reynolds number based on the cylinder diameter was between 2,000 and 17,000. The heat transfer results obtained for the case of a rotating cylinder with a single disk at a low-velocity crossflow showed a strong reduction in the value of the heat transfer coefficient on the disk surface in the laminar regime when the rotational speed was slow. On the contrary, for the low crossflow Reynolds number, the high rotational speed strongly induced local distribution of the convective coefficients and the mean Nusselt number on the disk surface from the interactions of the boundary layers developed on the cylinder and the disk with the air crossflow.

In this study, the configuration of a rotating cylinder with a spanwise disk subjected to a low-velocity air crossflow is considered. Despite the widely practical applications of rotating devices, few studies of the flow field and thermal behaviour on the disk surface of a rotating cylinder with fins or disks attached are available in the literature. The thermal behaviour and heat transfer results obtained on the disk are expected to link closely with the flow field patterns. However, the flow characteristics of these configurations are not fully understood because of the lack of available data.

The numerical calculations in this paper simulated the experimental setup of a rotating cylinder with a spanwise disk attached subjected to air crossflow, as in the previous heat transfer studies. RANS simulations using the k-ϵ realizable turbulence model with an enhanced wall treatment were performed for the cases of a rotating cylinder with a spanwise disk in still air, a stationary cylinder with a spanwise disk in air crossflow, and a rotating