CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Depending upon the distance of the confining boundaries from discharge, a jet can be analyzed as a free jet or a bounded one. If the boundaries (parallel to inlet axis) sufficiently away from the origin of the jet, the flow is termed as a free jet. However, a bounded jet will occur when it interacts with a parallel wall. Bounded jets can be classified into three types: (a) impinging jet aimed towards the boundary; (b) wall jet where fluid is discharged at the boundary; and (c) offset jet from a vertical wall of a stagnant pool issuing parallel to a horizontal solid wall. Viskanta (1993) reported different configurations of previous isothermal jet impingement heat transfer studies.

1.1.1 Free Impinging Jet

The jet coming from either from a round or a slot nozzle impinges over a plane surface (Figures 1.1 and 1.2). The jet flow is divided into two main regions, the stagnation and the wall jet regions. In the stagnation region, the jet impinges axially and fluid comes to rest with the impingement plate. Beyond the stagnation region, the fluid starts to flow radially and axisymmetrically in the case of the round nozzle and the fluid starts to flow along the impingement plate in a plane two-dimensional pattern in the case of the slot nozzle. This region is called as wall jet region. A stagnation point
forms in the axisymmetric circular jet, while a stagnation line forms in the two-dimensional slot jet.

1.1.2 Confined Impinging Jet

The jet coming from a nozzle impinges over a plane surface (impingement plate). A confinement plate is located at the jet exit as shown in Figures 1.3 and 1.4. The jet flow is divided into three regions, the stagnation, the wall jet and the channel flow regions. A counterclockwise primary vortex
is formed adjacent to the jet and below the confinement plate due to low-pressure formation near the mouth of the jet ejection. The secondary vortex is formed when the momentum of the jet is unable to overcome the opposing frictional force of the impingement plate and retarding effects of the primary vortex.

**Figure 1.3 Impinging circular jet with confinement disc**

**Figure 1.4 Impinging slot jet with confinement plate**

### 1.2 LITERATURE REVIEW

The fluid jets impinging normally to plane solid surfaces have numerous applications in various engineering industries. Impinging jets are used in applications where high convective heat transfer rate is required. The local heat transfer coefficient is high in the impingement and adjoined wall jet...
region. Impinging jets are used to heat, cool, and dry the surfaces in number of industrial applications. They are employed in gas turbine cooling to maintain the temperatures of turbine blades below metallurgically allowed limits, annealing of plastic sheets, tempering of glass, anti-icing of aircraft wings, drying of continuous sheets like papers, textiles, photographic films, and plywood etc. In aeronautics, vertical take-off helicopters and rockets create a downwash with considerable rates of cooling or heating. Impinging jets are also used for cooling of microelectronic components where intense cooling required over small areas. In microelectronic cooling, air velocities are small and, hence, the laminar regime is relevant for investigation (Chiriac and Ortega 2002). The low Reynolds number jets are preferred in order to avoid the high pressure in the impingement region.

1.2.1 Impinging Jet Flows

In recent years, many researches have carried out numerical and experimental investigations of impinging jet under various conditions. Single or multiple jets with cross sections of round, annulus or slot jets with or without confinement surface are considered for investigations. Miyazaki and Silberman (1972) analyzed theoretically the two-dimensional laminar jet impinging on a flat plate. They evaluated the local friction factor and Nusselt numbers. Sparrow and Wong (1975) employed naphthalene sublimation technique to analyze mass transfer coefficients due to an impinging slot jet in the laminar region. A mass-heat transfer analogy was used to convert mass transfer results into heat transfer results. Heiningen et al (1976) investigated numerically the effects of uniform suction and nozzle exit velocity profile on the flow and heat transfer characteristics of a semi-confined laminar impinging slot jet. They reported that two different nozzle exit velocity profiles, uniform and parabolic, affected the heat transfer and flow characteristics significantly.
Masliyah and Nguyen (1979) studied the problem using holographic technique. Law and Masliyah (1984a) studied experimentally and theoretically the local mass transfer due to impingement of a confined laminar two-dimensional air jet on a flat surface for a Reynolds number up to 400 and for two jet-to-plate spacings. The experimental study was made via double exposure and real-time holography. Law and Masliyah (1984b) numerically studied impinging jet flow with Reynolds numbers between 100 and 400, and jet-to-plate spacings between 2 and 4. The detailed flow characteristics are considered in steady state without any heat transfer. Schafer et al (1992) calculated the effects of the jet velocity profile and pertinent dimensionless parameters on flow and heat transfer conditions. For the different jet velocity profiles, uniform and fully developed profiles, heat transfer and flow field were compared. Al-Sanea (1992) presented numerical results for laminar slot-jet impinging on an isothermal surface for three cases namely, free-jet impingement, semi-confined-jet impingement, and semi-confined-jet impingement through a cross flow. It was found that cross flow degrades the nominal heat transfer rate.

