藉由底盤旋轉在垂直圓柱容器中空氣圓形噴流衝擊至一加熱圓盤抑制渦流結構之流場觀測研究

研究生：羅 文 賢　　指導老師： 林 清 發 博士

國立交通大學　機械工程學系

中 文 摘 要

本篇論文利用實驗流場觀測方法及溫度場量測方法探討藉由底盤旋轉在垂直圓柱容器中一空氣圓形噴流衝擊至一加熱圓盤抑制由浮力所驅動的穩態及非穩態渦流結構之流場特性進行研究。在本實驗研究操作範圍分別是：流量變化 0～12.0 slpm，加熱圓盤與入口冷空氣間的溫度差範圍 0～25.0℃，底盤轉速由 0~50 rpm，所相對的噴流雷諾數變化為 0～1,623，相對於雷利數 0～63,420，而旋轉雷諾數 0～3,892 另外噴流出口到加熱底板間的距離維持 20.0 mm，而噴流管徑分別是 10.0 與 22.1 mm。

由流場觀測可以清楚顯示典型噴流衝擊旋轉圓盤的結果有三種渦流，靠近噴流中心，產生了由於慣性力所驅動的渦流稱 Primary inertia-driven roll，而流道中間的渦流是由於底盤旋轉的離心泵送效應，稱之為 Rotation-driven roll。而靠近爐體壁面的渦流是由於加熱圓盤與入口冷空氣間的溫度所形成的浮力效應所引起，稱之為 Buoyancy-driven roll。在較高的底盤轉速下，由浮力所造成的渦流可以明顯受到抑制，甚至完全消除。此外，在高轉速下，由慣性力所形成的 primary inertia-driven roll 會變得較細長且強度較弱。而在足夠高的噴流雷諾數下所形成的 secondary, tertiary, quaternary inertia-driven rolls 亦會隨著底盤轉速提高而依序消失。由實驗結果可以進一步了解底盤旋轉對於由慣性力/浮力所造成的週期性

與非週期性流場有穩定的效果，此種不穩定的流場可以藉由一定高的底盤轉速而達穩定，在溫度場的結果上，由底盤旋轉可以減低徑向的溫度變化，並且明顯使得 Buoyancy-driven roll 出現的臨界浮慣比數延遲。

Suppression of Vortex Flow Resulting from a Round Jet of Air Impinging onto a Heated Horizontal Disk Confined in a Vertical Cylindrical Chamber by Disk Rotation

Student: Wen-Hsien Lo **Advisor: Prof. Tsing-Fa Lin**

Institute of Mechanical Engineering

National Chiao Tung University

ABSTRACT

An experiment combining flow visualization and temperature measurement is carried out in the present study to explore the possible suppression of the buoyancy-driven stable and unstable vortex flow resulting from a round jet of air impinging onto a heated horizontal disk in a vertical cylindrical chamber by the disk rotation. In this study the experiment is mainly conducted for the jet flow rate varied from 0 to 12.0 slpm (standard liter per minute) with two different injection pipes (diameter 10.0 and 22.1 mm) and the temperature difference between the disk and the air injected into the chamber is varied from 0 to 25.0℃ at a fixed jet-to-disk separation distance of 20.0 mm. The disk rotation speed is varied from 0 to 50 rpm. Thus the jet Reynolds number, Rayleigh number and rotational Reynolds number range respectively from 0 to 1,623, from 0 to 18,790, and from 0 to 3,892.

The results from the flow visualization clearly show that typically the steady mixed convective air jet impinging onto the rotating disk consists of three circular vortex rolls. The inner vortex roll is generated by the deflection of the impinging jet at the disk surface and hence termed as the inertia-driven vortex roll. The middle vortex

roll is mainly formed by the centrifugal pumping action produced by the disk rotation and hence termed as the rotation-induced roll. The buoyancy-induced vortex roll resulting from the temperature difference between the heated disk and the inlet air prevails in the outer zone of the processing chamber. At a high disk rotation rate, the buoyancy roll can be significantly suppressed and even wiped out by the disk rotation. Besides, the primary inertia-driven roll is stretched out to become slender and weaker. Moreover, the inertia-driven secondary, tertiary, and quaternary rolls dominated at high Re_j can be entirely wiped out. We further note that the disk rotation can effectively suppress the inertia-driven and/or buoyancy-driven time-dependent and nonperiodic vortex flows. The unstable vortex flows can be completely stabilized by the disk rotated at a high speed and the flows become steady. The disk rotation can also reduce the radial temperature variation in the flow and significantly delay the onset of the buoyancy-driven roll. Based on the present data, a flow regime map is provided to delineate the the axisymmetric and nonaxisymmetric vortex flows with various disk rotation rates for H=20.0 mm.

