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An Investigation into the Effect of Injection Parameter on Hydrodynamic and Heat Transfer over A Flat Plate in the Presence of Compound Wall Jet

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Abstract

In this paper the flat plate with constant heat flux is placed in the floor of a subsonic open wind tunnel which provides a main flow and simultaneously, a secondary flow is injected tangentially from a slot. The hydrodynamic and heat transfer behavior of the compound wall jet provided over the plate, was experimentally studied by measuring different variables. Experiments have been performed for different velocity ratios of main to injected flow values, (m) from 0.1 up to 4, with 1050 w/m2 heat flux. Our observations of temperature distribution on the plate show that for m>3, increasing the injection parameter doesn't increase cooling properties of the compound wall jet, but for m ≈1 the effect of this parameter is significant. Also the numerical procedure for solving the governing equations has been carried out using the finite volume method. The comparison of the numerical and experimental results shows good agreement between them and other results available in the literature.

Introduction

Heat transfer investigation of external flow over flat plates with tangential injection of a secondary flow has many applications in thermal systems and they are widely used in up-to-date apparatuses and technologies. The local control of heat transfer rate is an advanced problem in cooling the electronic devices. These types of heat transfer situation are found in the refrigerated air curtain, paper industry, electronically motor cooling, wind shield, combustion chamber, etc.

Wall jets have been studied by various investigators in the past given their many technological applications. An experimentally thorough review of such flows is provided by Lounder and Rodi [1]. P.Bhacharjee [2] has studied the effect of inflow velocity profile on temperature and jet thickness distribution on the flat wall. Several researchers have studied local heat transfer between a two-dimensional wall jet and the boundary surface. Sigala [3], for example, summarized velocity and heat transfer measurements for the plan wall jet. Evaluation of heat transfer from turbulent wall jet with an isothermal and a uniform heat flux boundary conditions have been reported by Akfirat [4] and Nizoh [5] respectively. Their studies were limited for x/w>30 (full developed region) and recently, with those boundary conditions an experimental investigation has been performed for developing flow, (x/w<13) by R.S.Abdulnour et al., [6]. Mabuchi and Kumada [7] determined the non-dimensional heat transfer rate for a wall jet by analogy.

Most investigations available in the literature have been carried out in presence of only injected flow without main flow. When both injected and main flows are presented, injection parameter is revealed as a significant factor that influences hydrodynamic and thermal characteristics of the flat plate. V.P.Lebedov et al., [8] have shown that heat transfer is increased by increasing turbulent level of the external flow within the m>1 regime, but in the m<1 regime, the turbulent level has no effect on the heat transfer.

The main objective of this study is to determine the effect of injection parameter $m = U_1/U_0$ on cooling properties of compound wall jet over the flat plate. So a suitable test section was prepared and experiments were performed for different values of injection parameter and eventually experimental results were compared with numerical ones and other results available in the literature.

Experimental equipments

All the experimental equipments used in present work (Figure 1) can be divided into three distinctive sections: Test section, injected flow generator and main flow generator.

Figure 1. Experimental equipments

Test section

The test section has been made up of an aluminum flat plate with a 312mm, 920mm and 2mm width, length and thickness respectively, and according to (Figure 2), has been placed on the floor of a subsonic wind tunnel as a working plate. Thermocouples and Preston tubes have been installed on it properly.

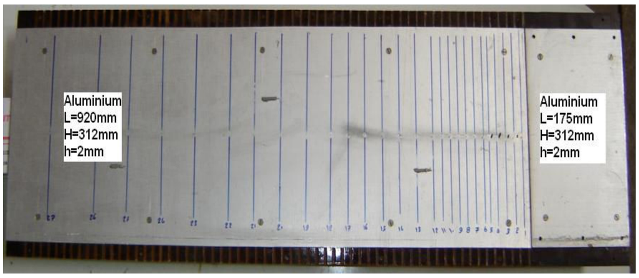

Figure 2. Working plate

In this heat transfer study, two physical boundary conditions were enacted: the first, adiabatic surface and the second, constant heat flux condition. In order to make adiabatic surface, backside of the working plate was coated with a thick heat-insulator layer made of Fiberglass and for the condition of $q_w = const.$, the heat flux was generated by ohmicaliy heating of the working plate backside. Several longitudinal slits were made on one side of the insulator for uniformly installing electrical resistors into them. The total heat transfer rate is equal to the electrical power applied to the system. The total heat flux that was applied to the system was 1150w/m2. The power losses due to conduction and radiation were calculated to be 10% of the total power. Thermal measurements were carried out by using Iron-Constantan thermocouples made of wire of 0.1 mm-diameters. A special temperature procedure system (Adam 4018) was used for reading the temperature. This system was made up of several ports which all of them are connected to a main converter port that transfers thermal signals to the computer in its own turn.

