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Experimental Investigation of the Vortex Dynamics in Circular Jet Impinging on Rotating Disk

Mouhammad El Hassan[1], Alexander J. Hunt[1], David S. Nobes[1*]

[1]University of Alberta, Department of Mechanical Engineering, Edmonton, Canada

*dnobes@ualberta.ca

Abstract

A circular jet impinging perpendicularly onto a rotating disc is studied in order to understand the influence of the centrifugal forces on the radial wall jet. Time-resolved PIV measurements are conducted in different jet regions in order to investigate the flow physics of the large-scale vortical structures and the boundary layer development on the impinging wall for both stationary and rotating impinging disks. The Reynolds number is $Re_D = 2480$, the orifice-to-plate distance $H = 4D$ (D is the jet-orifice diameter) and the rotation rate is 200RPM. It is found that the rotation of the impinging wall results in strong centrifugal effects which affect different regions of the jet. Both radial velocity profiles and turbulence intensity distributions show different behavior when comparing the stationary and rotating cases. Finite Time Lyapunov Exponent results illustrates the time-resolved behavior of the large-scale vertical structures and flow separation.

1 Introduction

Impinging jets have been extensively investigated because of their wide industrial applications, ranging from turbine blade cooling, to drying processes and cooling of electronic devices, etc. Despite their geometric simplicity, the flow physics of impinging jets is complex. The flow dynamics of a jet impinging on a rotating disk has received less attention than with stationary disk despite its relevance to cooling processes in many industrial applications, such as the cooling of bearings, gas turbines disks, and alternators of wind generators [1-3]. The focus of the existing literature on jets impinging on rotating disk is to investigate the jet flow in a rotor-stator configuration. The main difference in the present jet configuration is the absence of a flow confinement around the jet exit which would highly affect the flow dynamics.

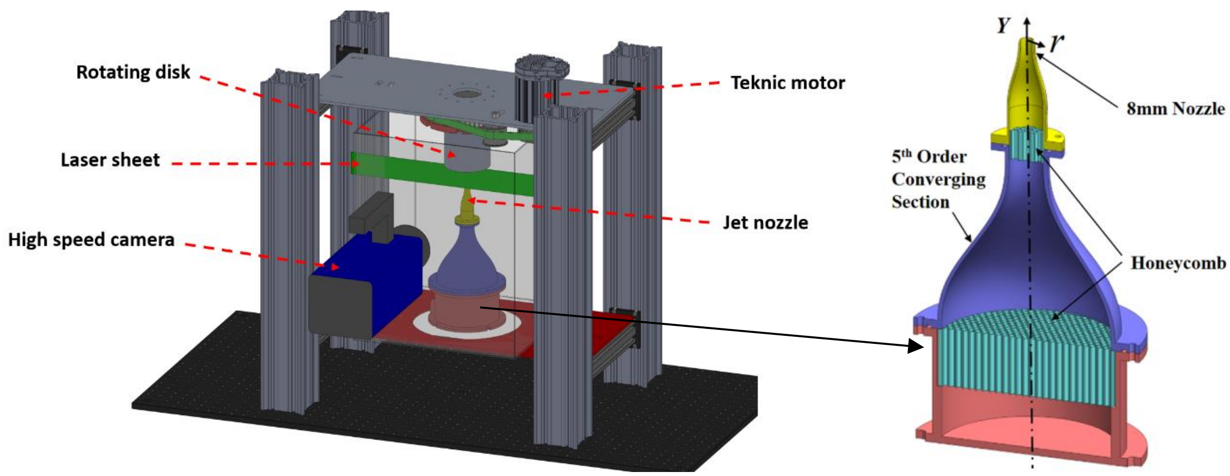
An impinging jet is usually decomposed into three regions: the free jet, the impinging region and the outer wall-jet region. The physical composition of impinging jets depends upon a number of parameters, such as Reynolds number, orifice shape, orifice-to-plate distance and inflow turbulence. Each region of an impinging jet features different turbulence dynamics and requires an in-depth flow physics analysis using advanced experimental techniques.

