CHAPTER 1

INTRODUCTION

1.1 Motivation

Over the past decades, the flow and heat transfer associated with a high speed jet impinging onto a heated stationary flat plate have been the subject of many investigations because of its superior heat transfer capability. Various vortex flow and heat transfer characteristics associated with the impinging jets have been reported in the literature. The heat transfer capacity can be further enhanced by rotating the plate. The advantage of the highly efficient cooling from the jet impinging onto a rotating plate has been applied to many technological processes such as the cooling of rotating machinery and electronic equipments, disk driver, jet and spray cooling, spin coating, etc. For some industrial applications such as electronic cooling of portable computers [1] and crystal growth by chemical vapor deposition (CVD) [2], both the high values and radial uniformity of heat and mass transfer rate over the plate are important. The interest in the flow of a gas jet impinging onto a rotating heated plate confined in a chamber has accelerated recently because of its importance in the growth of semiconductor thin crystal films on silicon wafers through chemical vapor deposition processes.

It is well known that in the CVD processes the jet is no longer at a high speed. At low jet speed the buoyancy generated by the heated plate can be relatively high compared with the jet inertia and the buoyancy driven flow recirculatiions tend to appear. Particularly, the flow recirculations in CVD processing chamber have detrimental effects on the film properties. In order to obtain good thin film properties, the flow in the chambers needs to be stable and contains no vortices. Thus the understanding and suppression of the inertia and buoyancy driven flow recirculations, which are normally in the form of vortex rolls, in the impinging jet flow are rather important in the thin crystal film growth. It is also known that the vortex flow in the CVD chamber is mainly affected by the jet inertia of the injected gas, the buoyancy force due to the heated wafer and pressure gradient associated with the disk rotation, along with the geometry of the chamber including the nozzle diameter, nozzle-to-wafer distance, wafer and chamber diameters. Biber et al. [3] showed that the buoyancy-induced recirculation could be suppressed by the disk rotation, resulting in a plug flow for certain conditions (Fig.1.1). But the details on how the flow recirculation is affected by the disk rotation remain largely unexplored.

1.2 Literature Review

The literature relevant to the present study is reviewed in the following.

1.2.1 Literature Review — Jet impinging onto a stationary plate

A considerable number of studies have been conducted in the past to investigate the fluid flow and heat transfer in the round or slot (two-dimensional) jet impinging onto a large horizontal plate. Most of the studies focus on quantifying the highly efficient heat transfer associated with the high speed impinging jets and the jets considered possess a much higher inertia force than the buoyancy force generated by the temperature nonuniformity in the flow. In what follows the relevant literature on jet impinging onto a stationary plate is briefly reviewed first. According to the flow characteristics of free jets, McNaughton and Sinclair [4] proposed four main types of jet in their experimental study and classified the jet by its Reynolds number Re_j: (1) the dissipated-laminar jet for $Re_j < 300$, (2) fully laminar jet for $300 < Re_j < 1000$, (3) semi-turbulent jet for $1000 < Re_j < 3000$, and (4) fully turbulent jet for $Re_j > 3000$. As illustrated in Fig. 1.2 [5], the flow in a jet impinging vertically onto a stationary plate can be divided into three regions: (1) free jet region: near the injection nozzle the jet flow mainly moves in the axial direction and is not affected to a noticeable degree by the presence of the impingement surface, (2) stagnation region: it is located between the free jet region and the wall jet region and is characterized by the significant changes in the flow direction, and (3) wall jet region: the dominated velocity component is in the radial direction and the boundary layer over the plate is subject to a nearly zero pressure gradient and thickens as it moves radially outwards. More complete information on various aspects of the flow and heat transfer associated with the impinging jets can be found from the critical reviews by Polat et al. [6], Viskanta [7], and Jambunathan et al. [8].