TABLE OF CONTENTS

ABSTRACT		**i**
TABLE OF CONTENTS		**v**
LIST OF TABLES		**vii**
LIST OF FIGURES		**viii**
NOMENCLATURE		**xviii**
CHAPTER 1	**INTRODUCTION**	**1**
	1.1 Motivation	**1**
	1.2 Literature Review	**2**
	1.3 Objective and Scope of Present Study	**10**
CHAPTER 2	**EXPERIMENTAL APPARATUS AND PROCEDURES**	**16**
	2.1 Experimental Apparatus	**16**
	2.2 Experimental Procedures	**20**
CHAPTER 3	**DIMENSIONLESS GROUPS AND UNCERTAINTY ANALYSIS**	**25**
	3.1 Dimensionless Groups	**25**
	3.2 Uncertainty Analysis	**25**
CHAPTER 4	**RESULTS AND DISCUSSION**	**30**
	4.1 Typical Steady Vortex Flow Patterns	**31**
	4.2 Influences of Inertia-driven Rolls by Disk Rotation	**33**

4.3 Effects of Disk Rotation on Buoyancy-driven Rolls **36**

4.4 Steady Temperature Distributions in Vortex Flow **37**

4.5 Effects of Disk Rotation on Inertia-driven Flow Instability **38**

4.6 Effects of Disk Rotation on Buoyancy-driven Flow Instability **41**

4.7 Effects of Disk Rotation on Onsets of Inertia- and Buoyancy-driven Rolls **44**

4.8 Flow Regime Map **44**

CHAPTER 5 CONCLUDING REMARKS 121

REFERECES 123

LIST OF TABLES

Table 1.1 Summary of literature for studies on rotating disk with jet impingement. ------------- 12
Table 3.1 Summary of uncertainty analysis. --- 29
Table 4.1 The effects of the disk rotation on the critical condition for appearance of the inertia-driven vortex roll (ΔT= 0℃, H=20.0 mm and D_j=10.0 mm). ------------------- 46
Table 4.2 The effects of the disk rotation on the critical condition for onset of the buoyancy-driven vortex flow (H=20.0 mm and D_j=10.0 mm). -------------------------- 47

LIST OF FIGURES

Fig. 1.1 Schematic of the flow patterns in a confined impinging jet depicting the plug-flow, the buoyancy-induced flow and the rotation-induced flow. ------------ 13

Fig. 1.2 Flow regimes associated with a circular jet impinging onto a flat plate. ----------- 14

Fig. 1.3 Flow close to a rotating disk in a fluid at rest (a) velocity profile, (b) boundary profile. -- 15

Fig. 2.1 Schematic diagram of the experimental apparatus.----------------------------------- 21

Fig. 2.2 Schematic diagram of the test section--- 22

Fig. 2.3 The heater consists of three parts: resistance heating element, holder and insulator.--- 23

Fig. 2.4 The locations of the detection points on the upper copper plate. -------------------- 24

Fig. 4.1 Steady vortex flow pattern in the chamber with D_j = 10.0 mm and H=20.0 mm for Re_j = 270 (Q_j = 2.0 slpm), Ra = 15,030 (ΔT = 20.0℃) and Re_Ω = 0 (Ω = 0 rpm): (a) top view flow photo taken at middle horizontal plane halfway between the pipe exit and heated disk, (b) side view flow photo taken at the vertical plane $\theta = 0^\circ$ & 180°, and (c) the corresponding schematically sketched cross plane vortex flow. -------------------- 48

Fig. 4.2 Vortex flow formation for D_j = 10.0 mm and H=20.0 mm at Re_j = 0, Ra = 0 and Re_Ω = 778 (Ω = 10 rpm): (a) top view flow photo taken at the middle horizontal plane between the disk and chamber top, and (b) side view flow photo taken at the vertical plane $\theta = 0^\circ$ & 180°. ----------------------- 49

Fig. 4.3 Steady vortex flow pattern for D_j = 10.0 mm and H=20.0 mm at Re_j = 270 (Q_j = 2.0 slpm), Ra = 15,030 (ΔT = 20.0℃) and Re_Ω = 2,335 (Ω = 30 rpm): (a) top view flow photo taken at the middle horizontal plane between the disk and chamber top, (b) side view flow photo taken at the vertical plane $\theta = 0^\circ$ & 180°, and (c) the corresponding schematically sketched cross plane vortex flow. --- 50