The primary objective of our study is to deepen the knowledge of the turbulent boundary layer that develops on a rotating disk through detailed experimental measurements, not only in terms of the mean velocity and turbulence statistics but also from a fundamental understanding of the vortex dynamics and their interaction with the impinging wall. Therefore, the complex flow physics of the impinging jet is investigated using time-resolved particle image velocimetry (TR-PIV) measurements.

2 Experimental Setup

The experimental setup shown in Figure 1 consists of a jet nozzle positioned inside a rectangular tank. The water jet impinges on a circular disk and the rotating motion is generated using a programmable electric servo motor. Proper flow conditioning is achieved using a converging chamber with a fifth order polynomial shape into the jet nozzle, 2 honey combs and a settling chamber as shown in Figure 1(b). The Reynolds number based on the jet exit velocity and the jet diameter, D = 8mm was Re_D = 2480. The rotational speed of the impinging disk was 200 RPM and the jet exit is located at H = 4D from the impinging wall.

Velocity fields in the jet and impingement regions are obtained using TR-PIV. The system is composed of a Phantom V611 camera of 1200×800 pixels^2 and a Photonics Industries Nd:YLF laser of 30 mJ energy and 527 nm wavelength. Small glass spheres, 40 μm in diameter, are used as tracer for the PIV measurements. Data sets of 2500 PIV image pairs were acquired at a frequency of 500 Hz for each acquisition run. The synchronization between the laser and the camera is controlled by a LaVision High-Speed Controller and the data acquisition is performed with DaVis 8.4 software. The images are processed by an adaptive multigrid algorithm correlation handling the distortion window and the sub-pixel window displacement. The final grid is composed of 32×32 pixels size interrogation windows with 50% overlap leading to a spatial resolution of 0.6 mm. The maximal displacement error is equal to 1.1% and 1.7% for the longitudinal and the vertical velocity components [6]. The accumulation of the rms error and the bias error gives a total error of about 3.2% of the mean axial velocity.



(a) (b)

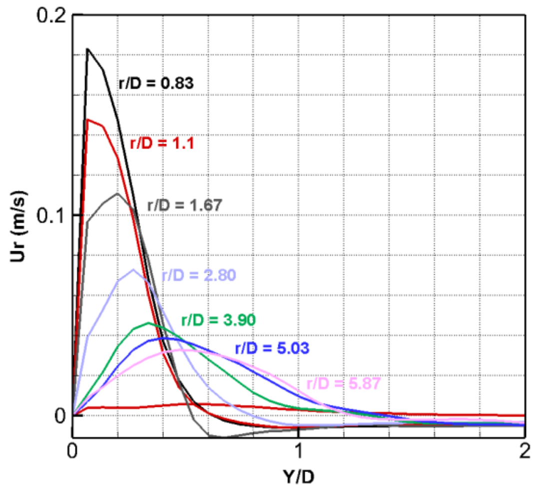
Figure 1: Schematic view of (a) the experimental setup and (b) the jet flow conditioning

3 Results

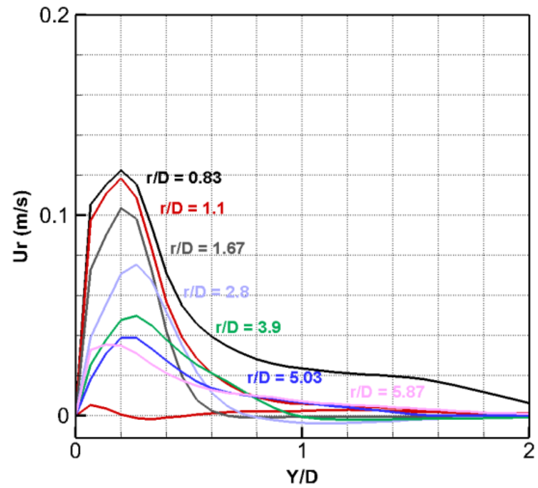
In order to study the influence of the impinging wall rotation on the velocity distribution, mean radial velocity profiles are extracted at different radial locations of the impinging wall for both the stationary and rotating disk, as shown in Figure 2. In the present study, the impinging region corresponds to $r/D < 1.7$ and the near-wall region, $Y/D < 0.1$. It is found that in the impinging region, the radial velocity is smaller with the rotating disk as compared to the stationary case ($r/D = 0$ is the jet centerline) in the near-wall region. However, the radial velocity becomes higher in the outer region of the impinging wall with the rotating disk as compared to the stationary case. Farther from the impinging wall ($Y/D > 0.1$), an opposite trend is observed.

