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Analytical investigation of the effects of free stream fluctuations on the flat plate heat transfer

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Abstract

The objective of this study is to investigate the effects of free stream turbulence intensity on the heat transfer from a flat surface. An analogy between conduction and convection is used by applying the simplified time-averaged turbulent energy equation to treat the problem. The emphasis is placed on explaining how free stream fluctuations affect the heat transfer rate. The effect of parameters such as the direction of temperature gradient, different flow regimes, and fluid types is discussed The approach taken in this work can be regarded as a rule of thumb to predict the heat transfer from/to a flat plate adjacent to a laminar or turbulent stream. The introduced method leads to the results in agreement with previous works. Some of the flow conditions considered in this work have not yet been investigated in the literature.

Keywords: Heat transfer, Free Stream Fluctuations, Turbulence intensity, Flat plate

Nomenclature

C_P	Specific heat capacity at constant pressure
k	Thermal conductivity
$\dot{q}$	Heat source strength
$\bar{T}$	Flow average temperature
$T_{\infty/w}$	Max(T_∞, T_w)
$T_{w/\infty}$	Min(T_∞, T_w)
$\bar{u}, \bar{v}$	Average velocity components along x- and y-coordinate, respectively
$\bar{U}$	Average velocity vector
u_t	Shear velocity
$\nabla\bar{T}$	Average temperature gradient
U_∞	Free-stream velocity
v', T'	Velocity and temperature fluctuations
B, C	Universal constants

Greek Symbols

δ_t	Thermal boundary layer thickness
δ_v	Velocity boundary layer thickness
Δ	Distance from a wall that fluctuations magnitude becomes noticeable
ρ	Density
υ	Kinematic viscosity
ε_H	Thermal eddy diffusivity
Π	Cole's wake parameter

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Subscripts

lam	Laminar flow
tur	Turbulent flow
w	Wall
∞	Free-stream

Notations

$O(A)$	Order of magnitude of parameter A

Non-dimensional Numbers

Re	Reynolds number
Pr	Prandtl number
Nu	Nusselt number
$\hat{v}', \hat{T}'$	Dimensionless velocity and temperature fluctuations
$\hat{\bar{U}}$	Dimensionless average velocity vector
$\nabla\hat{\bar{T}}$	Dimensionless average temperature gradient
Δ^*	Dimensionless parameter of Δ

1. Introduction

This work deals with the effects of turbulence intensity on the heat transfer from or to a flat plate by including the product of the spanwise velocity and temperature fluctuations in the simplified time-averaged energy equation for a two-dimensional turbulent boundary layer. Despite the initial discrepancies in the results of the early experiments [1, 2], now it is well known that heat transfer enhances by increasing the free stream turbulence intensity (FSTI) both for laminar and turbulent boundary layers. This introduces turbulence intensity as an important factor in heat transfer augmentation, in addition to the other parameters such as the velocity profile fullness, angle between the streamlines and temperature gradient, and the Reynolds and Prandtl numbers [3]. A collection of the experimental studies regarding the effect of turbulence intensity on heat transfer is available in the literature review carried by A. Kondjoyan et al. [4]. Almost in all of the experiments conducted by Kondjoyan et al either a constant wall temperature or isoflux plate, where wall was a heat source was considered.

In the previous studies, wall usually considered as a heat source used for warming up the adjacent flow. The presumption is heat transfer rate does not vary with the direction of the temperature gradient. Additionally, heating up a plate is more economical than increasing the free stream temperature. These explain why opposite case of heat transfer to the plate has attracted a little attention.

It is also recognized in heat transfer texts that the wall thermal boundary condition alters the heat transfer from a plate [5]. Isoflux plates have higher values of heat transfer coefficient in comparison with an isotherm wall. Herein, the dependency of enhancement rate on parameters such as velocity and temperature fluctuations is addressed. The direction of temperature gradient is also taken into account as a factor of interest. The analysis presented here is based on the significance of flow parameters in heat transfer.

2. Analytical investigation

No-slip boundary condition implies that a layer of fluid flow rests at the wall. The conduction heat transfer is assumed to be the main heat transfer mode within a distance very close to the plate, Fig. 1. It is easily can be shown that the total heat transfer rate for this area equals the conduction at the wall. The one-dimensional conduction and convection energy equations are written respectively as equations (1) and (2).

$$-\dot{q} = \frac{\partial}{\partial y}\left(k\frac{\partial \overline{T}}{\partial y}\right) \qquad (1)$$

From the other side the convection heat transfer can be expressed as,

$$\rho C_P\left(\overline{u}\frac{\partial \overline{T}}{\partial x} + \overline{v}\frac{\partial \overline{T}}{\partial y}\right) = \frac{\partial}{\partial y}\left(k\frac{\partial \overline{T}}{\partial y} - \rho C_P \overline{v'T'}\right) \qquad (2)$$

Comparing equations (1) and (2) shows that the first term on the right hand side of the equation (2) is identical to what describes by the conduction equation. Turbulent heat flux represents by $\overline{v'T'}$, putting it on the other side of the equation (2), inclines that the heat source intensity is a function of the convective and fluctuation terms.