Fig. 4.4 Steady side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° for various jet Reynolds numbers at Ra = 0 (ΔT = 0°C) and $Re_\Omega = 0$ (Ω = 0 rpm) for D_j = (a) 10.0 mm and (b) 22.1 mm. -------------------------------- 51

Fig. 4.5 Steady side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° for various jet Reynolds numbers at Ra = 0 (ΔT = 0°C) and $Re_\Omega = 778$ (Ω = 10 rpm) for D_j = (a) 10.0 mm and (b) 22.1 mm.------------------------------- 52

Fig. 4.6 Top view flow photos taken at the middle horizontal plane between the disk and chamber top with Ra = 0 (ΔT = 0°C), $Re_\Omega = 778$ (Ω = 10 rpm) and D_j = 10.0 mm for Re_j = (a) 135, (b) 270, (c) 406, (d) 541, and (e) 676. -- 53

Fig. 4.7 Top view flow photos taken at the middle horizontal plane between the disk and chamber top with Ra = 0 (ΔT = 0°C), $Re_\Omega = 778$ (Ω = 10 rpm) and D_j = 22.1 mm for Re_j = (a) 61, (b) 122, (c) 184, (d) 245, and (e) 306. -------- 54

Fig. 4.8 Steady side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° for various jet Reynolds numbers at Ra = 0 (ΔT = 0°C) and Re_Ω = 1,557 (Ω = 20 rpm) for D_j = (a) 10.0 mm and (b) 22.1 mm. ------------------------ 55

Fig. 4.9 Steady side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° for various jet Reynolds numbers at Ra = 0 (ΔT = 0°C) and Re_Ω = 2,335 (Ω = 30 rpm) for D_j = (a) 10.0 mm and (b) 22.1 mm. ------------------------ 56

Fig. 4.10 Steady side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° for various jet Reynolds numbers at Ra = 0 (ΔT = 0°C) and Re_Ω = 3,114 (Ω = 40 rpm) for D_j = (a) 10.0 mm and (b) 22.1 mm. ------------------------ 57

Fig. 4.11 Steady side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° for various jet Reynolds numbers at Ra = 0 (ΔT = 0°C) and Re_Ω = 3,892 (Ω = 50 rpm) for D_j = (a) 10.0 mm and (b) 22.1 mm. ------------------------ 58

Fig. 4.12 Steady vortex flow pattern in the chamber with D_j=10.0 mm: (a) side view flow photo taken at the vertical plane $\theta = 0^\circ$ for H=20.0 mm at Re_j=717 (Q_j=5.3 slpm) and Ra=3,760 (ΔT = 5.0 °C) and (b) the corresponding schematically sketched cross plane vortex flow, and (c) side view flow photo for H=10.0 mm at Re_j=1,150 (Q_j=8.5 slpm) and Ra=470 (ΔT = 5.0 °C) and (d) the corresponding schematically sketched cross plane vortex flow. -- 59

Fig. 4.13 Steady side view flow photos taken at the cross plane $\theta = 0°$ at H=20.0 mm for Ra=3,760 (ΔT = 5.0°C) and Re_j= 717 (Q_j=5.3 slpm) for rotational Reynolds number Re_Ω = (a)0, (b)778, (c)1,557, and (d)2,335. -------- 60

Fig. 4.14 Steady side view flow photos taken at the cross plane $\theta = 0°$ at H=20.0 mm for Ra=0 (ΔT = 0°C) and Re_j= 676 (Q_j=5.0 slpm) for rotational Reynolds number Re_Ω = (a)0, (b)778, (c)1,557, and (d)2,335.-------------------- 61

Fig. 4.15 Steady side view flow photos taken at the cross plane $\theta = 0°$ at H=20.0 mm for Ra=7,520 (ΔT =10.0°C) and Re_j= 730 (Q_j=5.4 slpm) for rotational Reynolds number Re_Ω = (a)0, (b)778, (c)1,557, and (d)2,335. -------- 62

Fig. 4.16 Steady side view flow photos taken at the cross plane $\theta = 0°$ at H=20.0 mm for Ra=11,270 (ΔT =15.0°C) and Re_j= 771 (Q_j=5.7 slpm) for rotational Reynolds number Re_Ω = (a)0, (b)778, (c)1,557, and (d)2,335. -------- 63

Fig. 4.17 Steady side view flow photos taken at the cross plane $\theta = 0°$ at H=20.0 mm for Ra=15,030 (ΔT =20.0°C) and Re_j= 811 (Q_j= 6.0 slpm) for rotational Reynolds number Re_Ω = (a)0, (b)778, (c)1,557, and (d)2,335. -------- 64