To the author’s knowledge, such distribution of the radial velocity in the impinging region has not been investigated in the literature and it therefore would be of significant interest to better understand the flow physics responsible of such velocity distribution. For a similar jet configuration using a numerical approach, Abdel-Fattah [4] found that the influence of the rotating disk appears only in the outer jet region. The difference between [4] and the present results could be attributed to a poor prediction of the vortex dynamics and flow separation in the impinging region in Abdel-Fattah’s study.

Figure 2 also shows that the maximum radial velocity is observed at $r/D = 0.83$. Minagawa and Obi [5] experimentally found a maximum radial velocity around $r/D = 1$. It can be suggested that this difference is due to a greater jet shear layer growth in [5] as compared to the present investigation due to the larger distance between the jet exit and the impinging wall.



(a)



(b)

Figure 2: Radial velocity profiles for the impinging jet onto (a) stationary and (b) rotational disk (200RPM)

Radial and longitudinal turbulence intensity distributions are plotted in the Figure 3 for the stationary and the rotating cases. For the rotational case, the radial turbulence intensity ($U_{r,rms}$) presents higher values upstream from the impinging plate and in the outer near-wall region of the plate, Regions 1 and 3 in the Figures 3(a) and 3(b). The vertical turbulence intensity ($U_{y,rms}$) shows higher amplitude in the impinging region, Region 2 in Figures 3(c) and 3(d), with the stationary disk as compared to the rotational case. This suggests that the centrifugal force of the rotational disk results in inducing swirl into the free jet just upstream from its impingement on the rotating wall. Such jet swirl results in a modified vortical structures and enhanced mixing which would be responsible of the distribution of the radial RMS observed in Region 1. The centrifugal force also results in an advection of the large vortical structures closer to the impinging wall when traveling from the jet center outward in the radial direction. For the stationary case, the large vortical structures separate from the wall in Region 2. This results in a lower vertical turbulence intensity observed in Region 2 for the rotational case and the higher radial turbulence intensity close to the wall in the outer region, Region 3 in Figures 3 (a) and 3 (b).

