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Large eddy simulation of turbulent heat transfer from a rotating disk subjected to a forced parallel air stream

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ABSTRACT

Nowadays, rotating disks are an important part of most industries such as turbo machines, heat exchangers, braking systems, rotating sawing machines, and computer disk drives. Working temperature and consequently heat transfer have a profound effect on performance and lifetime of rotating disks. There is a noticeable difference between numerical and experimental results in the studies of turbulent heat transfer from a rotating disk subjected to parallel air stream. The main objective of this study is numerical simulation of turbulent convective heat transfer from a rotating disk subjected to parallel air stream. In this study, the 2nd order finite volume scheme and large eddy simulation (LES) with the dynamic Smagorinsky procedure in sub-grid-scale is used. Two limit cases called rotating disk in still air (von Karman's swirling flow), stationary disk subjected to parallel air stream are investigated as well. The mean Nusselt number of the disk surface is obtained at statistical steady state for a wide range of rotational and cross flow Reynolds numbers. The influence of flow separation and finite disk thickness on heat transfer is investigated and followed by a detailed discussion. The effect of convection and diffusion on temperature field is illustrated. Comparison with experimental data shows that the LES dynamic Smagorinsky results are by far better than available numerical results. It is discussed in detail that there is a critical value for ratio of crossflow Reynolds number to rotational Reynolds number which above that the influence of disk rotation on mean Nusselt number is negligible.

1. Introduction

Nowadays, the rotating disks are an important part of most industries such as turbo machines, heat exchangers, brake systems, rotating sawing machines, and computer industries. Working temperature and consequently heat transfer have a profound effect on performance and lifetime of a rotating disk. Accordingly, heat transfer from rotating disks is of great importance in most industries. Study of fluid flow and heat transfer over a rotating disk have been triggered by von Karman [1] and is still ongoing.

In this paper, heat transfer from a rotating disk is investigated under three different configurations; namely a rotating disk in still air as shown by Fig. 1 (a), a stationary disk subjected to parallel air flow as shown by Fig. 1(b), and a rotating disk subjected to parallel air stream as depicted in Fig. 2.

The later configuration is the main subject of the present investigation. The main aim of the present study is the calculation of mean Nusselt number at the statistical steady state and under constant surface temperature. The mean Nusselt number is defined by Eq. (1).

$$Nu_m = \frac{h_m R}{k_{air}} = \frac{\dot{q}_m R}{k_{air}(T_d - T_\infty)} \tag{1}$$

In equation Eq. (1), $\dot{q}_m$ is the surface-averaged heat flux as defined in Eq. (2).

$$\dot{q}_m = \frac{1}{A}\int \dot{q}\,dA \tag{2}$$

In forced convection, Nusselt number is generally a function of Reynolds and Prandtl number. It can be inferred that, for rotating disks, the mean Nusselt number would be a function of both cross flow and rotational Reynolds numbers as well as the Prantle number [2]. Therefore, in general form, it can be written as follow:

$$Nu_m = Nu_m(Pr, Re_u, Re_\Omega) \tag{3}$$

The cross flow and rotational Reynolds numbers are defined by

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Nomenclature

Variables

$\dot{q}$	heat flux (Wm^{-2})
A	disk surface area (m^2)
C_s	LES sub-grid-scale coefficient
h	heat transfer coefficient ($Wm^{-2}K^{-1}$)
k	thermal conductivity ($Wm^{-1}K^{-1}$)
N_x,	N_y, N_z maximum number of cells in x, y, z direction
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
R	disk radius (m)
Re	Reynolds number
S_{ij}	strain rate tensor
T	temperature (K)
u	velocity components
x	Cartesian coordinate (m)

Greek Symbols

α	thermal diffusivity (m^2s^{-1})
Δx,	Δy, Δz grid size
Δ	grid spacing
δ_{ij}	Kronecker symbol
ω	angular velocity (rad s^{-1})
ρ	density (kg m^{-3})
τ_{ij}^{r}	reduced stress tensor (m^2s^{-2})
υ	kinematic viscosity (m^2s^{-1})

