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Technical Note

An experimental investigation into impinging forced convection heat transfer from stationary isothermal circular disks

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1. Introduction

Extensive experimental and theoretical research has been conducted for forced convection heat transfer over many different geometries as indicated by dimensionless correlations presented in current heat transfer textbooks [1,2]. A geometry that is largely missing from these extensive lists is that of a simple circular disk, which is an important geometry when considering the cooling of disk-shaped electronic components and silicon wafers, and shell-and-tube heat exchangers with disk-and-doughnut baffles [3], to name just a few. Some research has been performed with forced, natural and combined forced and natural (mixed) convection over stationary circular disks with the disk-axis perpendicular to the direction of the fluid flow [4] (crossflow). Research is also available in the archival literature involving a jet impinging locally on a stationary disk *surface* [5–7], as well as on one that is rotating [8,9]. However, no research exists, to the best knowledge of these authors, dealing with forced convection over a stationary three-dimensional disk geometry with the disk-axis parallel to the direction of fluid flow (impinging flow). The difference between the characteristics of crossflow forced convection and that due to impinging flow is worthy of comparison, as will be shown in this paper. Also, the current data and correlation are compared with prior forced convection research where the flow was not impinging; this comparison illustrating a dramatic difference in heat transfer at high values of the Reynolds number, while a negligible difference at low values.

2. Experimental technique and apparatus

The experimental apparatus utilized in the current study is the same system described in prior research [4] with little modification, and therefore will only be summarized here. Briefly, the system consists of a miniature wind tunnel connected to an air supply. The thermistor disk heat transfer models were self-heated by means of Joule heating; this heating being essentially equal to the convective heat dissipation rate, which in turn is used to indirectly measure the convective heat transfer coefficient and eventually the Nusselt number. Experimental uncertainties, also discussed in detail in [4] remained at about ±10% for both the Reynolds and Nusselt numbers.

In the prior research, the disk axis was perpendicular to the direction of the air flow and the disks were mounted inside the wind tunnel. For this research the disk axis is parallel to the direction of the fluid flow so the disk is mounted just outside the wind tunnel. In this case, the disk had to be placed just outside the wind tunnel test section because of the significant blockage that would have occurred if the model were placed inside,

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forcing the air to momentarily accelerate past the heat transfer model. This was not a significant factor in the prior research [4]. However, the disk needed to be close enough to the end of the tunnel so the fluid velocity around the disk is the same as the measured fluid velocity in the tunnel. To be sure that an insignificant amount of entrainment of ambient air was occurring at the point of measurement, a hot-wire anemometer was utilized in the early stages of experimentation confirming the impinging flow onto the disk was essentially uniform over the entire range of data presented, which is similar to the velocity verification done by Kobus and Wedekind [4]. An illustration of the disk orientation and a schematic of the apparatus are shown in Fig. 1.

As the thermistor temperature increases, the thermistor resistance correspondingly decreases. The thermistor heat transfer models were precalibrated such that temperature data could be obtained by measuring voltages [4]. In order to keep the thermistor from overheating, it was connected in series with a protection circuit, which would shut off power in the event of thermistor overheat. The thermistors have lead wires soldered to each flat side. The flat sides were painted with high electrical conductivity silver paint for even current distribution. The lead wire length and diameter were chosen to create a negligible "fin effect", so that the internal joule heating in the thermistor is approximately equal to the heat transfer from the thermistor [4] directly to the surrounding fluid. When experiments were run, care was taken to ensure that natural convection effects (when the velocity was low) were minimal. This was done by limiting the value of the Richardson Number, Ri_d, above a critical threshold, $Ri_d \sim 1$ [4].