To explore the detailed vortex flow structure, Popiel and Trass [9] visualized the detailed flow behavior of turbulent free and impinging round jets, showing the toroidal vortex initiation, vortex pairing, and fluid entrainment processes. They pointed out that the development of these large-scale vortex structures considerably enhanced the entrainment rate and mixing processes. Recently, the recirculating flow resulting from a confined impinging gas jet at low Re_j was visualized by Santen et al. [10 & 11], Cheng et al. [12] and Hsieh et al. [13]. It has been noted that the impinging jet flow can become unstable as the Rayleigh number exceeds certain critical level. Santen et al. [10 & 11] explained the weakening of the buoyancy-induced flow at increasing Reynolds numbers. Hsieh et al. [13] experimentally observed that the gas flow recirculation was in the form of three circular vortex rolls including a primary vortex roll around the jet, a secondary vortex roll in the middle region and a buoyancy-induced vortex roll in the outer zone of the processing chamber. The inner and middle vortex rolls are driven by the viscous shear due to a nonuniform velocity distribution in the jet and are stronger and bigger at a high Re_j. Hence, they are called the inertia-driven rolls. The buoyancy driven outer vortex roll results from the temperature difference between the heated disk and inlet gas and is important at high buoyancy-to-inertia ratio. The secondary inertia-driven vortex roll only appears at certain high Re_j and is much smaller and weaker than the primary inertia-driven vortex roll. Cheng et al. [12] indicated that increasing the chamber pressure and the plate-to-jet temperature difference caused the outer roll to become larger, and the inner roll to become correspondingly smaller. Moreover, at high buoyancy and inertia the flow becomes time dependent and no steady flow exists at long time. Hsieh et al. [13] further showed that the vortex flow became time periodic at a certain high buoyancy-to-inertia ratio and the oscillation frequency of the vortex flow increased with Re_j. In a rapid chemical vapor deposition (RCVD) reactor, Horton and Peterson [14] conducted both flow visualization and Rayleigh light scattering (RLS) experiments and showed that the flow field was momentum dominated prior to the heating initiation, but became unstable at the buoyancy-to-inertia ratio $Gr/Re_j^2 = 5$. Recently, in our research group Hsieh et al. [15] visualized the detailed flow patterns of a round air jet impinging onto a heated disk confined in a cylindrical chamber and revealed that the flow acceleration and local buoyancy reduction associated with the chamber top inclination can effectively suppress the buoyancy-driven roll to become smaller and weaker. At low and middle buoyancy-to-inertia ratios the buoyancy-induced roll can be completely wiped out. Furthermore, at high buoyancy-to-inertia ratios the unsteady vortex flow oscillation can be completely stabilized and the flow becomes steady. In a continuing study Wu [16] showed that at sufficiently high Re_j the inertia-driven tertiary and quaternary rolls could be induced. At even slightly higher Re_j the vortex flow becomes unstable due to the inertia-driven flow instability. More specifically, at increasing jet Reynolds number the primary, secondary, tertiary and the quaternary inertia-driven rolls appear in sequence.

1.2.2 Literature Review— Jet impinging onto a rotating plate

It has been known for some time that the plate rotation induces a centrifugal pumping action, which in turn can deform the jet trajectories and changes the distribution of impingement heat transfer rate. The boundary layer near the plate is thrown outwards under the action of centrifugal force. In the ideal case of an infinitely large rotating disk without jet impingement in an isothermal fluid, the flow produces a uniform boundary layer with the velocity profile and edge of the boundary layer shown in Fig. 1.3 [17 & 18]. The thickness of the boundary layer decreases as the rotation rate is increased and it scales with $Re_{\Omega}^{-1/2}$.

(A) Fluid flow characteristics

For the vertical MOCVD reactors with a rotating substrate, three distinct flow regimes have been identified-plug-flow, buoyancy-induced flow, and rotation-induced flow [3], as shown in Fig.1.1. The detailed flow field measurement by utilizing Laser-Doppler-Velocimeter (LDV) for an eccentric jet impinging onto a rotating disk conducted by Metzger and Grochowsky [19] suggested that the higher rotation speed favored a rotationally dominated flow, whereas the opposite conditions favored an impingement dominated flow.