Fig. 4.18 Steady side view flow photos taken at the cross plane $\theta = 0°$ for Re_j=1,150 (Q_j=8.5 slpm) for various rotational Reynolds numbers at H=10.0 mm for (a) Ra=0 (ΔT =0°C) and (b) Ra=470 (ΔT =5.0°C), (c) Ra=940 (ΔT =10.0°C), (d) Ra=1,410 (ΔT =15.0°C), and (e) Ra=1,880 (ΔT =20.0°C).-- 65

Fig. 4.18 Continued. -- 66

Fig. 4.19 Side view flow photos taken at the cross plane $\theta = 0°$ & 180° for various Rayleigh numbers at Q_j = 1.0 slpm and Re_Ω = 0 (Ω = 0 rpm) for (a) D_j =10.0 mm & Re_j =135 and (b) D_j= 22.1 mm & Re_j =61. ---------------- 67

Fig. 4.20 Steady side view flow photos taken at the cross plane $\theta = 0°$ & 180° for various Rayleigh numbers at Q_j = 3.0 slpm and Re_Ω =0 (Ω = 0 rpm) for (a) D_j =10.0 mm & Re_j = 406 and (b) D_j =22.1 mm & Re_j = 184.------------------ 68

Fig. 4.21 Steady side view flow photos taken at the cross plane $\theta = 0°$ & 180° for various Rayleigh numbers at Q_j = 5.0 slpm and Re_Ω = 0 (Ω = 0 rpm) for (a) D_j = 10.0 mm & Re_j = 676 and (b) D_j = 22.1 mm & Re_j = 306. ------------- 69

Fig. 4.22 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° for various Rayleigh numbers at Q_j = 1.0 slpm and Re_Ω = 778 (Ω = 10 rpm) for (a) D_j =10.0 mm & Re_j =135 and (b) D_j = 22.1 mm & Re_j =61.----------------- 70

Fig. 4.23 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° for various Rayleigh numbers at Q_j = 3.0 slpm and Re_Ω =778 (Ω = 10 rpm) for (a) D_j =10.0 mm & Re_j = 406 and (b) D_j =22.1 mm & Re_j = 184. -------------- 71

Fig. 4.24 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° for various Rayleigh numbers at Q_j = 5.0 slpm and Re_Ω = 778 (Ω = 10 rpm) for (a) D_j = 10.0 mm & Re_j = 676 and (b) D_j = 22.1 mm & Re_j = 306. ------------- 72

Fig. 4.25 Steady side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° for various Rayleigh numbers at Q_j = 1.0 slpm and Re_Ω = 1,557 (Ω = 20 rpm) for (a) D_j =10.0 mm & Re_j =135 and (b) D_j = 22.1 mm & Re_j =61. ---------- 73

Fig. 4.26 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° for various Rayleigh numbers at Q_j = 3.0 slpm and Re_Ω =1,557 (Ω = 20 rpm) for (a) D_j = 10.0 mm & Re_j = 406 and (b) D_j =22.1 mm & Re_j = 184. -- 74

Fig. 4.27 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° for various Rayleigh numbers at Q_j = 5.0 slpm and Re_Ω = 1,557 (Ω = 20 rpm) for (a) D_j = 10.0 mm & Re_j = 676 and (b) D_j = 22.1 mm & Re_j = 306. -- 75

Fig. 4.28 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° for various Rayleigh numbers at Q_j= 1.0 slpm and Re_Ω = 2,335 (Ω = 30 rpm) for (a) D_j =10.0 mm & Re_j = 135 and (b) D_j = 22.1 mm & Re_j = 61.--------- 76

Fig. 4.29 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° for various Rayleigh numbers at Q_j = 3.0 slpm and Re_Ω = 2,335 (Ω = 30 rpm) for (a) D_j =10.0 mm & Re_j = 406 and (b) D_j =22.1 mm & Re_j = 184. -- 77

Fig. 4.30 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° for various Rayleigh numbers at Q_j = 5.0 slpm and Re_Ω = 2,335 (Ω = 30 rpm) for (a) D_j = 10.0 mm & Re_j = 676 and (b) D_j = 22.1 mm & Re_j = 306. -- 78

Fig. 4.31 Steady side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° for various jet Reynolds numbers at Ra = 15,030 (ΔT= 20.0℃) and Re_Ω = 2,335 (Ω = 30 rpm) for D_j = (a) 10.0 mm and (b) 22.1 mm.------------------------ 79