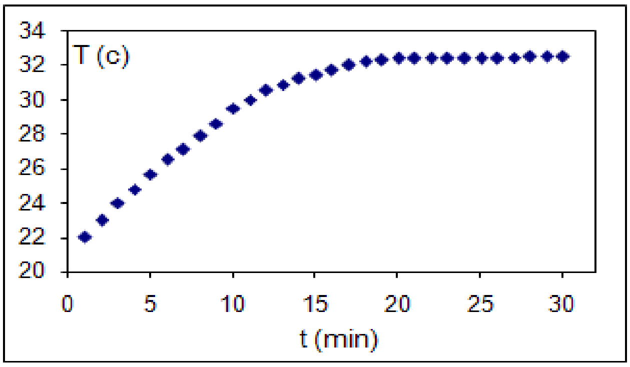

Figure 3. An instance for a special point of working plate temperature respect to time

Also by using ADAM4000 company facilities, a suitable program was set up to make easy relation with thermocouples. This program can receive signals of thermocouples, one time within the every given time period and shows the values of measured temperatures in a diagram on the monitor screen. By watching the temperature diagram, an investigator can easily recognize when steady state occurs. A typical of mentioned diagrams is shown in Figure 3. As it seems, temperature of tenth thermocouple varies by passing the time, but eventually it gets a steady state in constant value.

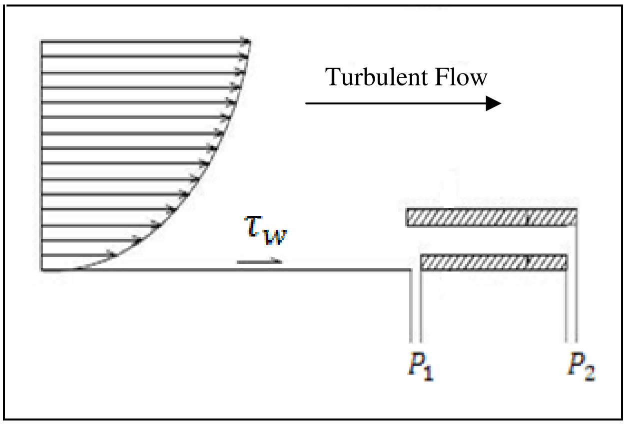

Figure 4. Preston method for measuring shear stress

The three Preston tubes (0.1mm diameter, 30mm length, made of aluminum) were assembled on working plate in order to measure shear stress according to Preston method [9] based on momentum variations in full developed flow .i.e. [10]

$$\tau_w = \frac{\gamma . d}{4L}[(\frac{p_1}{\gamma} + z_1) - (\frac{p_2}{\gamma} + z_2)] \quad (1)$$

Micro-manometer was employed for measuring p_1, p_2 .

Injected flow generator

Injected air flow was generated by a fan which works at constant speed. In order to change flow rate, a flow control valve was employed in the stream path before orifice which was used to evaluate the value of flow rate. Orifice used in the present investigation conforms to a French standard NF X10-102 with an accuracy of 1g/sec. The jet discharge slot width wide of 3.5mm was constructed using a peace of an aluminum flat plate(wide 312mm, length 175mm), joined on the starting part of working plate. Mean velocity value of injected flow is calculated according to

$$V_j = \frac{\dot{m}}{\rho A_s} \quad (2)$$

In this equation, A_s is area of injection slot and its value is 312mm×3.5mm. The jet temperature T_j was acquired using a thermocouple inserted in the exit part of slot. Mean velocity of injected flow for all experiments was maintained in constant value of 10m/s and its temperature is equal to main flow one and both of them are equal to environment temperature that is 22 C.

Main flow generator

A subsonic open wind tunnel was employed for providing main flow. The stationary air of environment is sucked by a fan placed in the end part of tunnel. At first the air stream passes through a honey comp for decreasing perturbations. Passing through nozzle, it develops so that the main stream established in test section is kind of developed flow with almost 7% turbulence level.

Evaluating experimental equipment

For evaluating experimental equipment, a comparison is done between some experiments of present work and some experimental results available in the literature. As an instance we have compared the heat transfer coefficient in the screen region that is calculated a cording to:

$$h = \frac{q_w}{T_w - T_{aw}} \quad (3)$$

The experiments were carried out in two steps. First, the wall jet (injected flow) of temperature T_j was injected into the steam of temperature T_0 at a fixed injection parameter and temperature T_{aw} of the adiabatic wall of the working plate was measured. Then the working plate was heated up in the regime $q_w = const.$ and the wall temperature T_w was determined. By substituting values of T_w, T_{aw}, q_w into equation (3), the heat transfer coefficients were computed. As shown in Figure 6, there is very good agreement between them.