At a high rotation speed of the disk with $u_R/u_j \geqq 5$, Popiel and Boguslawski [20] showed that the effect of the jet impingement could be ignored and the rotation-dominated regime appeared. They reported that the dominant flow regimes for air in terms of the ratio Q_j/Q_p versus Re_{Ω}, where Q_p was the disk pumping flow rate. According to the velocity measurement by LDV, Brodersen and Metzger [21] later indicated that the interaction between the impingement and rotation was mainly determined by the strength of the cross-flow. With a higher jet flow rate, the jet was found to penetrate very deeply into the wall boundary layer. Their recent work [22 & 23] introduced a parameter $\alpha = (Re_j / Re_{\Omega})$ to measure the relative strength between the jet and rotationally induced flows. They suggested that for $\alpha < 0.125$ the jet did not appear to be able to penetrate into the wall boundary layer although mixed with it downstream. But for $\alpha > 0.125$ the jet characteristics became similar to those of jet impinging on a stationary surface. Kohama and Sendai. [24] examined the behavior of spiral vortices generated by a disk rotating in transition regime with Re_{Ω} ranging from 8.8×10^4 to 3.2×10^5 and indicated that the number of spiral vortices counted from the visualized picture was the same as the frequency counted from the hot wire signal between two spike signals. Besides, the spiral vortices were fixed relative to the disk surface and without phase velocity.

Soong et al. [25] presented the effects of gas flow, rotation of susceptor and natural convection on flow patterns in a model MOCVD reactor and found that the chaotic flow at a high buoyancy-to-inertia ratio could be stabilized by the susceptor rotation. They [26] further located the boundaries for the three flow regimes: buoyancy-dominated, plug and rotation-dominated flows. Van Santen et al. [27 & 28] numerically examined the symmetry breaking of the flow owing to the buoyancy effects in cold-wall stagnation flow CVD reactors and indicated that for the aspect ratio (height/diameter) of the reactor larger than one, stable non-axisymmetric flows could occur. A relatively high flow and/or rotation rate of the wafer was noted to be able to suppress the asymmetric flows. They also proposed that the symmetry-breaking of the flow can be suppressed by reducing the aspect ratio of the reactor. Recently, Vanka and his colleagues [29-31] conducted a series of computational studies to explain the effects of the reactor pressure, substrate rotation rate, inlet flow rate, and reactor thermal boundary conditions on the flow in impinging jet CVD reactor. The buoyancy driven force is opposed by the inlet jet momentum and the force owing to substrate rotation. Therefore, they can create a uniform mass transfer rate over the wafer.

A numerical study from Evans and Greif [32] to predict the fluid flow in a vertical rotating disk reactor revealed that for the small value of $Gr/Re_{\Omega}^{3/2}$ (< 3), there was no recirculation of the gas except close to the disk edge where the flow turned the corner and left the reactor. They further noted that the gas flow recirculation could be reduced or eliminated by increasing the inlet flow speed. Palmateer et al. [33] showed that the susceptor rotation was useful in creating a uniform boundary layer and could lead to the growth of highly uniform epilayers. Mihopoulos et al. [34] used a three-dimensional model to study the effects of the operating conditions and reactor geometry on the flow patterns, growth rate and growth rate uniformity in vertical, close-spaced reactors for metal organic vapor phase epitaxy film growth. The buoyancy-induced recirculation was suppressed by increasing the forced convection through the inlet flow rate increase. However, a flow rate increase leaded to poor reactant utilization. They further showed that rotating the disk provided a second mechanism for achieving flow stability, but the flow stability also broke down if the susceptor was rotated too fast. Meanwhile, a counterclockwise rotating eddy formed in the outer part of the reactor due to the interaction of the radial outflow with the reactor wall.