3. Experimental results

Significant amounts of experimental data were obtained in the current research. The non-dimensional data are plotted in Fig. 2. Six different circular disk models were tested, ranging in diameter, $5.2 \leqslant d \leqslant 19.97$ mm, and in thickness-to-diameter aspect ratio, $0.063 \leqslant (t/d) \leqslant 0.163$ (Table 1). Reynold's numbers ranged from about 30 to 45,000. The lower range limit was established as the point of full forced convection based on the research of [4]. The experimental data diverged with the orientation at $Re_d \approx 1000$. Below $Re_d = 1000$ the orientation of the disk thermistors had negligible effect on heat transfer. Above $Re_d = 1000$ the disk orientation had an increasing effect on the heat transfer. It is likely that at higher Reynolds numbers, flow separation becomes an increasingly important factor. A summary of the correlations based on the current experimental data is presented in Table 2. It should be noted that the authors did attempt to collapse the experimental data at the higher velocities where disk orientation was clearly seen to be an influence by utilizing the method of Hassani and Hollands [10], who proposed a new characteristic length to collapse different geometries at various orientations in natural convection. Utilizing their characteristic length based on the square root of the area, the experimental data displayed in Fig. 2 did not show any type of increased collapse and thus the resulting correlation would have been of no greater use than that already presented in this research based simply upon the disk diameter, d. Interestingly, this prior research [10] did obtain experimental data for circular disks in different orientation, but again only for pure

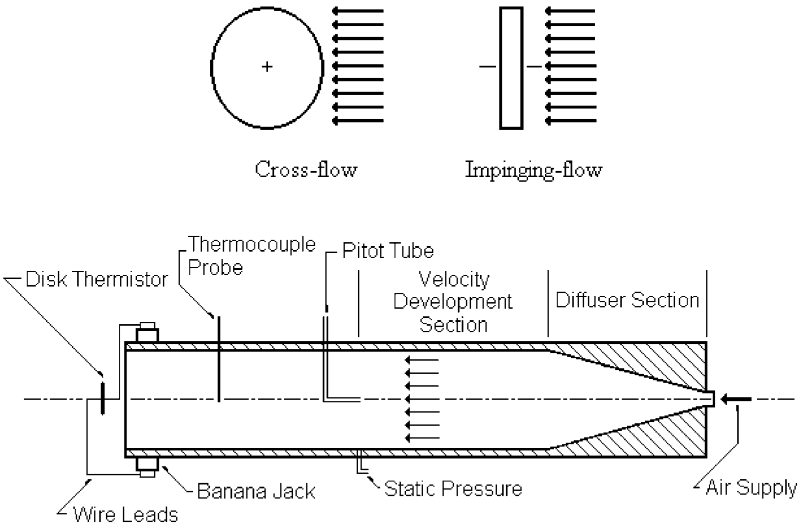

Fig. 1. Schematic of experimental apparatus and disk orientation.

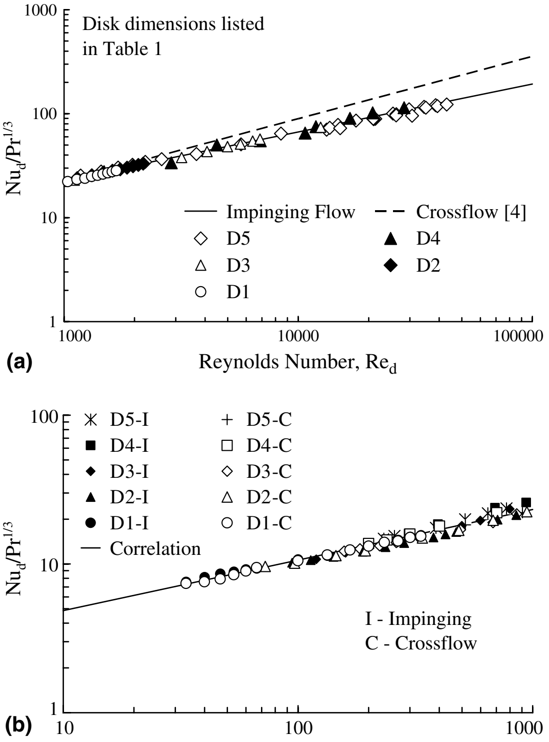

Fig. 2. Comparison of crossflow and impinging-flow orientations. (a) Prior crossflow correlation to current impinging-flow data for Re_d Over 1000. (b) Current crossflow and impinging-flow data for Re_d below 1000.