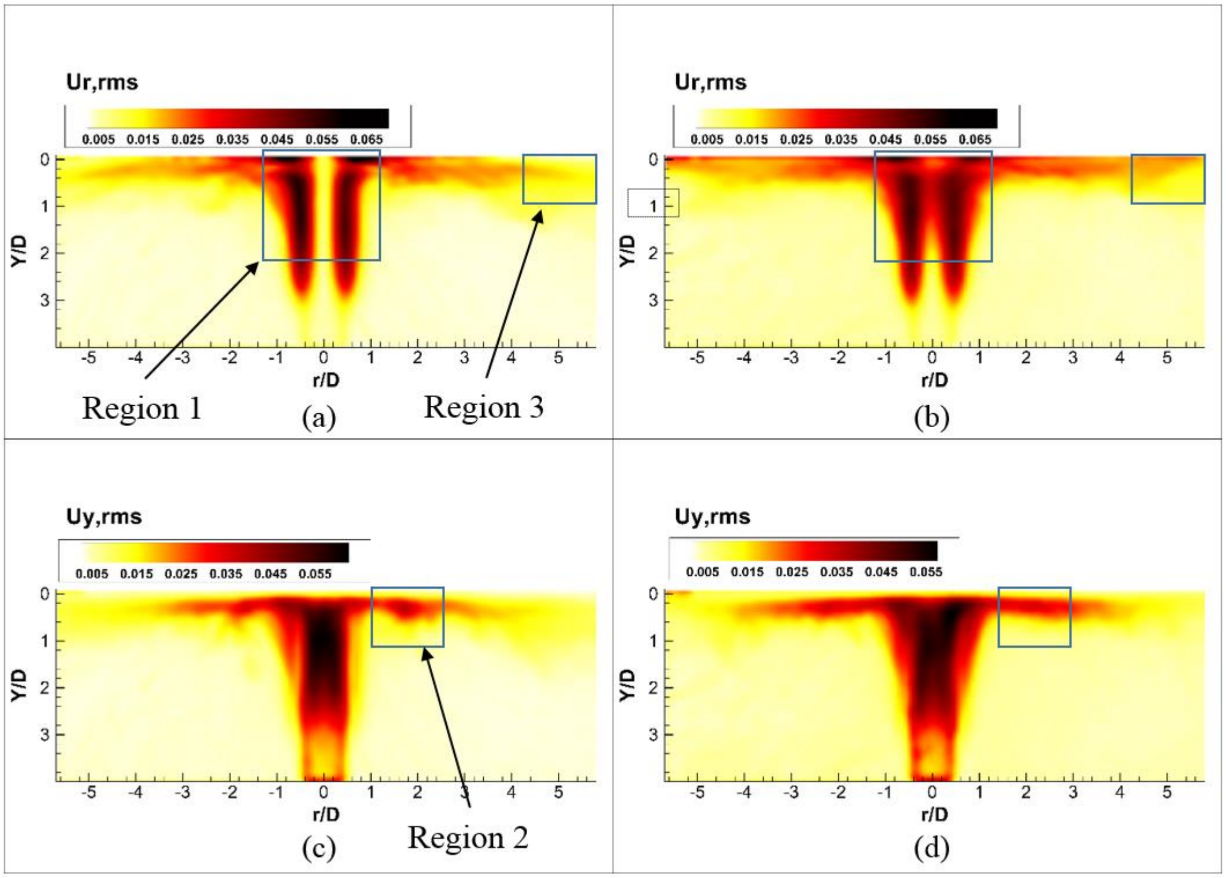
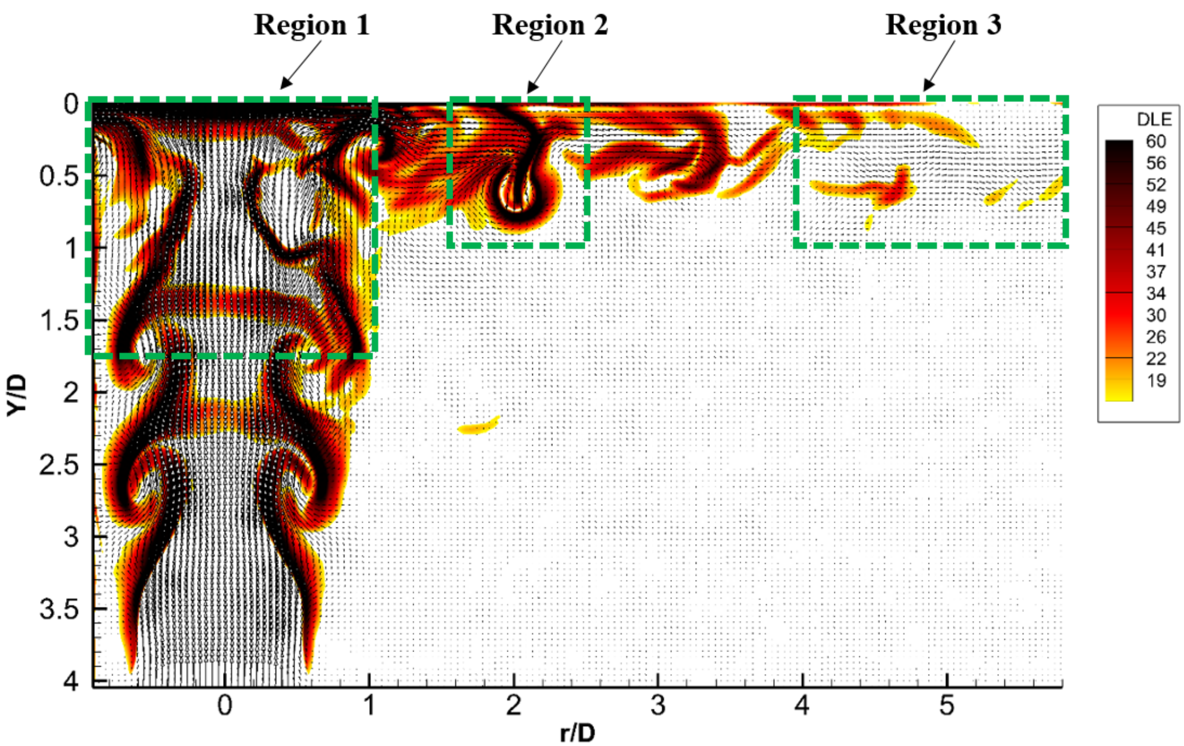