(B) Heat transfer characteristics

Early work performed by Wanger [35] to evaluate the heat transfer from a rotating disk to the ambient air in case of a boundary layer was based on the von Ká rmán calculation of flow conditions. He indicated that the average convection heat transfer coefficient over the entire disk surface could be expressed as $\overline{h} = 0.335 \cdot k \cdot (\Omega/\nu)^{1/2}$. Cobb and Saunders [36] conducted an experiment for a disk rotating from 30 to 2,500 rpm. The measured mean heat transfer coefficient for the laminar condition ($Nu_{mean} = 0.36 Re_{\Omega}^{0.5}$) was quite similar to the Wagner's result and for the limiting turbulent flow conditions $Nu_{mean} = 0.015 Re_{\Omega}^{0.8}$, with Re_{Ω} exceeding 2.4×10^5. Kreith et al. [17] experimentally evaluated the mass transfer rates from a rotating disk using naphthalene sublimation method under the laminar and turbulent flow conditions and related their results to the heat transfer coefficients by means of an analogy method. They found good agreement with the published theoretical data in the laminar range for Pr =0.74 and located the onset of flow transition in the range $2.0 \times 10^5 < Re_{\Omega} < 2.5 \times 10^5$. Popiel and Boguslawski [37] reported a more accurate distribution of the local heat transfer coefficient over the isothermal disk surface rotating in still air. Their data were expressed by the equation $Nu = 0.33(Gr + Re_{\Omega}{}^2)^{0.25}$ for Re_{Ω} ranging from 10^4 to 1.95×10^5. Furthermore, they suggested the onset of flow transition at $Re_{\Omega} \approx 1.95 \times 10^5$. More complete information on various aspects of the flow and heat transfer over a rotating surface can be found from the critical review by Dorfman [38].

For a jet impinging onto a rotating disk Metzger et al. [19] experimentally found that the heat transfer rates were essentially independent of the jet flow rate in the rotationally dominated regime, but increased strongly with the jet flow rate in the impingement dominated regime. Popiel and Boguslawski [20] further showed that the convective heat transfer on a rotating disk could be considerably enhanced with jet impingement having a jet Reynolds number $Re_j > 1000$. When the radial wall jet induced by the rotating disk was turbulent, a much higher jet Reynolds number should be used to increase the local heat transfer. Sparrow et al. [39] used the naphthalene sublimation technique to measure mass transfer of an air jet impinging onto a stationary confined disk. The confined geometry assured a precise control of the surface area affected by the impinging jet. They found that the heat (mass) transfer distribution increased with the jet Reynolds number. A more recent work by Metzger et al. [40] employed liquid crystal for mapping local heat transfer distributions from a rotating disk with a jet impingement flow. The radial location of the jet was varied in separate steps from the disk center to the disk edge. They concluded that the most efficient use of disk cooling fluid was attained with the center impingement and the radial heat transfer distribution decreased with increasing impingement radius. Chou and Gong [41] presented the effect of wall cooling on the heat and flow structure in a vertical rotating-disk CVD reactor. They also determined the flow regime map in the design and operation of CVD reactors. Saniei et al. [42 & 43] measured the local heat transfer and found that it was mainly affected by the jet dominated or rotation dominated flow, which were determined by the jet and rotation Reynolds numbers. They further showed that the jet impingement penetrated into the boundary layer and changed the onset of transition to turbulence regardless of the location of the jet impingement. Besides, the impinging jet mixed with the rotationally induced flow and enhanced heat transfer from the disk. Chen et al. [44] used naphthalene sublimation technique to measure the local heat and mass transfer from a rotating disk with jet impingement. They revealed that the Sherwood number consisted of the two components governed by the impinging jet and the rotating disk.

A numerical study from Evans and Greif [45 & 46] to predict heat transfer in a vertical rotating disk reactor showed that for the mixed convection parameter $Gr/Re_{\Omega}^{3/2}$ less than approximately 3, the heat transfer was uniform over most of the disk except close to the disk edge where the flow turned the corner and left the reactor. One- and two-dimensional analyses of the flow and heat transfer in a vertical high speed rotating disk and stagnation flow CVD reactor were carried out with a particular emphasis on the effects of the spacing between the stationary gas inlet and the rotating disk by Joh and Evans [47]. Numerical simulation and experimental measurements from Wang et al. [48] indicated that the buoyancy-driven recirculations could be eliminated by careful reactor design and by appropriate choices of operating pressure, gas flow rate and susceptor rotation rate. A comprehensive overview of the transport phenomena in various CVD reactors was given by Patnaik et al. [49] and Fotiadis et al. [50 & 51]. They examined the effects of the operating parameters, reactor geometry, heat transfer characteristics on the flow patterns and deposition rate uniformity of reactant by using detailed transport models of vertical MOCVD reactors. They observed two types of recirculation cells in the vertical reactors: (1) natural convection cells driven by unstable density gradients due to large temperature gradients and (2) cells due to flow separation associated with sudden expansion in the flow cross-sectional area. The results demonstrated that natural convection effects could be reduced and thus the uniformity could be improved by increasing the inlet flow rate, rotating the susceptor, reducing the pressure, inverting the reactor, shortening the distance between inlet and susceptor, introducing baffles, and reshaping the reactor wall. The susceptor rotation improved film uniformity by reducing the thickness of the boundary layer above the substrate. Beyond a critical rotation rate, however, recirculating flow forms near the reactor wall and destroys radial uniformity and interface abruptness. Finally, the literature relevant to the fluid flow and heat transfer over a rotating disk with the jet impingement are summarized in Table 1.1.