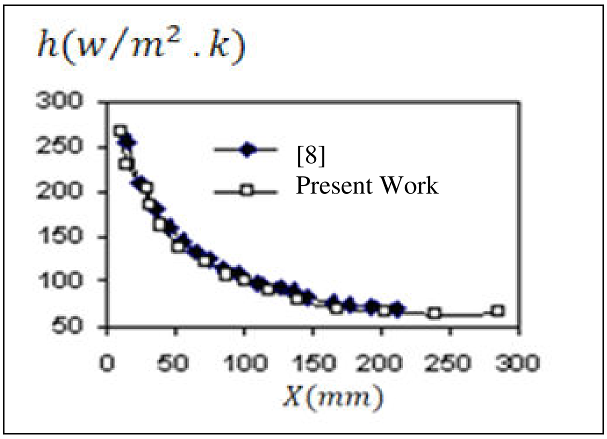

Figure 5. Heat transfer coefficient Comparison between present work and **[8]** in the screen region

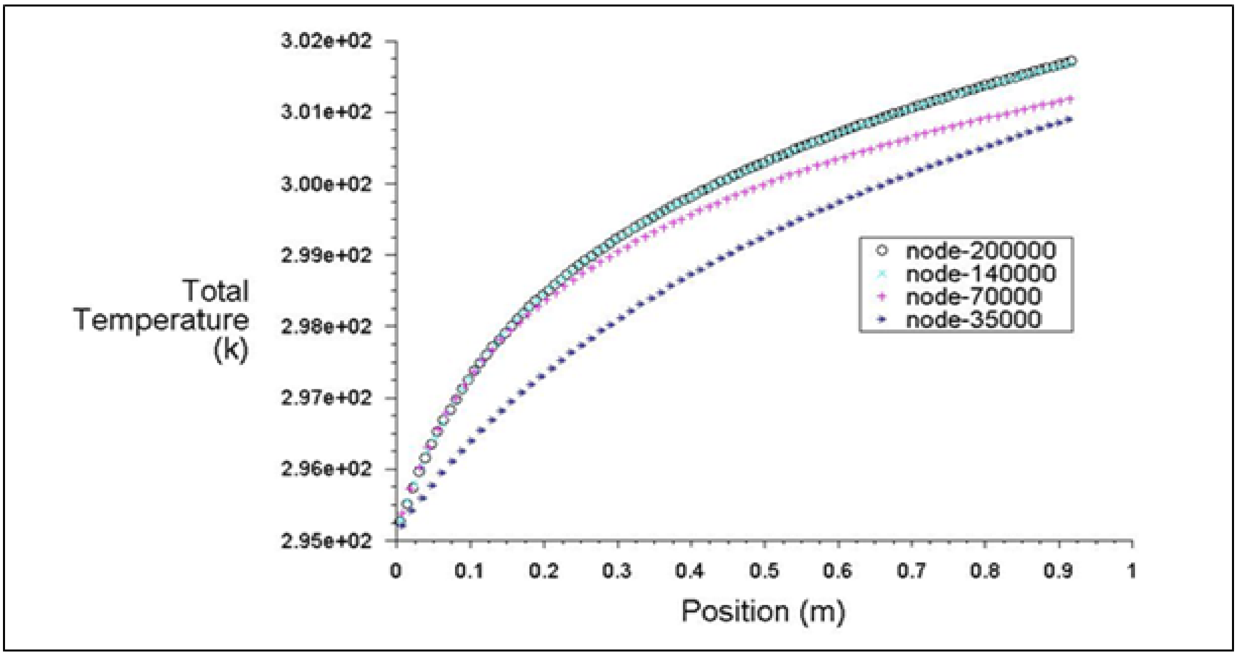

Figure 6. Procedure of grid independence

Numerical solution

The finite volume method and a standard $\kappa - \varepsilon$ model were employed for numerical procedure in this work. The governing equations and also the turbulence kinetic energy and the dissipation rate equations were discretized by the second order upwind scheme. The well known "standard" approach was used for discretizing of the pressure equation. Also Standard wall function was chosen for near wall treatment

In order to solve discretized equations (for coupling pressure equation with velocity ones), SIMPLEC method was used. For making solutions independent from grid, several computational domains with different count of cells were tried to predict the working plate temperature and as is seen in Figure 6, numerical solution for 140000 and 200000 number of cells coincidences on each other. Therefore independency is reached for 140000 cells and all of numerical procedure was carried out by this number of sells. Starting part of the problem geometry is shown in Figure 7. Space of cells for region close to injection slot are fine enough and gradually expand in the X-direction, also this way was used in the Y-direction.