Fig. 4.32 Steady top view flow photos taken at the middle horizontal plane between the disk and chamber top with Ra = 15,030 (ΔT = 20.0℃) and Re_Ω = 2,335 (Ω = 30 rpm) for D_j =10 mm at Re_j = (a) 135, (b) 406, and (c) 676 and D_j = 22.1 mm at Re_j = (d) 61, (e) 184, and (f) 306. --------------------- 80

Fig. 4.33 Steady side view flow photos at the cross plane $\theta = 180^\circ$ with Re_Ω =0(Ω =0 rpm), Ra=11,270 (ΔT=15.0℃), H=20.0 mm, and D_j=10.0 mm at Re_j= (a)541 and (b)676, and (c) the corresponding radial variations of non-dimensional steady air temperature at Z=0.5. -------------------- 81

Fig. 4.34 Steady side view flow photos at the cross plane $\theta = 180^\circ$ with Re_j =135 (Q_j=1.0 slpm), Ra=3,760 (ΔT=5.0℃), H=20.0 mm and D_j=10.0 mm at Re_Ω = (a)0, (b)778, (c)1,557 and (d)2,335, and (e) the corresponding radial variations of non-dimensional steady air temperature at Z=0.5. ------------ 82

Fig. 4.35 Steady side view flow photos at the cross plane $\theta = 180^\circ$ with Re_j = 406 (Q_j=3.0 slpm), Ra=3,760 (ΔT=5.0℃), H=20.0 mm, and D_j=10.0 mm at Re_Ω = (a)0, (b)778, (c)1,557, (d)2,335 and (e) the corresponding radial variations of non-dimensional steady air temperature at Z=0.5. ------------ 83

Fig. 4.36 Steady side view flow photos at the cross plane $\theta = 180^\circ$ with Re_j =541 (Q_j=5.0 slpm), Ra=3,760 (ΔT=5.0℃), H=20.0 mm, and D_j=10.0 mm at Re_Ω = (a)0, (b)778, (c)1,557, and (d)2,335 and (e) the corresponding radial variations of non-dimensional steady air temperature at Z=0.5. ------------ 84

Fig. 4.37 Steady side view flow photos at the cross plane $\theta = 0^\circ$ & 180° with (a) Re_j = 541 (Q_j= 4.0 slpm), Ra=11,270 (ΔT=15.0℃), H=20.0 mm, D_j=10.0 mm and Re_Ω =0 (Ω =0 rpm), (b)the corresponding schematically sketched cross plane vortex flow at $\theta = 180^\circ$, and (c) the radial variations of non-dimensional steady air temperature at Z=0.5. ------------ 85

Fig. 4.38 Steady side view flow photos at the cross plane $\theta = 0^\circ$ & 180° with (a) Re_j = 541 (Q_j= 4.0 slpm), Ra=11,270 (ΔT= 15.0℃), H=20.0 mm, D_j=10.0 mm and Re_Ω =2,335 (Ω = 30 rpm), (b)the corresponding schematically sketched cross plane vortex flow at $\theta = 180^\circ$ and (c) the radial variations of non-dimensional steady air temperature at Z=0.5. ------------ 86

Fig. 4.39 Time-periodic vortex flow for H=20.0 mm, $Re_\Omega = 0$ ($\Omega = 0$ rpm), and Ra=0 ($\Delta T = 0$ ℃) at Re_j=839 (Q_j=6.2 slpm) illustrated by (a) side view flow photos taken at the vertical plane $\theta = 0^\circ$ & 180° at selected time instants in a typical periodic cycle and (b) top view flow photo taken at middle horizontal plane halfway between the injection pipe exit and heated disk at certain time instant in the cycle (t_p= 1.4 sec). ------------------------ 87

Fig. 4.40 Time-periodic vortex flow for H=20.0 mm, $Re_\Omega = 389$ ($\Omega = 5$ rpm), and Ra=0 ($\Delta T = 0$ ℃) at Re_j= 839 (Q_j=6.2 slpm) illustrated by (a) side view flow photos taken at the vertical plane $\theta = 0^\circ$ & 180° at selected time instants in a typical periodic cycle and (b) top view flow photo taken at middle horizontal plane halfway between the injection pipe exit and heated disk at certain time instant in the cycle (t_p= 1.0 sec). ------------------------ 88

Fig. 4.41 Vortex flows for H=20.0 mm, and Ra=0 ($\Delta T = 0$ ℃) at Re_j=839 (Q_j=6.2 slpm) illustrated by side view flow photos taken at the vertical plane $\theta = 0^\circ$ & 180° at selected time instants in a typical periodic cycle for various rotational Reynolds number: (a) Re_Ω = 778 (t_p=0.6 sec), (b) Re_Ω = 1,168 (t_p=0.4 sec), and (c) Re_Ω =1,557 (steady state).--------------------- 89