Taking the integral of equation (2) over the thermal boundary layer reads

$$\int_0^{\delta_t} \rho C_P\left(\overline{u}\frac{\partial \overline{T}}{\partial x} + \overline{v}\frac{\partial \overline{T}}{\partial y}\right)dy = -\left(k\frac{\partial \overline{T}}{\partial y}\right)_w - \int_0^{\delta_t}\rho C_P\frac{\partial \overline{v'T'}}{\partial y}dy \qquad (3)$$

Due to the high resistance of turbulence to wall damping, the fluctuations are significant even at close distance from the wall. The Integral on the right side of the equation (3) is broken into two parts to avoid the region near the wall, where fluctuations suddenly drop to zero.

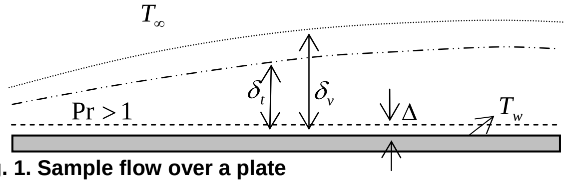

Fig. 1. Sample flow over a plate

$$\int_0^{\delta_t}\rho C_P\frac{\partial \overline{v'T'}}{\partial y}dy = \int_0^{\Delta}\rho C_P\frac{\partial \overline{v'T'}}{\partial y}dy + \int_{\Delta}^{\delta_t}\rho C\frac{\partial \overline{v'T'}}{\partial y}dy$$

and the following criterion held to be true:

$$\begin{cases} y < \Delta, & \overline{v'T'} = 0 \\ y > \Delta, & \overline{v'T'} = -\varepsilon_H\dfrac{\partial \overline{T}}{\partial y} \end{cases} \qquad (4)$$

here ε_H is the thermal eddy diffusivity and Δ is a distance from a wall that the magnitude of the fluctuations becomes noticeable $0 < \Delta < \delta_t$. In this case thermal eddy diffusivity is a positive entity.

Equation (3) can be interpreted as the relation which pictures the contribution of each flow parameters in the heat transfer. From this equation, it implies that increasing the heat transfer is analogous to increasing the magnitude of the terms lie on the left hand side of the equation. The influence of each parameter can be better shown by rearranging the equation (3) in a vector form. The non-dimensionalized energy equation is used to describe the relation of the variables independent of their absolute values, as demonstrated by equation (5). The thermo-physical properties are assumed to be constant in the thermal boundary layer.

$$\mathrm{Re}_{\delta_t}\,\mathrm{Pr}\left\{\int_0^1\left(\hat{\overline{U}}\cdot\nabla\hat{\overline{T}}\right)d\hat{y} - \overline{\hat{v}'\hat{T}'}\Big|_{\hat{y}=\Delta^*}\right\} = Nu_{\delta_t} \qquad (5)$$

where

$$\hat{\overline{U}} = \frac{\overline{U}}{U_\infty},\quad \nabla\hat{\overline{T}} = \frac{\nabla\overline{T}}{\left(T_{\infty/w} - T_{w/\infty}\right)/\delta_t},\quad \hat{y} = \frac{y}{\delta_t}$$

The first integral component of equation (5) and its role in heat transfer is well discussed by Z. Y. Guo et al. [4]. In this work the effects of the turbulent heat flux on the total heat transfer rate between a wall and a free stream flow are mainly discussed.

According to equation (5) heat transfer represented by the Nusselt number, increases or decreases depending on the sign of the fluctuations product component. The $\overline{v'T'}$ can be replaced by what is defined in equation (4), at distance sufficiently close to the wall. Equation (4) indicates that the sign of the time-average products of fluctuations is always opposite of the sign of the average temperature gradient. On the other hand, the sign of the average temperature gradient is a function of the thermal boundary conditions imposed on the wall. It means that $\partial\overline{T}/\partial y$ is negative when a plate is getting cold and it is positive when it is getting warm. So, despite the average product of velocity component $\overline{u'v'}$, which is always negative in sign, the sign of $\overline{v'T'}$ varies according to the temperature gradient.