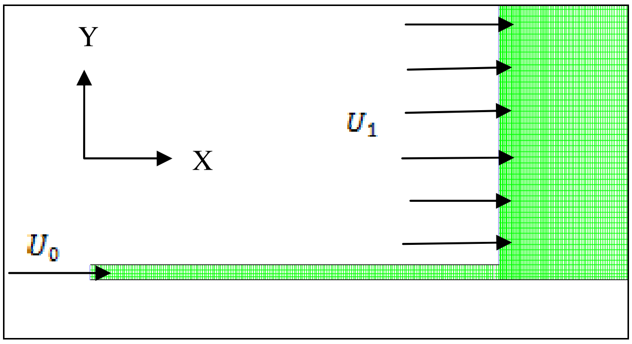

Figure 7. Inlet portion of geometry used in numerical simulation

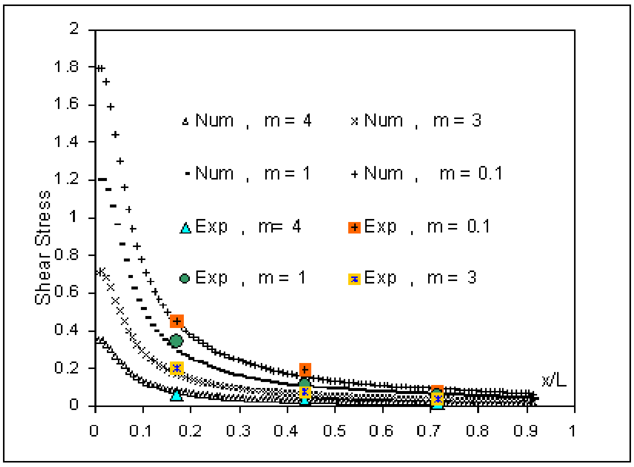

Figure 8. Shear Stress distribution on the working plate at different injection parameters

Results and discussion

Figure 8 shows the shear stress on the working plate surface in the points close to slot is greater than that is at the other points one. This behavior occurs because of two reasons. At first, the contraction of the injected and the main flows with each other causes perturbations to be increased and at the second, velocity in the region close enough to the mouth of the slot is greater than that is in the other parts of the plane plate.

According to figure 9 and 10 there is a good agreement between the numerical and the experimental results for both low and high values of the injection parameter. It should be noticed that the experimental data for low m (m=0.1) are not entirely matched with the numerical ones in the starting region of the working plate, while this disagreement doesn't exist in high values of the injection parameter. This problem arises because between the momentum of the injected and main flow, there is much difference which in turn causes to arise reverse flow in the slot exit and $\kappa - \varepsilon$ model has not adequate ability to predict reverse flows. Also by considering Figure 9 and 10 we understand that relation between the temperature of the working plate surface and points location from the slot exit to $x \approx 300mm$ $(x/w \approx 85)$ is similar to:

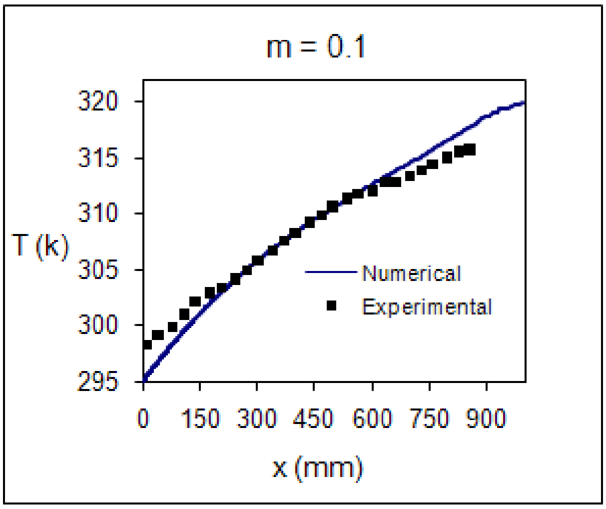

Figure 9. Comparison of Numerical and Experimental T for m=0.1

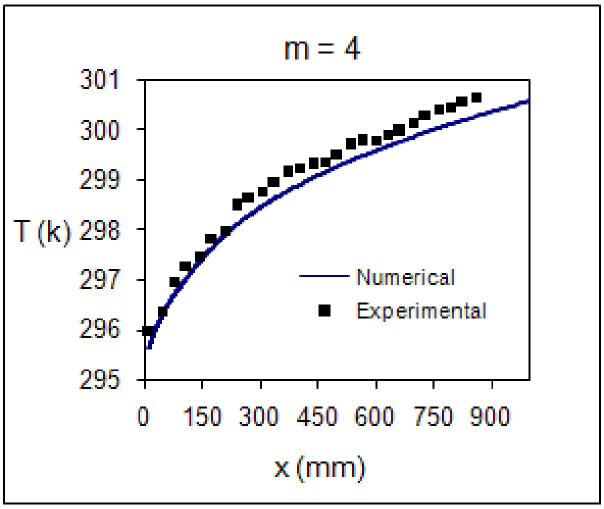

Figure 10. Comparison of Numerical and Experimental T for m=4

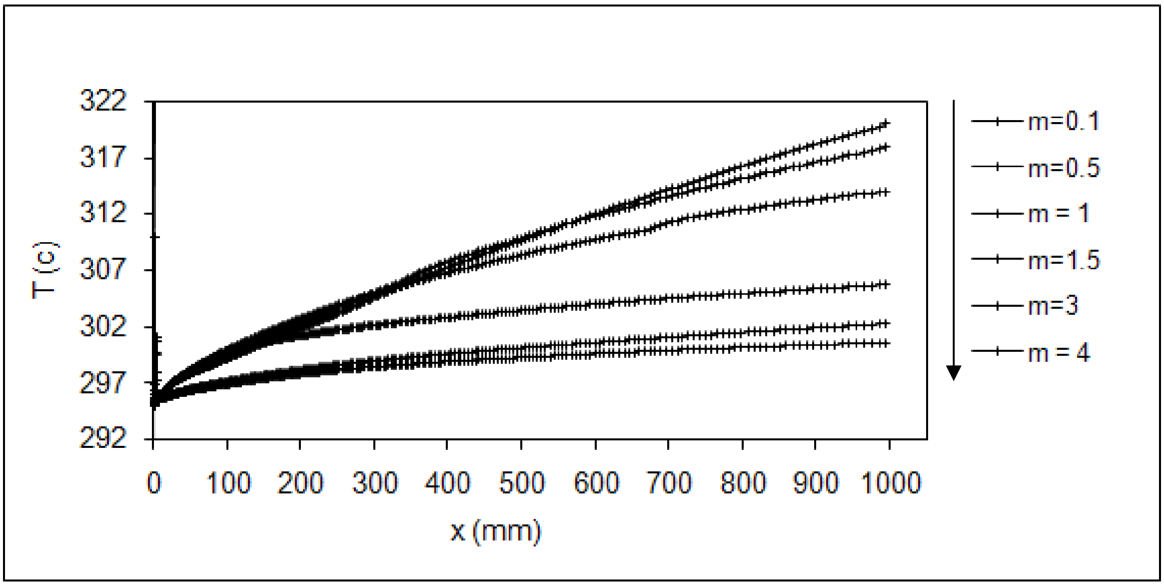

Figure 11. Temperature distribution on working plate surface at different injection parameter (numerical solution)

$$T(x) \approx k.\sqrt{x} \tag{4}$$

(k is a constant coefficient that depends on q_w) and after $x \approx 300mm$, it varies linearly.

The temperature of working plate respect to distance of points from slot exit for expand range of injection parameter is shown in figure 11. According to these results, cooling properties of the compound wall jet are very sensitive to the injection parameter when its value is close to 1. Because in this condition, momentum values of the injected and the main flows are close to each other. So that a little variation in one of them causes a considerable change in cooling properties of the compound wall jet. As it can be seen from the Figure 11, further increase of the injection parameter over almost 3 has not remarkable effect on the cooling properties of the compound wall jet. For example temperature profiles for m=4, and m=3 haven't a considerable difference with each other. Therefore irregular increase of the injection parameter won't work well and also isn't economical.

Conclusion

In the present work, the hydrodynamic and the heat transfer of the compound wall jet were experimentally and numerically studied. The effect of the injection parameter on the temperature distribution over a the plane plate and simultaneously, the cooling properties of the compound wall jet were investigated .This effort reveals that more increase in the injection parameter to obtain better cooling isn't a good idea. Also as a result of this study, it should be noticed that effect of increasing the injection parameter at the ending region of plane plate is more remarkable than that is at the initial one. Also it's better to point that the $\kappa - \varepsilon$ model can predict the shear stress on the working plate properly.

Acknowledgments

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