Scripts

$\overline{(.)}$	filtered variable
$\widehat{(.)}$	filtered variable through second filter
$\widehat{(.)}$	filtered variable through second filter
∞	reference
$\langle . \rangle$	space averaging
ω	rotational
d	disk
i,	j, k 1, 2, 3
in	inflow
m	mean
t	turbulent
u	crossflow

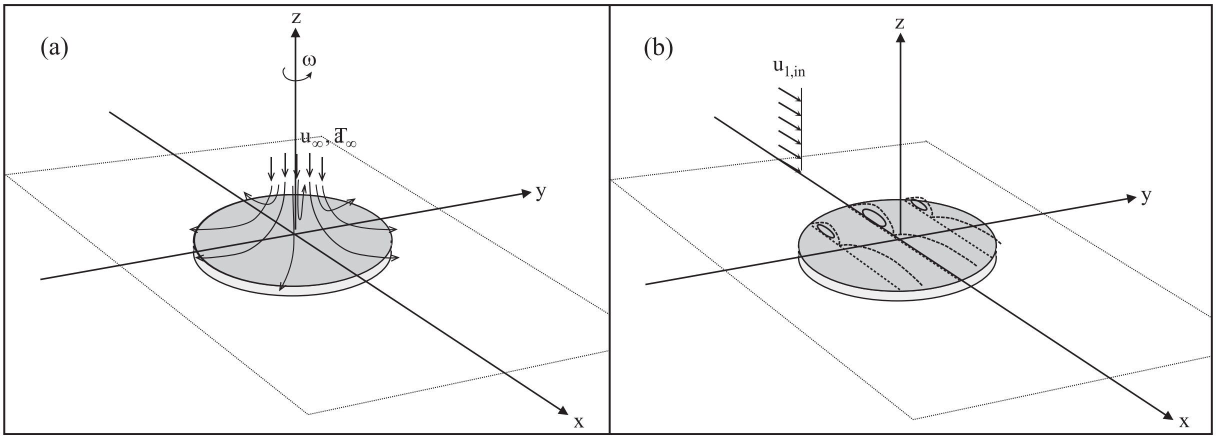

Fig. 1. Schematic of rotating disk in still air and stationary disk subjected to parallel air stream.

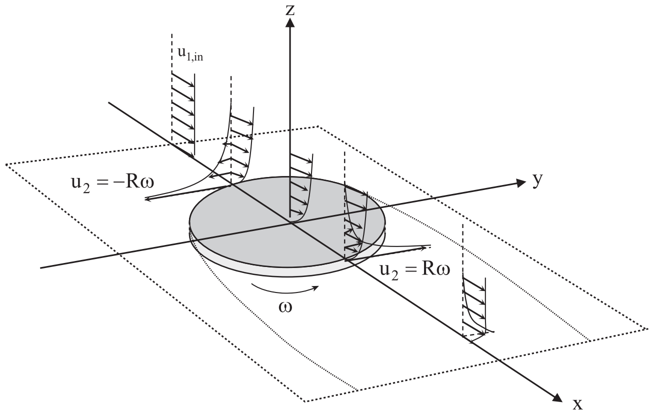

Fig. 2. Schematic of a rotating disk subjected to parallel air stream.

equations (4) and (5) respectively.

$$Re_u = \frac{u_{1,in}R}{\upsilon} \tag{4}$$

$$Re_\omega = \frac{\omega^2 R}{\upsilon} \tag{5}$$

Laminar and turbulent heat transfer from a rotating disk in still air (the first configuration as shown in Fig. 1(a)) have been widely studied by authors through both numerical and experimental approaches [3–6]. Almost all the researchers have considered air with $Pr = 0.7$ as the surrounding fluid. In a general form, $Nu_m = C_1 Re_\omega^{0.5}$ and $Nu_m = C_2.Re_\omega^{0.8}$ have been suggested by the authors for laminar and turbulent regimes respectively.

The laminar and turbulent heat transfer from a stationary disk subjected to parallel air stream (the second configuration as shown in Fig. 1(b)) have also been widely studied through both numerical