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Theoretical and experimental study on heat transfer characteristics of normally impinging two dimensional jets on a hot surface

Mayank Modak, Krati Garg, Srikaanth Srinivasan, Santosh K. Sahu*

Discipline of Mechanical Engineering, School of Engineering, Indian Institute of Technology Indore, Indore, 453552, Madhya Pradesh, India

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ABSTRACT

A theoretical model is proposed to study the fluid flow and heat transfer behavior of two dimensional impinging jet on a solid surface. Energy integral method is used to obtain the solution. Based on the analysis a generalized expression involving various modelling parameter such as Nusselt number, nozzle to plate distance, Prandtl number, Reynolds number and the modelling parameter k is obtained. Experimental investigation is performed to evaluate the heat transfer characteristics of a two dimensional impinging jets on the hot foil. Tests have been carried by using a two dimensional nozzle with length to diameter (l/d_h) ratio of 70. Reynolds number based on nozzle exit condition is varied between 7000 and 17 000 and jet-to-plate spacing between 1 and 10. A hot foil of 0.15 mm (SS 304) is used as the test specimen and air is used as fluid during experiments. The local heat transfer characteristics are estimated from the thermal images obtained from infrared thermal imaging camera (A655sc, FLIR System). The results obtained from the theoretical model are compared with test data obtained during present experimental investigation. In addition, a correlation for Nusselt number is proposed as a function of nozzle to plate distance, Prandtl number, Reynolds number, radial distance.

1. Introduction

Impinging jets are used widely in various scientific and industrial applications due to their capability of achieving higher rates of heat transfer from comparatively smaller surface area. Several industrial processes that utilizes impinging jets includes cooling of gas turbine blades, processing of metals and glass, drying of textile and food products and cooling of electronics components. The heat transfer and fluid flow during jet impingement is a complicated phenomenon. The jet issues from the nozzle and impinges on the hot surface, the flow field is divided into two main regions namely, a stagnation region and a wall jet region. The parameters that affect the heat transfer rates in these regions are different. In the case of stagnation region, the external flow just outside the boundary layer and the maximum free jet velocity arriving at the stagnation region affects the heat transfer rates. The boundary layer flow close to the stagnation point may be considered laminar because of lower Reynolds number. Therefore, one can assume the flow to remains laminar for the entire stagnation region [1]. The heat transfer from the hot surface is maximum at the stagnation point and decreases in the direction away from the stagnation point. Several studies involving experimental investigations and theoretical simulations have been made to analyze the heat transfer phenomenon during jet impingement. The free jet region consists of following zones: the potential core, where the jet maintains its exit velocity at the centerline while mixing and diffusing with the ambient fluid in its shear layers; the transition zone, where the core velocity has decayed completely, and the shear layer interacts with the centerline and fully developed zone from where the jet intensity starts decreasing.

In general, two configurations are utilized for the jet impingement: circular jet with axisymmetric flow profile and a slot jet with a two-dimensional flow profile. Several studies have been made to study the fluid flow and heat transfer characteristics of axisymmetric jet [2–5]. It is observed that single jet usually have a small impingement zone over the heated surface. Although multiple jets enhances the rate of cooling, but these jets promote flow blockage between the jets and complicate fluid distribution downstream from the impingement zone [6–8]. These problems become critical during cooling of electronic panels which requires cooling of large number of small electronics chips and rejection of fluid from comparatively small volume. In order to overcome such problems,

* Corresponding author.
E-mail address: santosh.sahu04@gmail.com (S.K. Sahu).

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the slot jet configuration is used [9]. A two dimensional jet provides a larger impingement area and better uniformity of fluids flow over the test surface. It is argued that a two-dimensional or slot air jet offers various beneficial features including cooling effectiveness, uniformity and controllability on compact electronic packages [9]. This has motivated various researchers to study the heat transfer and fluid flow behavior of two dimensional jet through both theoretical and experimental investigation. Several experimental studies have been performed to analyze the effect of various parameters such as: nozzle to plate distance, nozzle width, nozzle diameter, Reynolds number and inclination angle of impinging jets on the heat transfer behavior of two dimensional jets [9–19]. It is argued that for lower nozzle to plate distance (L/B < 5) and lower Reynolds number (Re < 3000), the heat transfer characteristics of stagnation point is independent of nozzle to width and nozzle to plate distance, the nozzle with higher diameter exhibits better heat transfer performance.

Also, efforts have been made to obtain analytical and numerical solution pertaining to the heat transfer behavior of two dimensional jets [20–33]. The two-dimensional flow of a fluid near a stagnation point is a classical problem in fluid dynamics and its solution was first given by Hiemenz [21]. Schlichting [22] utilized the potential flow boundary conditions and developed a one dimensional axisymmetric model for an infinite diameter jet impingement on a plate. Kee et al. [23] extended the one dimensional model of Schlichting [22] to allow both velocity and velocity gradient this providing more flexible boundary condition.

