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Convective heat transfer on a rotating disk with a centred impinging round jet

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Abstract

Flow visualisations and heat transfer measurements on a rotating disk, with a relatively small centred jet perpendicularly impinging on it, are accomplished by means of infrared (IR) thermography associated with the heated-thin-foil thermal sensor. Flow visualisations show a strong interaction between the turbulent jet and the laminar boundary layer over the rotating disk. A new governing similitude parameter is introduced and a heat transfer correlation for the Nusselt number at the disk centre is proposed. In most cases, the Nusselt number radial profiles tend to overlap if they are normalised with the Nusselt number computed by means of this correlation.

Keywords: Rotating disk; Jet impingement; Local convective heat transfer; Infrared thermography

1. Introduction

The characteristics of the flow field and of the convective heat transfer distribution in rotating systems are both experimentally and theoretically relevant. Of all the possible geometrical shapes, probably the rotating disk is one of the simplest and many design configurations may be realistically represented by it. As a matter of fact, flywheels, disks turbine blades are attached to, disk brakes and even modern high speed CD-ROMs are all examples of practical applications of this model. Very often, the fluid resistance induced by rotation is irrelevant but there are a number of cases where the disk thermal behaviour is of utmost importance.

A possible way to increase both the local and the average heat transfer rates over a rotating disk is to make use of jets impinging on it. The overall increase of the convective heat transfer coefficient h may be caused by two effects: the increased momentum over the disk connected with the jet flow rate and a possible anticipation of transition to turbulence. For centred jets and relatively small nozzle exit diameters, the former effect enhances the convective heat transfer coefficient mostly near the disk centre, while the latter has an influence further away.

Due to their wide use in many processes, round jets perpendicularly impinging on a stationary surface have been widely investigated; two extensive reviews of these studies are given by Martin [1] and Viskanta [2]. For relatively high values of the ratio between the nozzle-to-surface distance and the nozzle exit diameter, the radial distribution of the convective heat transfer coefficient has a bell shaped profile with a maximum at the stagnation impinging point and a monotonic decrease when radially moving downstream (i.e., outward). At smaller distances and for relatively high Reynolds number values, by starting from the stagnation point the radial h profile practically shows a plateau which extends for nearly half a nozzle diameter D followed by a minimum at about 1.2 D, a second maximum at about 2 D and finally a monotonic decrease [3].

Because of its obvious useful applications, also the distribution of the convective heat transfer coefficient over a disk rotating in still air, in both laminar and turbulent

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Nomenclature

a	constant, dimensionless
b	constant, dimensionless
c	constant, dimensionless
D	nozzle exit diameter, m
h	local convective heat transfer coefficient, $\mathrm{W/(m^2\,K)}$
h_0	convective heat transfer coefficient at the disk centre as predicted by Eqs. (16) and (17), $\mathrm{W/(m^2\,K)}$
k	thermal conductivity coefficient of air, W/(m K)
Nu	jet Nusselt number ($=hD/k$), dimensionless
Nu_0	jet Nusselt number at $r = 0$ ($=h_0D/k$), dimensionless
Nu_r	local Nusselt number ($=hr/k$), dimensionless
Pr	Prandtl number, dimensionless
q_j	Joule heat flux, $\mathrm{W/m^2}$
q_k	conductive tangential heat flux, $\mathrm{W/m^2}$
q_nc	heat flux by natural convection to ambient, $\mathrm{W/m^2}$
q_r	radiative heat flux, $\mathrm{W/m^2}$
Q_d	disk induced momentum, N
Q_j	jet momentum rate, N
r	local radius, m
r_t	local radius of transition, m
R	disk radius, m
Re_j	jet Reynolds number ($=VD/\nu$), dimensionless
Re_R	disk Reynolds number ($=\omega R^2/\nu$), dimensionless
Re_r	local Reynolds number ($=\omega r^2/\nu$), dimensionless
Re_rt	local Reynolds number of transition ($=\omega r_\mathrm{t}^2/\nu$), dimensionless
T_aw	adiabatic wall temperature, K
T_w	wall temperature, K or C
V	initial average jet velocity, m/s
z	nozzle exit to disk distance, m

Greek symbols

δ	boundary layer thickness, m
$\Delta T = T_\mathrm{w} - T_\mathrm{aw}$	Temperature difference, K
ζ	dimensionless nozzle to disk distance ($=z/D$), dimensionless
η	dimensionless nozzle to disk distance ($=z/r$), dimensionless
ν	kinematic viscosity coefficient of air, $\mathrm{m^2/s}$
ξ	similitude parameter, dimensionless
ρ^2	square correlation factor
ω	disk angular speed, rad/s

regimes, has been extensively studied in the past; e.g., the papers by Millsaps and Pohlhausen [4] Cobb and Saunders [5], Northrop and Owen [6] and Cardone et al. [7] are herein recalled.

For small values of the local Reynolds number based on the local radius, the induced flow is laminar and the boundary layer thickness turns out to be constant over the disk surface. Consequently, the convective heat transfer coefficient is also independent of the local radius and is practically a sole function of the angular speed:

$$h = ak\sqrt{\frac{\omega}{\nu}} \tag{1}$$

where h is the above mentioned convective heat transfer coefficient, a is a dimensionless constant, ω the disk angular speed, k and ν, respectively, the thermal conductivity and the kinematic viscosity coefficients of air.

The constant of Eq. (1) is a function of the Prandtl number and can be evaluated from the existing exact solution of the governing equations [4]; in particular, for air at ambient temperature ($Pr = 0.71$), a turns out to be equal to 0.33. Often, Eq. (1) is expressed in terms of non dimensional quantities:

$$Nu_r = a\sqrt{Re_r} \tag{2}$$

where Nu_r is the local Nusselt number and Re_r is the local Reynolds number, both based on the local radius r.

For relatively high values of the local Reynolds number, the flow becomes unstable and transition to turbulent flow eventually occurs. Clearly the transitional Reynolds number is strongly dependent on the experimental conditions and generally ranges between 200,000 and 320,000.

In the turbulent regime the convective heat transfer coefficient is an increasing function of the local radius [7] and can be expressed as:

$$Nu_r = 0.0163Re_r^{0.8} \tag{3}$$

The condition of a jet impinging on a rotating surface is more complex because of the interaction between the jet and the boundary layer due to the disk rotation. Several articles analyse the convective heat transfer coefficient from a rotating disk to a uniform stream parallel to the disk axis of rotation such as those of Evans and Greif [8] and Yen et al. [9]. Many other papers report on relatively small non-centred jets: e.g., Metzger et al. [10], Popiel and Boguslawski [11], Brodersen and Metzger [12] and Brodersen et al. [13] and [14]. To the authors' knowledge, only few works consider a small centred jet.

Chen et al. [15] study the local convective heat transfer coefficient over a rotating disk with, and without, an impinging jet by means of the naphthalene sublimation technique. Experiments carried out on the disk with no jet appear to be in agreement with those already existing in the literature. The majority of the authors' work deals with non-centred jets but they also show one test for a cen-