Fig. 4.42 Steady and time-periodic vortex flows for H=20.0 mm and Ra=3,760 ($\Delta T = 5.0$ ℃) at Re_j=839 (Q_j=6.2 slpm) for (a) Re_Ω=778 (t_p=0.5 sec), (b) Re_Ω=1,557 (steady state), and (c) Re_Ω=2,335 (steady state). ---------------------- 90

Fig. 4.43 Steady and time-periodic vortex flows for H=20.0 mm and Ra=7,520 (ΔT=10.0 ℃) at Re_j=893 (Q_j=6.6 slpm) for (a) Re_Ω=778 (t_p=0.6 sec), (b) Re_Ω=1,557 (steady state), and (c) Re_Ω=2,335 (steady state). ----------------- 91

Fig. 4.44 Steady and time-periodic vortex flows for H=20.0 mm and Ra=11,270 (ΔT=15.0 ℃) at Re_j=933 (Q_j=6.9 slpm) for (a) Re_Ω=778 (t_p=0.6 sec), (b) Re_Ω=1,557 (steady state), and (c) Re_Ω=2,335 (steady state). ----------------- 92

Fig. 4.45 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° at steady state or at certain instant in the statistical state at H=20.0 mm for Re_j=893 (Q_j=6.6 slpm), Ra=7,520 (ΔT=10.0 ℃), at Re_Ω = (a)0, (b)389, (c)778, (d)1,168, (e)1,557, and (f)2,335.--- 93

Fig. 4.46 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° at selected time instants in the statistical state for D_j=10.0 mm at Ra= (ΔT= 0℃), Re_j=1,082 (Q_j=8.0 slpm), and $Re_\Omega = 0$ ($\Omega = 0$ rpm).------------------- 94

Fig. 4.47 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° at steady stae or selected time instants in the statistical state for D_j=10.0 mm at Ra=0 (ΔT= 0℃), Re_j=1,082 (Q_j=8.0 slpm), and Re_Ω = (a)778, (b)1,557, and (c)2,335.-- 95

Fig. 4.48 Top view flow photos taken at middle horizontal plane at certain time instants in the steady or statistical state for Ra=0 (ΔT=0℃), Re_j=1,082 (Q=8.0 slpm), H=20.0 mm, and Re_Ω = (a)0, (b)778, (c)1,557, and (d)2,335.-- 96

Fig. 4.49 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° at selected time instants in the statistical state for D_j=10.0 mm at Ra=7,520 (ΔT=10.0℃), Re_j=1,190 (Q_j=8.8 slpm), and Re_Ω = 0 ($\Omega = 0$ rpm).---------------- 97

Fig. 4.50 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° at selected time instants in the steady or statistical state for D_j=10.0 mm at Ra=7,520 (ΔT=10.0℃), Re_j=1,190 (Q_j=8.8 slpm), and Re_Ω = (a)778, (b)1,168, (c)1,557, and (d)2,335. --- 98

Fig. 4.51 Top view flow photos taken at middle horizontal plane at certain time instants in the steady or statistical state for Ra=7,520 (ΔT=10.0℃), Re_j=1,190 (Q=8.8 slpm), H=20.0 mm, and Re_Ω = (a)0, (b)778, (c)1,557, and (d)2,335.-- 99

Fig. 4.52 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° at selected time instants in the statistical state for D_j=10.0 mm at Ra=15,030 (ΔT=20.0 ℃), Re_j=1,244 (Q_j=9.2 slpm), and Re_Ω = 0 ($\Omega = 0$ rpm). -- 100

Fig. 4.53 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° at certain time instants in the steady or statistical state for D_j=10.0 mm at Ra=15,030 (ΔT=20.0℃), Re_j=1,244 (Q_j=9.2 slpm), and Re_Ω = (a)778, (b)1,168, (c)1,557, and (d)2,335. --- 101

Fig. 4.54 Top view flow photos taken at middle horizontal plane at certain time instants in steady or statistical state for Ra=15,030 (ΔT=20.0℃), Re_j=1,244 (Q_j=9.2 slpm), H=20.0 mm, and Re_Ω = (a)0, (b)778, (c)1,557, and (d)2,335.-- 102

Fig. 4.55 Side view flow photo taken at the cross plane $\theta = 0^{\circ}$ & 180° at certain time instant in the statistical state and time records of air temperature at selected locations in middle horizontal plane Z=0.5 with H=20.0 mm for Re_j=1,190 (Q=8.8 slpm), Ra=7,520 (ΔT=10.0℃), D_j=10.0 mm and $Re_{\Omega} = 0$ (nonperiodic flow).-- 103