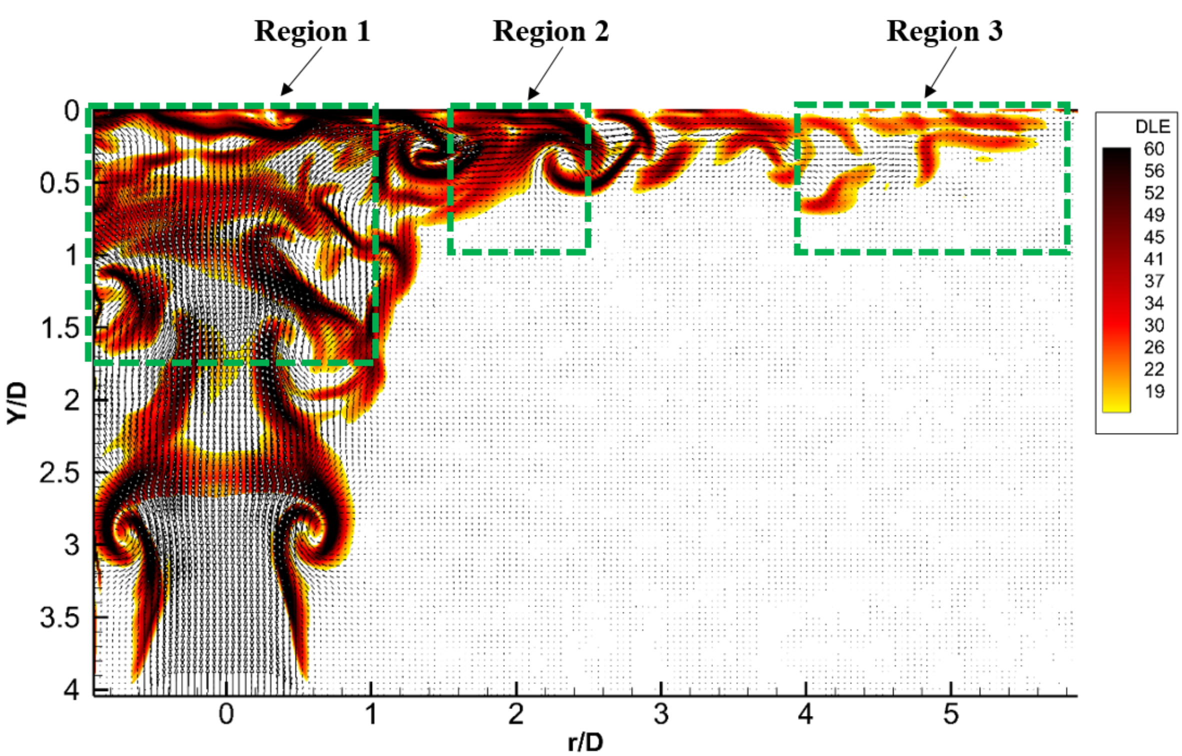