1.3 Objective and Scope of Present Study

The above literature review reveals clearly that the detailed flow characteristics associated with a jet impinging onto a rotating disk in a confined vertical chamber remain largely unexplored. Particularly, most studies focus mainly on the characteristics of heat or mass transfer. Little attention has been given to the complex vortex flow structures resulting from the simultaneous presence of the disk rotation and jet impingement. To promote our understanding of the detailed recirculating flow patterns associated with a vertical MOCVD reactor, experimental flow visualization is conducted in the present study to explore the complex vortex flow structures in a confined single air jet impinging onto a heated rotating disk in a vertical cylindrical chamber. In the present study we intend to explore the possible suppression of the buoyancy induced vortex rolls by the disk rotation. Particular attention will be paid to examining how the steady and time dependent inertia and buoyancy-driven rolls are affected by the disk rotation. Moreover, the inertia and buoyancy-driven instabilities influenced by disk rotation will be explored in detail. Meanwhile, steady temperature distributions and transient temperature variations will be measured to delineate the steady and unsteady thermal characteristics of the flow.

Table 1.1 Summary of literature for studies on rotating disk with jet impingement

Authors	Methods	Transport Phenomena	Fluid	Parameters	Results
Metzger et al. (1977)	Experiment (LDV)	Flow and heat transfer	Air	Re_Ω (r)=8×10^3~3×10^5 Re_j=10^3~4×10^3	Rotation and impingement dominated regime
Popiel et al. (1986)	Experiment	Local heat transfer	Air	Re_Ω (r)=10^4~10^6 Re_j=10^4~7×10^5	Nu(r)~ $Re_j^{0.68}$
Brodersen et.al. (1992)	Experiment (LDV)	Flow structure	Water	Re_Ω (r)=486,221 Re_j=6,601	Flow field measurement and turbulence intensity
Brodersen et al. (1996)	Experiment (LDV)	Flow structure	Air	Re_j=6.6×10^3~6.8×10^4 Re_Ω =3.4×10^5~6.2×10^5	α (the ratio of Re_j and Re_Ω) α >0.125 (jet dominated flow) α <0.125 (disk dominated flow)
Soong et al. (1997)	Experiment	Flow structure	Air	Re=47 and 94 Ra=0 and 4.55×10^5 Ro=0 to 2.096	Flow visualization
Saniei et al. (1998&2000)	Experiment (liquid crystal)	Local heat transfer	Air	Disk rotation speed =250~4,000 rpm Re_j=6.8×10^3~4.8×10^4 H/D_j= 2~8	Nu(r)~(r/R, H/D, $Re_{\Omega\,(R)}$, Re_j) $\overline{Nu}$ ~($Re_{\Omega\,(R)}$, Re_j)
Chen et al. (1998)	Experiment (naphthalene sublimation)	Local heat and mass transfer	Air	Disk rotation speed =60~4,000 rpm Re_j=2×10^3~1×10^5 H/D=5 R/D=0~12	Sh_{rj}= Sh_j+Sh_r =C $Re_j^{0.7}(R/D)^{0.1}$.. impinging component $+\begin{cases} Sh_r = 0.59Re_r^{0.5} \text{ (laminar)} \\ Sh_r = 2\times10^{-19} Re_r^{4} \text{ (transition)} \\ Sh_r = 0.0512Re_r^{0.8} \text{ (turbulent)} \end{cases}$ ……………………rotational component
Santen et al. (2000)	Numerical	Flow and heat transfer	Air	Ra=2×10^3 and 10^5 aspect ratio (height/diameter) of the reactor>>1.	Effects of Re_{in}, Ra, Re_Ω , H/D