Fig. 4.56 The time records of non-dimensional air temperature for Re_j=1,190 (Q=8.8 slpm), and Ra=7,520 (ΔT=10.0℃) at location (R, Z) = (0.54, 0.5) on the cross plane $\theta = 0^{\circ}$ with H=20.0 mm for Re_{Ω}= (a)0, (b)778, (c)1,668,(d)1,557, and (e)2,335. -- 104

Fig. 4.57 Side view flow photo taken at the cross plane $\theta = 0^{\circ}$ & 180° at certain time instant in the statistical state and time records of non-dimensional air temperature at selected locations in the middle horizontal plane Z=0.5 with H=20.0 mm for Re_j=1,244 (Q=9.2 slpm), Ra=15,030 (ΔT=20.0℃), D_j=10.0 mm and $Re_{\Omega} = 0$ (nonperiodic flow). -------------------- 105

Fig. 4.58 The time records of non-dimensional air temperature for Re_j=1,244 (Q=9.2 slpm), and Ra=15,030 (ΔT=20.0℃) at location (R, Z) = (0.54, 0.5) on the cross plane $\theta = 0^{\circ}$ with H=20.0 mm for Re_{Ω}= (a)0, (b)778, (c)1,168,(d)1,557, and (e)2,335. -- 106

Fig. 4.59 Time-periodic vortex flow for Ra = 11,270 (ΔT= 15.0℃) at Re_j = 135 (Q_j = 1.0 slpm) and Re_{Ω} = 0 (Ω = 0 rpm) for D_j=10.0 mm and H=20.0 mm illustrated by side view flow photos taken at the vertical plane $\theta = 0^{\circ}$ & 180° at selected time instants in a typical periodic cycle (t_p=21.1 sec).--- 107

Fig. 4.60 Side view flow photo taken at the cross plane $\theta = 0^{\circ}$ & 180° at certain time instant in a typical periodic cycle and time records of air temperature at selected locations in middle horizontal plane Z=0.5 with H=20.0 mm for Re_j=135 (Q_j = 1.0 slpm), Ra=11,270 (ΔT= 15.0 ℃), $Re_{\Omega} = 0$ and D_j=10.0 mm (t_p=21.1 sec). -- 108

Fig. 4.61 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° at certain time instants in the steady or time-periodic state at H=20.0 mm for Re_j=135 (Q_j=1.0 slpm), Ra=11,270 ($\Delta T = 15.0$ °C) and various rotational Reynolds number Re_Ω = (a)0, (b)778, (c)1,557, (d)2,335, (e)3,114 and (f)3,892.-- 109

Fig. 4.62 Time records of non-dimensional air temperature for Re_j=135 (Q_j =1.0 slpm), and Ra=11,270 (ΔT= 15.0℃) at location (R, Z) = (0.54, 0.5) on the cross plane $\theta = 0^\circ$ with H=20.0 mm for Re_Ω = (a)0, (b)778, (c)1,557, (d)2,335, (e)3,114 and (f)3,892. -- 110

Fig. 4.63 Nonperiodic vortex flow for Ra = 15,030 (ΔT= 20.0℃) at Re_j =135 (Q_j = 1.0 slpm) and $Re_\Omega = 0$ ($\Omega = 0$ rpm) illustrated by side view flow photos taken at the vertical plane $\theta = 0^\circ$ & 180° at selected time instants in the statistical state. --- 111

Fig. 4.64 Side view flow photo taken at the cross plane $\theta = 0^\circ$ & 180° at certain time instant in the statistical state and time records of air temperature at selected locations in the middle horizontal plane Z=0.5 with H= 20.0 mm for Re_j =135 (Q_j=1.0 slpm), Ra=15,030 (ΔT=20.0℃), D_j=10.0 mm and $Re_\Omega = 0$ (nonperiodic flow).--- 112

Fig. 4.65 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° at certain time instants in the steady or statistical state at H=20.0 mm for Re_j=135 (Q_j=1.0 slpm), Ra=15,030 ($\Delta T = 20.0$ °C) and Re_Ω = (a)0, (b)778, (c)1,557, (d)2,335, (e)3,114, (f)3,892, (g)5,838, and (h)7,785. --------------------- 113

Fig. 4.66 Time records of non-dimensional air temperature for Re_j=135 (Q_j = 1.0 slpm) and Ra=15,030 (ΔT= 20.0℃) at location (R, Z) = (0.54, 0.5) on the cross plane $\theta = 0^\circ$ with H=20.0 mm for Re_Ω = (a)0, (b)778, (c)1,557, (d)2,335, (e)3,114, (f)3,892, (g)5,838, and (h)7,785. --------------------- 114