Chou and Hung (1994) reported numerical results of confined slot jet impinging on an isothermal surface. The effect of jet Reynolds number, ratio of separation distance to jet width, and jet velocity profile on stagnation and local heat transfer characteristics were explored. Nusselt number correlations were presented for predicting stagnation and local heat transfer characteristics. Seyedein et al (1994) presented the numerically simulated results of two-dimensional flow field and heat transfer due to laminar heated multiple slot jets discharging normally into a converging confined channel. The parameters studied were the jet Reynolds number (600 < $Re$ < 1000), and the angle of inclination of the upper surface (0° < $\theta$ < 20°). Inclination of the confined surface so as to accelerate the exhaust flow was found to level the Nusselt number distribution on the impingement surface.
Lin et al (1997) reported the experimental study on heat transfer behaviours of confined slot jet impingement. The parametric effect of jet Reynolds number and jet separation distance on heat transfer characteristics of the heated target surface were studied. It has been found that the heat transfer performance increases with increasing the jet Reynolds number and the effect of jet separation distance is not significant in the heat transfer behaviours on stagnation region. They classified an impinging jet flow into laminar or turbulent according to the turbulent intensity. San et al (1997) reported experimental results for a confined circular air jet impinging a surface with constant heat flux. The jet flow after impingement was constrained to exit in two opposite direction. Four diameter of impinging jet 3, 4, 6, and 9 mm and the jet Reynolds number range of 30,000-67,000 were considered.

Fitzgerald and Garimella (1997) experimentally studied the flow field of an axisymmetric, confined, submerged, turbulent jet impinging normally on a flat plate. Reynolds number range of 8500-23000 was considered. A recirculation zone was observed moving radially outward from stagnation zone, with an increase in both Reynolds number and nozzle-to-plate spacing. Baydar (1999) experimentally investigated the flow field between two horizontal surfaces arising from jet issuing from the lower surface and impinging normally on the upper surface. The effects of Reynolds number and nozzle-to-plate spacing on the flow structure were examined. It is reported that there exists a linkage between the sub-atmospheric region and peaks in heat transfer coefficients.

Chen et al (2000) carried out an experimental and numerical study to investigate the high Schmidt number mass transfer to a line electrode in laminar impinging slot jet flows for the slot-based Reynolds number from 220 to 690. Their experimental and theoretical results showed that the peak values
in mass transfer occur at a point one-half to one jet width away from the stagnation point, which was not observed by the earlier studies. Phares et al (2000) presented a method for the theoretical determination of the wall shear stress under impinging jets for a wide range of Reynolds numbers and jet heights. They compared their theoretically predicted results with available wall shear stress measurements. They found that the electrochemical method in submerged impinging liquid jets could predict the wall shear stress in the impingement region most accurately among any of the indirect methods and determine an empirical relation describing the rise in wall shear stress due to compressibility effects in high-velocity impinging jets. Chatterjee and Deviprasath (2001) presented the role of upstream vorticity diffusion for off-stagnation point Nusselt number maxima in laminar impinging jets at small height ratios.

Aldabbagh and Sezai (2002) investigated the flow and heat transfer characteristics of impinging laminar multiple square jets through the solution of the three-dimensional Navier Stokes and energy equations in steady state for different jet-to-jet spacings and nozzle exit to plate distances. Chiriac and Ortega (2002) numerically studied the steady and unsteady flow and heat transfer due to a confined two-dimensional slot jet impinging on an isothermal plate. It was found that the flow becomes unsteady at a Reynolds number above 650. Chung and Luo (2002) and Chung et al (2002) studied the unsteady heat transfer caused by a confined impinging jet using direct numerical simulation (DNS) for low Reynolds number and presented the influence of primary vortex on flow field and stagnation Nusselt number. It was found that the secondary vortices influence the Nusselt number distribution away from the impingement point. Park et al (2003) predicted the flow and heat transfer characteristics of two dimensional confined impinging slot jets in the laminar and turbulent cases.
Sahoo and Sharif (2004a) numerically studied the flow and heat transfer characteristics in the cooling of an isothermal hot surface by impinging slot jets for a range of jet exit Reynolds numbers (100-500) and Richardson numbers (0-10). Sahoo and Sharif (2004b) numerically studied the flow and heat transfer characteristics in the cooling of a constant heat flux surface by impinging slot jets. The average Nusselt number does not change significantly with Richardson number, indicating that the buoyancy effects are not very significant in the overall heat transfer process for the range of jet Reynolds number considered.