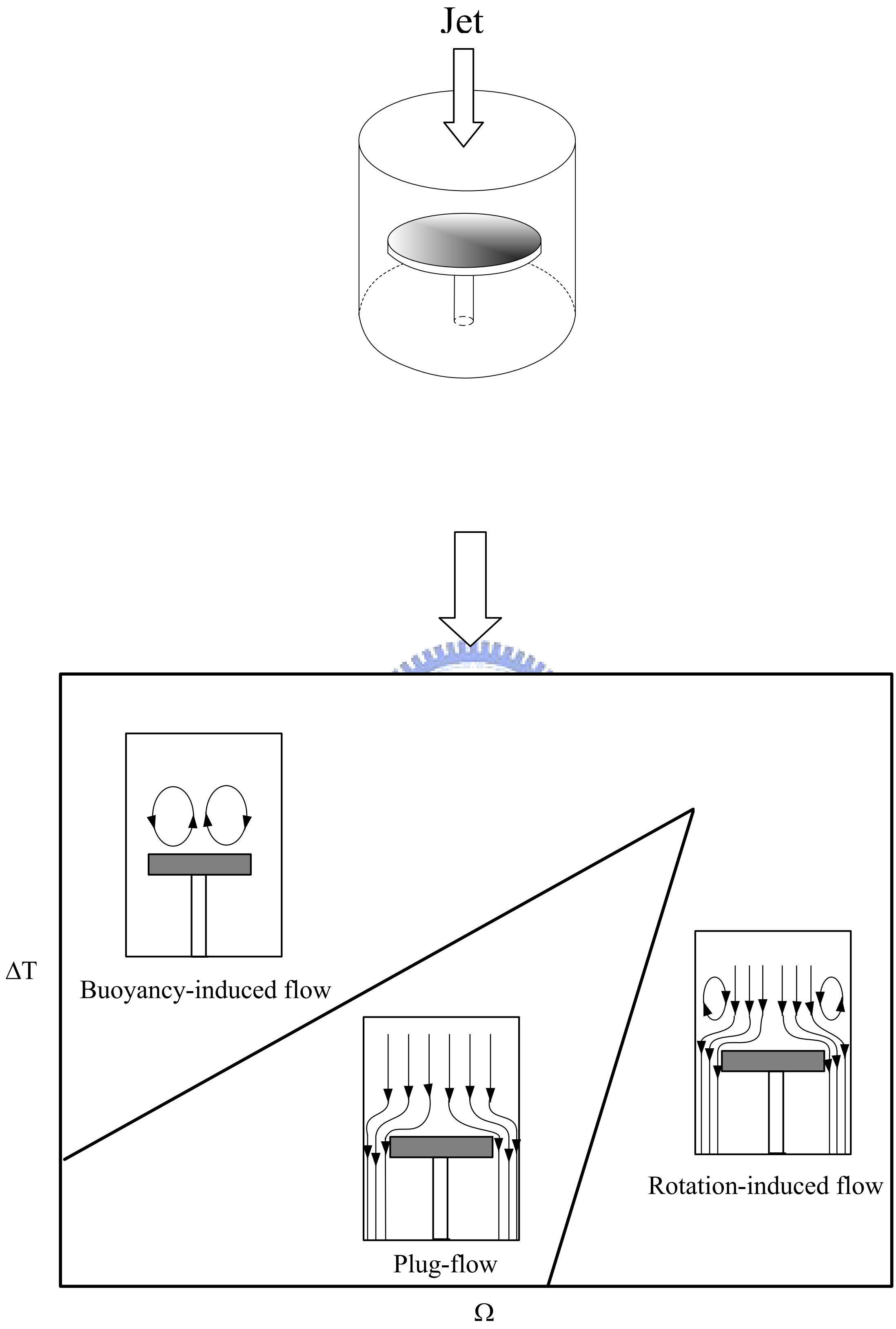

Fig. 1.1 Schematic of the flow patterns in a confined impinging jet depicting the plug-flow, buoyancy-induced flow and rotation-induced flow.