Table 1
Disk model dimensions

Disk label	d (mm)	(t/d)
D1	5.207	0.163
D2	7.402	0.156
D3	10.330	0.091
D4	15.479	0.063
D5	19.910	0.068

Table 2
Comparison of correlation results

Dimensionless correlation: $Nu_d = CPr^{1/3}Re_d^n$

Disk orientation	Re_d range	C	n	Research
Crossflow	1000–50,000	0.356	0.60	Prior [4]
Impinging flow	1000–50,000	0.966	0.46	Current
Crossflow/impinging	30–1000	2.22	0.34	Current

natural convection. This does not, however, preclude the possibility of eventually obtaining an appropriate characteristic length for pure forced convection that would be capable of collapsing the experimental data for various orientations to a single curve.

4. Discussion and conclusion

According to the experimental results in the current research, disk orientation can greatly affect forced convection heat transfer for $Re_d > 1000$. Impinging flow heat transfer appears to be lower than that of a crossflow orientation in this range. For $Re_d < 1000$, heat transfer data for the crossflow orientation are virtually indistinguishable from their impinging-flow counterparts. One reason may be the possibility of significant separation of the flow over the disk at higher Reynolds numbers.

All of the data in this and the comparative prior research was taken for air ($Pr = 0.72$) as the working medium. It would be interesting to see both the influence of the Prandtl number and of inclination angle between the crossflow and impinging orientations, the latter of which was investigated by [11] but for pure natural convection only. This could be an area of some future research.

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References

[1] J.P. Holman, Heat Transfer, seventh ed., McGraw-Hill, New York, 1990 (Chapter 6).
[2] F.P. Incropera, D.P. DeWitt, Fundamentals of Heat and Mass Transfer, third ed., Wiley, New York, 1990 (Chapters 6, 7 and 9).
[3] H. Li, V. Kottke, Analysis of local shell side heat and mass transfer in the shell-and-tube heat exchanger with disc-and-doughnut baffles, Int. J. Heat Mass Transfer 42 (1999) 3509–3521.
[4] C.J. Kobus, G.L. Wedekind, An experimental investigation into forced, natural, and combined forced and natural convection heat transfer from stationary isothermal circular disks, Int. J. Heat Mass Transfer 38 (18) (1995) 3329–3339.
[5] M. Monde, Critical heat flux in saturated forced convection boiling on a heated disk with an impinging jet, J. Heat Transfer 109 (1987) 991–996.
[6] E.A. Siba, M. Ganesa-Pillai, K.T. Harris, A. Haji-Sheik, Heat transfer in a high turbulence air jet impinging over a flat circular disk, J. Heat Transfer 125 (2) (2003) 257–265.

[7] A.J. Bula, M.M. Rahman, J.E. Leleand, Axial steady free surface jet impinging over a flat disk with discrete heat sources, Int. J. Heat Fluid Flow 21 (1) (2000) 11–21.

[8] B. Banerjee, K.V. Chalapathi, Rao, V.M.K. Sastri, Heat transfer from corotating and stationary parallel concentric disks with internal heat generation, Exp. Therm. Fluid Sci. 1 (1988) 195–206.

[9] J. Wojtkowiak, J.M. Hyun, Flow and heat transfer in a pipe containing a coaxially-rotating disk, Fluid Dyn. Res. 26 (2000) 377–391.

[10] A.V. Hassani, K.G.T. Hollands, A simplified method for estimating natural convection heat transfer from bodies of arbitrary shape, in: Proceedings of the 24th National Heat Transfer Conference, Pittsburgh, PA, August 9–12, 1987.

[11] C.J. Kobus, G.L. Wedekind, An investigation into natural convection heat transfer from isothermal thin circular disks at arbitrary angles of inclination, Int. J. Heat Mass Transfer 45 (5) (2002) 1159–1163.