Baonga et al (2006) presented experimental results of the hydrodynamic and the thermal characteristics of free liquid jet impinged on a heated disk. Kanna and Das (2005a) numerically studied impingement region developed due to offset jet with respect to offset ratio and Reynolds number. Lee et al (2005) numerically investigates two-dimensional laminar slot jet phenomena in the presence of an applied magnetic field to control vortices and enhance heat transfer. The visualization and measurement of heat transfer characteristics were conducted by Hsieh et al (2006) for the jet Reynolds number varying from 0 to 1623. They noted that vortex flow at even higher Reynolds numbers becomes unstable due to the inertia driven flow instability. Lee et al (2008) investigated the dependency of flow and thermal fields of the confined impinging jet on the Reynolds number and height ratio.

1.2.2 Conjugate Heat Transfer

Conjugate heat transfer occurs when the fluid medium as well as the solid medium are involved simultaneously and the heat flux is balanced at the fluid and solid interface boundary. Many publications are devoted to conjugate heat transfer on flat plate (Payvar 1971, Luikov 1974, Pozzi and Lupo 1989, Pop and Ingham 1993, Vynnycky et al 1998). Wang et al (1989) analytically reported the conjugate heat transfer characteristics of a laminar
circular jet impinging on the plane surface of a solid disk, which is laterally insulated with an arbitrary temperature or heat flux distribution prescribed at the non-impingement surface. Faghri et al (1993) studied the conjugate heat transfer from a heated disk to a thin liquid film formed by a controlled impinging jet. Ruocco (1997) discussed the conjugate heat transfer from a finite thickness plate to a laminar confined, impinging planar jet in order to determine the solid-fluid coupling characteristics that minimize the rate of entropy generation.

Bula et al (2000a) analyzed a free jet of high Prandtl number fluid impinging perpendicularly on a solid substrate of finite thickness containing small discrete heat sources on the opposite surface. Both solid and fluid regions were modeled and solved as a conjugate problem. It was found that the local heat transfer coefficient is maximum at the center of the disk and decreases gradually with radius as the flow moves downstream. The thickness of the disk as well as the location of discrete sources showed strong influence on the maximum temperature and the average heat transfer coefficient. Bula et al (2000b) numerically solved the conjugate heat transfer from discrete heat sources to a two-dimensional jet of a high Prandtl number fluid discharging from a slot nozzle. It was found that in addition to jet Reynolds number plate thickness and its thermal conductivity have significant influence on temperate distribution and average Nusselt number.

Kanna and Das (2005b) analytically investigated for forced convection heat transfer from a laminar plane wall jet as conjugate case. Kanna and Das (2005c) numerically reported the steady-state conjugate heat transfer study of a slab and fluid for a two-dimensional laminar incompressible offset jet. The conjugate heat transfer characteristics were studied with four parameters, $Re$, $Pr$, $S/h$ and $k$. When $k$ is increased, its effect on $Nu$ is reduced. Kanna and Das (2006) studied the conjugate heat transfer
characteristics for backward-facing step flow problem. Yang and Tsai (2007) presented the numerical study of transient conjugate heat transfer in a high turbulence air jet impinging over a flat circular disk. The numerical simulation of transient, two-dimensional cylindrical coordinate, turbulent flow and heat transfer was adopted to test the accuracy of the theoretical model. High turbulence values lead to greater heat transfer coefficients in the stagnation region.

Lallave et al (2007) studied the conjugate heat transfer for a confined liquid jet impinging on a rotating and uniformly heated solid disk of finite thickness and radius. It was found that plate materials with higher thermal conductivity maintained a more uniform temperature distribution at the solid fluid interface. A higher Reynolds number increased the local heat transfer coefficient reducing the wall to fluid temperature difference over the entire interface. The rotational rate also increased local heat transfer coefficient under most conditions. Rahman and Lallave (2007) studied the convective heat transfer of a free liquid jet impinging on a rotating and uniformly heated solid disk of finite thickness and radius and proposed a generalized correlation for average Nusselt number.