Fig. 4.67 Side view flow photo taken at the cross plane $\theta = 0^\circ$ & 180° at certain time instant in the statistical state and time records of non-dimensional air temperature at selected locations in middle horizontal plane Z=0.5 with H= 20.0 mm for Re_j =135 (Q_j=1.0 slpm), Ra=18,790 (ΔT=25.0℃), D_j=10.0 mm and $Re_\Omega = 0$ (nonperiodic flow). -------------------------------------- 115

Fig. 4.68 Side view flow photos taken at the cross plane $\theta = 0^\circ$ & 180° at certain time instants in the steady or statistical state at H=20.0 mm for Re_j=135 (Q_j=1.0 slpm), Ra=18,790 ($\Delta T = 25.0$ °C) and Re_Ω = (a)0, (b)778, (c)1,557, (d)2,335, (e)3,114, (f)3,892, (g)5,838, and (h)7,785. --------------------- 116

Fig. 4.69 Time records of non-dimensional air temperature for Re_j=135 (Q_j= 1.0 slpm), Ra=18,790 (ΔT= 25.0℃) at location (R, Z) = (0.54, 0.5) on the cross plane $\theta = 0^\circ$ with H=20.0 mm for Re_Ω = (a)0, (b)778, (c)1,557, (d)2,335, (e)3,114, (f)3,892, (g)5,838, and (h)7,785.---------------------------------- 117

Fig. 4.70 Time records of non-dimensional air temperature and the corresponding power spectrum densities for Re_j=135 (Q_j = 1.0 slpm), Ra=11,270 ($\Delta T = 15.0$ ℃) at location (R, Z)=(0.54, 0.5) for $\theta = 0°$ with H=20.0 mm and D_j=10.0 mm for Re_Ω = (a)0, (b)778, (c)1,557, and (d)2,335. ------------ 118

Fig. 4.71 Time records of non-dimensional air temperature and the corresponding power spectrum densities for Re_j=135 (Q_j = 1.0 slpm), Ra=15,030 ($\Delta T = 20.0$ ℃) at location (R, Z)=(0.54, 0.5) for $\theta = 0°$ with H=20.0 mm and D_j=10.0 mm for Re_Ω = (a)0, (b)778, (c)1,557, and (d)2,335. ------------ 119

Fig. 4.72 Flow regime map delineating the axisymmetry and non-axisymmetric vortex flows for H= 20.0 mm.--- 120

NONMENCLTURE

D_j	Diameter of jet at the injection pipe exit (mm)
D_w	Diameter of disk (mm)
Gr	Grashof number, $g\beta\Delta TH^3/\nu^2$
g	Gravitational acceleration (m/s^2)
H	Distance between the exit of injection pipe and heated disk (mm)
Nu	Nusselt number
Nu_{mean}	Mean Nusselt number
Q_j	Jet flow rate (Standard Liter per Minute, slpm)
Q_p	Disk pumping flow rate (Standard Liter per Minute, slpm), $0.886\pi r\nu\, Re_{\Omega}^{1/2}$
r,θ,z	Dimensional coordinates in cylindrical coordinate system
R,Θ,Z	Dimensionless coordinates $r/R_c,\theta,z/H$
Pr	Prandtl number, ν/α
Ra	Rayleigh number, $g\beta\Delta TH^3/\alpha\nu$
Rc	Radius of cylindrical chamber (mm)
R_w	Radius of disk (mm)
Re_j	Jet Reynolds number, $\overline{V}_j D_j/\nu$
Re_{Ω}	Rotational Reynolds number, $\Omega R_w^{\,2}/\nu$
Ri	Richardson number, Gr/Re_j^2
Sc	Schmidt number
$\overline{Sh}$	Average Sherwood number
T_a	Ambient Temperature (℃)
T_f	Temperature of the heated disk (℃)

T_j	Temperature of jet at the injection pipe exit (°C)
t	Time (sec)
u_j	Average velocity of the jet at the nozzle exit (m/s)
u_R	Tangential velocity of the disk at the jet impingement radius (m/s)
$\overline{V}_j$	Average velocity of the air jet at the injection pipe exit (m/s)

Greek symbols

α	Thermal diffusivity (cm^2/s)
β	Thermal expansion coefficient (1/K)
ΔT	Temperature difference between the heated disk and the air injected into the chamber (°C)
ν	Kinematic viscosity (cm^2/s)
Φ	Non-dimensional temperature, $(T - T_j)/(T_f - T_j)$
Ω	Disk rotation rate (rad/s)