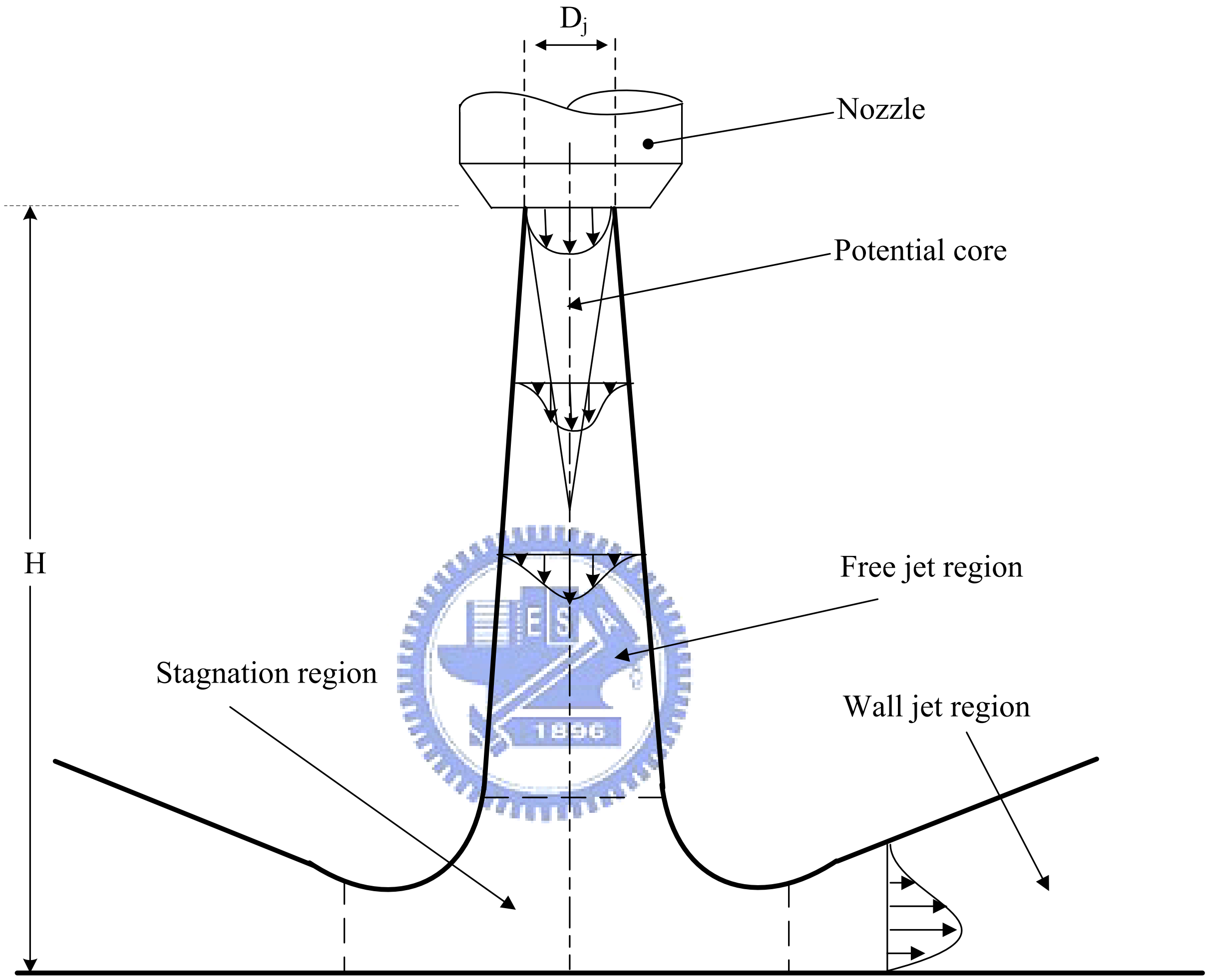

Fig. 1.2 Flow regimes associated with a circular jet impinging onto a flat plate.

