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Investigation of flow characteristics from an inclined jet on a heated rotating disk

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ABSTRACT

Impinging jet directly hits the object surface to achieve drying, heating or cooling purpose. Jet flow and rotation parameters will affect the flow field. In this paper, the flow pattern and velocity distribution of the inclined jet on a rotating disk under different experimental conditions were investigated using particle image velocimetry (PIV). The investigated parameters included: jet Reynolds number (173–979), jet angle (45°, 60°, and 90°), rotational Reynolds number (0–21,000), and Grashof number (0–300,000). The result showed that inclination angle could cause unsymmetrical flow velocities in the radial direction of the stationary disk. Also, the flow above the heated stationary disk was influenced by the vortex flow generated by the buoyancy force at lower inlet flow rate. However, the flow pattern was not affected by the jet angle at lower jet flow rate on the high-speed rotating disk. The flow pattern can be characterized by using a series of dimensionless parameters, including rotational Reynolds number, jet Reynolds number, and Grashof number.

1. Introduction

The use of impinging jet for drying, heating, or cooling can be found in a variety of industries, such as paper drying, tempering of glass, and electronics cooling. The flow field induced by impinging jet on stationary surfaces can be influenced by a series of parameters, including nozzle diameter, nozzle-to-plate spacing, inclined angle, jet Reynolds number, etc. The impinging jet is also frequently used on rotating surfaces, such as rotating disk reactors and stator-rotor disks in gas turbine engine. However, compared with the flow field on stationary surfaces, the flow field on rotating surfaces is even more complex due to the impact of rotating boundary layer on the velocity and turbulence intensity in the impinged area and the wall jet area. Also, buoyancy force is crucial in the flow field development when there is a temperature difference between the impinging jet and rotating surfaces. The flow field triggered by the intertwined effect of impinging jet, rotation, and buoyancy could be extremely complex. Therefore, extensive efforts were taken aiming at characterizing the flow field with such complexity.

Fitzgerald et al. [1] experimentally studied the flow field of an axisymmetric, confined, and submerged turbulent jet impinging normally on a flat plate using Laser Doppler Velocimetry over a range of nozzle diameter, nozzle-to-plate spacing, and Reynolds number. The results showed that the center of the vortex in the induced flow field moved radially outward with increases in the Reynolds number. Also, an increase in the nozzle-to-target plate spacing could reduce the magnitude of the radial velocities as well as the peak turbulence intensities in the flow field. Carcasci [2] conducted an experimental flow visualization to determine the flow pattern for a single jet and a pair of jets impinging on a flat plate with a subsonic velocity. The results showed that a pair of reverse vortices were formed between the main vortices and the topmost flat plate when a pair of jets was introduced, which led to a local peak of heat transfer coefficient. Narayanan et al. [3] conducted an experimental study of flow field, surface pressure, and heat transfer rates of a submerged, turbulent, slot jet impinging normally on a flat plate. The heat transfer data showed high heat transfer rates in the impinged region for transitional jet impingement, and a nonmonotonic decay in heat transfer coefficient for potential-core jet impingement. Hsieh et al. [4] conducted an experimental study combining flow visualization and temperature measurement of a heated horizontal circular disk confined in a vertical cylindrical chamber. The results indicate that at sufficiently high jet Reynolds number a third and fourth vortices could be induced aside from the primary and secondary vortices driven by inertia forces. Wang et al. [5] investigated the flow patterns induced by a fully-developed turbulent round jet impinging normally onto a flat plate. It was found that the flow patterns were

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Nomenclature

D	diameter of the nozzle (m)
g	gravitational acceleration (m/s^2)
Gr	grashof number ($=g\beta\Delta TH^3/\nu^2$)
H	chamber height (m)
Q	inlet volume flow rate (LPM)
R	radius of the rotating disk (m)
Re_j	jet Reynolds number ($=\rho V_j D/\mu$)
Re_ω	rotational Reynolds number ($=\omega R^2/\nu$)
T_i	inlet fluid temperature (°C or K)
T_w	disk temperature (°C or K)
ΔT	temperature difference between the disk and the inlet fluid (°C or K)
V_j	jet flow velocity (m/s)
V_r, V_z	radial and axial velocity components (m/s)
x, y, z	cartesian coordinate
β	thermal expansion coefficient (K^{-1})
μ	dynamic viscosity of fluid (Pa·s)
ν	kinematic viscosity (m^2/s)
ρ	density of fluid (kg/m^3)
λ	wavelength of laser (nm)
ω	rotational speed (rad/s)

highly dependent on the jet-to-plate distance ratio and insensitive to the Reynolds number. The vertical velocity decreased as the jet approaching to the plate. In the proximity of the plate, a wall jet area was formed by deflecting the jet into the radial direction. After reaching the maximum velocity at the edge of the plate, the jet was deflected again by the wall and formed vortices. The above literature showed that the flow field induced by impinging jets on stationary surfaces is dependent on a series of flow parameters.