1.2.3 Impinging Slot Jet Flows Through Porous Medium

The jet impingement cooling through horizontal porous layer are important from theoretical as well as application points of view. The buoyancy driven phenomena in porous media has attracted researchers interests due to number of technical applications, such as, fluid flow in geothermal reservoirs, insulation of buildings, separation processes in chemical industries, dispersion of chemical contaminants through water saturated soil, solidification of casting, migration of moisture in grain storage system, crude oil production, solar collectors, electronic components cooling, etc. Comprehensive literature survey concerned with this subject is given by

Recently many researchers considered the impinging jet through porous media. Fu and Huang (1997) investigated numerically the effects of a laminar jet on the heat transfer performance of three different shape (rectangle, convex and concave) porous blocks mounted on a heated plate. They neglected the buoyancy effects and considered the forced convection mode only. Their results show that the heat transfer is mainly affected by a fluid flowing near the heated region. For a lower porous block, all the three type of porous blocks enhance the heat transfer. However, for a higher porous block, the concave porous block only enhances heat transfer. A detailed flow visualization experiment was carried out by Prakash et al (2001) to investigate the effect of a porous layer on flow patterns in an overlying turbulent flow without heat transfer. They studied the effect of the parameters such as the jet Reynolds number, the permeability of the porous foam, the thickness of the porous foam and the height of the overlying fluid layer. Jeng and Tzeng (2005) studied numerically the air jet impingement cooling of a porous metallic foam heat sink in the forced convection mode. They found the porous aluminum foam heat sink could enhance the heat transfer from the heated horizontal source by impinging cooling. Their results show that the heat transfer performance of the aluminum foam heat sink is 2-3 times larger than that without it.
Saeid and Mohamad (2006) studied numerically the jet impingement cooling of heated portion of an isothermal horizontal surface immersed in a fluid saturated porous media in the mixed convection regime. It was found for high values of Péclet number at increasing either Rayleigh number or jet width lead to increase the average Nusselt number. Narrowing the distance between the jet and the heated portion could increase the average Nusselt number. Jeng et al (2008) carried out experimental investigation on heat transfer associated with air jet impingement on rotating porous Aluminum foam heats sink. They investigated the effects of jet Reynolds number \((Re)\) in the forced convection mode, the relative nozzle-to-foam tip distance \((C/d)\), the rotational Reynolds number and the relative side length of the square heat sink \((L/d)\). They found that, when \(Re\) and \(L/d\) were small and \(C/d\) was large, the increase in rotational Reynolds number increases the average Nusselt number.

Tong and Subramanian (1985) Lauriat and Prasad (1987), and Prasad et al (1988) demonstrated the Brinkman-extended Darcy flow model in the numerical investigation on natural convection in a vertical porous layer. They highlighted the importance of Brinkman equation in convection of porous media. Hadim and Chen (1993) reported a numerical study of buoyancy-aided mixed convection in an isothermally heated vertical channel filled with a fluid-saturated porous medium using the Darcy-Brinkman-Forchheimer model. Their results show that, the effect of decreasing Darcy number is, however, important only at low values of Darcy number (in the Darcy Regime). At large Darcy number, the flow in this region is dominated by forced convection and the Nusselt number is almost independent of \(Da\). Wong and Saeid (2009) numerically investigated the jet impingement cooling of heated portion of an isothermal horizontal surface immersed in a confined porous channel under mixed convection conditions with Brinkman-extended Darcy model.
1.3 OBJECTIVES OF THE PRESENT WORK

The following situations are considered for carrying out the research.

- Fluid flow study of laminar impinging slot jet flow.
- Heat transfer study of laminar impinging slot jet flow.
- Conjugate heat transfer study of laminar impinging slot jet flow.
- Mixed convection study of jet impingement cooling in a confined porous layer.
- Mixed convection study of jet impingement cooling in an unconfined porous medium.

1.4 THESIS ORGANIZATION

The thesis is organized as follows. In Chapter 1, background information on jet impingement flow is provided along with literature review. Chapter 2 presents hydrodynamic study of confined impinging slot jet flow problem. Chapter 3 discusses the heat transfer study of confined impinging slot jet. Chapter 4 deals with the conjugate heat transfer study of confined impinging slot jet. Chapter 5 presents mixed convection study of jet impingement cooling of a constant heat flux horizontal surface in a confined porous layer. Chapter 6 discusses mixed convection study of jet impingement cooling of an isothermal horizontal surface in an unconfined porous medium. Finally, Chapter 7 covers the conclusion and suggestions for future work.