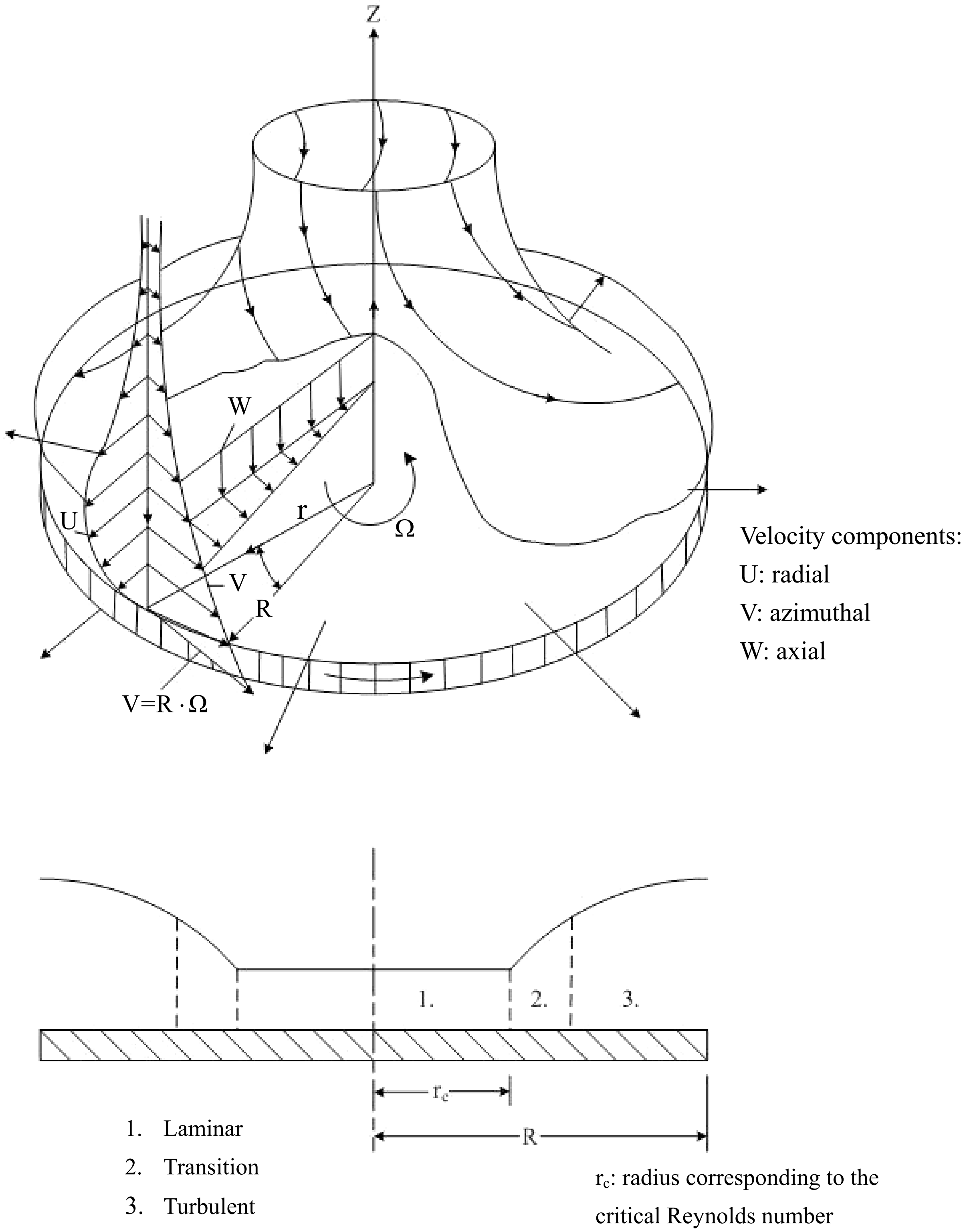

Fig. 1.3 Flow close to a rotating disk in a fluid at rest: (a) velocity profile and (b) boundary profile.