Several studied were also conducted to investigate the flow field on rotating surfaces induced by impinging jet. For example, Brodersen et al. [6,7] experimentally studied the flow field resulted from the interaction between an impinging jet and a rotating disk through localized laser-Doppler velocimetry measurements. The results showed that the flow field and the turbulence intensity were determined by the ratio of jet Reynolds number to the disk Reynolds number. When this ratio was greater than 0.125, the characteristics of the flow field was similar to that observed on a stationary surface. Itoh et al. [8] measured the mean velocity distributions and all six components of Reynolds stress using a hot-wire anemometer for the investigation of the rotation effect on a radial wall jet. It was revealed that the velocity profile showed a similarity when the ratio of maximum radial velocity component to the disk speed at the same radial location was greater than 0.2. Chiang et al. [9] explored the flow field on a rotating disk confined in a rectangular chamber through numerical simulation over a range of Reynolds number from 500 to 2000. The analysis of experimental results revealed the existence of secondary recirculation flow and vortices at corners in the plane perpendicular to the rotating disk. Minagawa and Obi [10] quantified the rotational effect on the wall jet area by measuring the velocity in the turbulent boundary layer developed on a rotating disk. Based on the experimental results, a non-dimensional parameter correlating the radial location and the disk rotational speed was proposed for the simple classification of the resulting velocity field. Abdel-Fattah [11] studied the influence of wall rotation on the characteristics of an impinging jet through the calculation of quasi-three-dimensional momentum equations. The results showed that the radial velocity and turbulence intensity increased with increasing the rotation speed and decreased with increasing the nozzle to disk spacing.

Recently, the particle image velocimetry (PIV) is broadly used for flow measurement on the rotating disk because it provides instantaneous and time-averaged flow field. Wu et al. [12] investigated the coherent flow between enclosed co-rotating disks at a fixed rotational speed and Reynolds number using flow visualization and PIV. The results showed that the flow between the disks could be characterized by eight sub-flow regions. Nguyen et al. [13] experimentally investigated the flow characteristics of an air jet impinging on an open rotor-stator system with a low non-dimensional spacing and a low aspect ratio using PIV. A recirculation flow region, which was centered at the impingement point and possessed high turbulence intensities, was observed. Liu et al. [14] studied the flow field of a jet impingement on a rotating heated disk to simulate the flow field induced by the rotating disk of a chemical vapor deposition (CVD) reactor. The experimental results showed that upward buoyancy, caused by the heated disk, produced flow cells and broke the flow uniformity above the disk. When the rotational Reynolds number increased, the rotational effect eventually dominated the flow field that increased the flow velocity and generated flow cells near the chamber wall. Afterwards, the flow field in a high temperature rotating disk CVD chamber with perforated showerhead inlet was studied [15]. It was discovered that the buoyancy-induced flow could be suppressed through disk rotation or chamber height reduction. Manceau et al. [16] investigated a turbulent round jet impinging perpendicularly onto a rotating, heated disk to understand the influence of rotation on the radial wall jet and associated heat transfer. The above literature indicate that the vortices caused by the rotational effect will affect the flow field induced by impinging jets on rotating disks.

Although significant studies focus on the jet impingement on surfaces normal to the flow direction, few studied were conducted on the inclined jet impingement. Yang et al. [17] conducted a numerical study on the flow field and heat transfer characteristics of multiple impinging slot jets with an inclined confinement surface using two turbulence models. The numerical results show that the maximum local Nusselt number and pressure on the impinging surface moved downstream as the inclination angle increased. Additionally, the recirculation region was significantly affected by the inclination angle but insensitive to the jet Reynolds number. Crafton et al. [18] studied the flow field resulted from a water jet impinging onto a surface at an inclined angle. The results indicated that the location of the stagnation point was a strong function of impingement angle and a weak function of impingement distance and pressure ratio. Jalil et al. [19] experimentally studied the impingement of turbulent water jet on a horizontal plate with varying inclined angles. The thickness profile of the deflected jet in the center plane and the transverse thickness profiles in the deflected jet varied mainly with the angle of jet impingement. The maximum velocity was observed when the impinging height was equal to the boundary layer thickness. O'Donovan et al. [20] experimentally investigated the heat transfer to an impinging air jet. The surface heat transfer results were reported over a range of nozzle-to-plate distance and angle of impingement. The results showed that the displacement magnitude of the stagnation point was inversely proportional to the angle of impingement and was not influenced by the nozzle-to-plate distance. Akansu et al. [21] determined the effects of inclination of an impinging two-dimensional slot jet on the heat transfer from a flat plate. As the inclination angle increased, the location of the maximum heat transfer shifted towards the uphill side of the plate and the value