Miyasaka and Silberman [24] obtained solutions for skin friction coefficient by using the boundary layer and energy equation for different nozzle to plate distance. Sparrow and Lee [25] utilized similar approach [24] and obtained solutions for two dimensional jet with parabolic flow profile at the nozzle exit. Brahma [26] studied the fluid flow and heat transfer characteristics of two dimensional jet impinging over a flat plate. The authors presented correlations for Stanton number at the stagnation point in terms of velocity gradient and Reynolds number. Kayansayan and Kucuka [27] reported the solutions by employing the numerical technique on the jet impingement cooling of concave channel using slot jet. However, authors observed significant deviation between the test data's and numerical results. Beitelmal et al. [28] reported approximate solutions for stagnation and wall jet region for a two dimensional jet impingement on a flat plate using simplified flow assumptions. The solutions are analyzed and compared with the available test data [28]. Benmouhoub and Mataoui [29] studied the turbulent heat transfer from a slot jet impingement on a flat plate by employing numerical technique. Authors [29] presented the effect of plate to jet velocity and Reynolds number on the Nusselt number and skin friction. Zumbrunnen [30] proposed an analytical model for a single planer laminar impinging slot jets onto a moving plate subjected to a constant heat flux boundary conditions. The heat transfer becomes more effective during the plate motions. This may be due to the reduced development of boundary layer due to plate motions. Chattopadhyay and Saha [31] numerically investigated the turbulence heat transfer of an array of slot jets impinging over a moving plate by using large eddy simulations (LES). The authors observed that Nusslet number distribution is more uniform for lower velocity of the hot plate. The stagnation point heat transfer for a slot jet impinging on the flat plate has been analyzed by using Blasius-Frossling series solution method. The friction factor and Nusselt number have been evaluated as a function of nozzle to plate distance. From the stagnation point [32]. Chen et al. [33] proposed a theoretical model to analyze the heat transfers of horizontal surfaces of normally impinging slot jets with arbitrary heat-flux condition. The fluid flow and heat transfer analysis were studied by employing the energy integral method [33]. Earlier, the integral method was used by Rao and Arakeri [34] to get the solutions for the free liquid jets on the surface. While, their analysis did not consider the heat transfer analysis. Later on, the method is used to obtain the heat transfer characteristics of liquid jet on heated plate [35] and rotating disks [36] and concave hemispherical surface [37]. Although the technique is simple, it provides the results with reasonable accuracy.

Kendoush [38] proposed a theoretical model to analyze the heat transfer characteristics of slot jets on heated surface. The deviation between the theoretical prediction and the test data was found to be 15.8%. Recently, Modak et al. [39] proposed a theoretical model to analyze the heat transfer heat transfer behavior of axisymmetric impinging jets on hot surface. A unified expression for the Nusselt number is present as a function of Reynolds number (Re), Prandtl number (Pr), nozzle to plate distance (L/B) and modelling parameter k by employing integral method. The theoretical prediction exhibited excellent agreement with the test data involving varied range of flow rate, coolant type and nozzle to plate distance. Based on the analyses a mechanistic correlation was proposed. With the success of the model, the analysis is extended for the two dimensional jet. The objective of the present study is to analyze theoretically the heat transfer characteristics of two dimensional jets in the stagnation region. In addition to the theoretical analysis an experimental investigation is carried out on the heat transfer characteristics of normally impinging two dimensional air jet on a flat plate. Subsequently, the tests results are compared with the theoretical model for various Reynolds number and nozzle to plate distance. Based on the experimental investigation a correlation is presented for Nusselt number.

2. Theoretical analysis

2.1. Physical model

Fig. 1 depicts the impingement of fluid through a two dimensional nozzle of width B on a heated horizontal surface, which is maintained at a distance H from the nozzle. The fluid jets moves past a stagnation layer of fluid and entrainment of the surrounding fluid occurs and the fluid jet broadens linearly with its length upto a limiting distance H_g from the solid surface. At the impingement surface, the flow is divided into two distinct regions, namely, stagnation region and wall jet region. The stagnation region is usually affected by the external flow just outside the boundary layer. The boundary layer flow in the immediate vicinity of the stagnation point can be considered as laminar due to low local Reynolds number in the region. Thus it can be assume that the flow remains laminar for the entire stagnation region. Here, the stagnation flow begins adjacent to the heated horizontal plate and the distance H_g can be approximated as 1.2 times of the nozzle diameter [1]. In the stagnation flow region, the vertical component of the velocity is decelerated and transformed into an accelerated horizontal one. The exact analytical solution of Navier-Stokes equations are obtained for several limiting cases of infinitely extended plane and axisymmetric stagnation flows (Schlichting [22], pp. 76–81). In order to apply the laminar boundary layer method, velocity and pressure gradient are required. These are boundary layer flows and the influence of viscosity is limited to a very thin layer adjacent to the heated surface.

The velocity components of the stagnation flow outside the boundary layer (potential flow) for the Cartesian coordinates are given by Schlichting [22] as:

$$V_x = Ax, V_z = -Az \tag{1}$$

The value of constant A is experimentally found by Schrader [1]