Figure 3: Turbulence intensities distribution for (a, c) stationary and (b, d) rotating disk

In order to better understand the physics of what would generate these velocity distributions, an in-depth analysis of the velocity fields is needed. The finite time Lyapunov exponent (FTLE), also called direct Lyapunov exponent (DLE) can be used to identify vortices in the flow. In order to better illustrate the vortex dynamics in both the stationary and rotational cases, the instantaneous velocity and FTLE fields are presented in the Figure 4. Further details about this vortex identification method for impinging jet flows can be found in [7]. It can be seen that the flow separates from the impinging wall just downstream from the jet impact in Region 2 for the stationary case in Figure 4(a) whereas the vortical structures are advected along the wall due to the centrifugal force for the rotating case shown in Figure 4(b). As a consequence, the flow is shown to be attached to the impinging wall when traveling farther radially towards Region 3 due to the centrifugal force. It is also noted the more organized flow structures in the stationary case as compared to the rotational case before the impact of the large-scale vortices in Region 1. Such vortex dynamics thus confirms the analysis presented from the turbulence intensity fields regarding the effect of the centrifugal force on the jet flow dynamics.



(a)



(b)

Figure 4: Finite Time Lyapunov Exponent and velocity fields (a) stationary and (b) rotating disk

4 Conclusion

The present experimental investigation illustrates the influence of the centrifugal force of a rotational impinging wall on the vortex dynamics of different regions of a circular jet impinging on a flat wall. It is found that the velocity distribution is affected by the rotating motion in the free jet region, the impinging location and the outer region of the impinging wall. Despite numerous studies on this subject, the influence of the rotating motion on the velocity field was neglected in the impinging zone. It is interesting to note that the inertial force results in a swirling-like dynamics of the large-scale vortices just upstream from their impact on the rotating disk. For the stationary case, the flow separation would be responsible for the lower turbulence intensity and higher radial velocity observed in the near-wall impinging region. It is also found that while the boundary layer detaches from the wall just after the vortex rings impact, the large-scale vortices are advected farther radially along the impinging wall for the rotational case. The present findings are of high interest for both the scientific and engineering communities. For example, a better understanding of the flow physics in impinging jets help improving the design of engineering devices that requires enhanced heat transfer or particular wall friction distributions.

Acknowledgements

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References

[1] Chen YM, Lee WT, Wu SJ (1998) "Heat (mass) transfer between an impinging jet and a rotating disk" Heat Mass Transfer 34:195–201

[2] Benim A, Ozkan K, Cagan M, Gunes D (2005) "Computational investigation of turbulent jet impinging onto rotating disk" Int. J. Numer. Methods Heat Fluid Flow 17: 284–301

[3] Harmand S, Pelle J, Poncet S, Shevchuk I (2013) "Review of fluid flow and convective heat transfer within rotating disk cavities with impinging jet" Int. J. Therm. Sci. 67: 1–30

[4] Abdel-Fattah, A. (2007) "Numerical simulation of turbulent impinging jet on a rotating disk" Int. J. Numer. Meth. Fluids 2007; 53:1673–1688

[5] Minagawa Y, Obi S (2004) "Development of turbulent impinging jet on a rotating disk" Int. J. Heat Fluid Flow. 25: 759–766

[6] Westerweel, J. "Digital Particle Image Velocimetry: Theory and application" Delft University Press, The Netherlands, 1993.

[7] El Hassan M, Assoum HH, Martinuzzi R, Sobolik V, Sakout A (2013) "Experimental investigation of the Wall Shear Stress in a circular orifice imping jet" Physics of Fluids, 25(7): 077101-10