The momentum and energy equations are quite similar in terms, but the velocity gradients are replaced by the temperature gradients in the energy equation. Additionally, temperature fluctuation is substituted for the streamwise velocity fluctuation component by comparing the right hand side of equation (2) and the momentum equation, equation (6) for a two-dimensional time-averaged flow.

$$\bar{u}\frac{\partial \bar{u}}{\partial x}+\bar{v}\frac{\partial \bar{u}}{\partial y}=\frac{1}{\rho}\frac{\partial}{\partial y}\left(\mu\frac{\partial \bar{u}}{\partial y}-\overline{u'v'}\right) \quad (6)$$

Therefore, any differences between the momentum and heat transfer, reflects the different behavior of the components involved in the momentum and energy equations. Dependency of $\overline{v'T'}$ to the direction of the temperature gradient may explain the dissimilarity observed in the literature [6-9] between the momentum and heat transfer

3. Discussion and results

3.1 Free stream fluctuations and Temperature gradient direction

When free stream temperature exceeds the wall temperature $T_\infty > T_w$, average temperature gradient will be positive. Consequently $\overline{\hat{v}'\hat{T}'}$ is negative in sign according to equation (4). This is a case that heat transfer increases as fluctuations increase.

For the case that plate is at a temperature higher than the free stream temperature, the average temperature gradient is negative. Therefore, the component $\overline{\hat{v}'\hat{T}'}$ is positive on the left hand side of the equation (6). In other words, when average temperature gradient is negative, the fluctuations depreciate the total heat transfer rate. A worth noting point is the effect of the FSTI on the mean velocity profile. By increasing the fluctuations the wake parameters decreases and, from equation (7) and for given value of $\left(u_\tau \delta_v/\upsilon\right)$, the ratio of shear velocity over marginal boundary layer velocity, increases.

$$\frac{U_{y=\delta_v}}{u_\tau}=\frac{1}{B}\ln\frac{u_\tau \delta_v}{\upsilon}+C+\frac{2\Pi}{B} \quad (7)$$

Consequently, at higher turbulence intensities a flatter velocity distribution within the thermal boundary layer magnifies the part of the convection term in heat transfer, independent of the temperature gradient direction. Additionally, this explains that increasing the level of fluctuations; does not necessarily diminish the heat transfer rate between the plate and free stream. In other words, fluctuations explicitly appear as $\overline{\hat{v}'\hat{T}'}$ in the energy equation as well as having an implicit effect on the mean velocity profile and accordingly the convective terms.

The previous experimental studies [10-15] conducted on a heated flat plate at zero pressure gradients; confirm the effective role of turbulence intensity in either turbulent or laminar heat transfer enhancement. Taking the experimental achievement together with the aforementioned analysis, reveals the prominent part of the convective terms either in laminar or turbulent heat transfer, which is elaborated parametrically in the present work.

3.2 Free stream fluctuations and Fluid type

For fluid flows with $\Pr < 1$, the thermal boundary layer is thicker than the velocity boundary layer $\left(\delta_v < \delta_t\right)$. Hence the fluctuations component in equation (6) will be more under the influence of free stream fluctuations. On the other hand, when $\Pr > 1$, the velocity profile developed faster than the temperature profile, Fig. 1. So, the $\overline{v'T'}$ will be evaluated at a point within the velocity boundary layer and closer to the wall. In this case, the thermal boundary layer is covered by velocity boundary layer and free stream fluctuations will be mitigated through their penetration inside the boundary layer. As a result, it might be concluded that the effect of FSTI is more evident on the heat transfer within a low Prandtl number fluid flows than a fluids with $\Pr >> 1$.

In fluid flows with higher values of thermal conductivity, temperature fluctuations are smaller than their identical values in low conductivity fluid flows. The mixing associated with turbulence leads to a more uniform thermal field, and smaller values of temperature fluctuations. So, for two turbulent and laminar boundary layers of identical fluids and with the same levels of free stream fluctuations, it is expected that laminar heat transfer will be influenced more significantly by FSTI than turbulent heat transfer as it is shown schematically in Fig. 2. However, as it is explained in the next section the product of fluctuations $\overline{\hat{v}'\hat{T}'}$ is not a main term in laminar heat transfer, although it varies more by FSTI.

3.3 Free stream fluctuations and Fluid type

Turbulence intensity decreases exponentially over the longitudinal distance from the leading edge. However, in the following discussion It has been assumed that the fluctuations do not mitigate and FSTI remains approximately constant.

The included angle between streamlines and temperature gradient decreases towards downstream of the flow. This angle achieves its maximum value at the beginning of laminar boundary layer, where flow starts, and becomes smaller as streamlines incline to the wall in downstream regions. As a result, the part of the integral term on the left hand side of equation (6) should be more significant in laminar heat transfer, comparing to the turbulent heat transfer of the same flow. Thus, increasing the FSTI affects turbulent heat transfer more than laminar heat transfer. So, it is possible to conclude that the influence of both convective and fluctuations terms on the turbulent heat transfer, are of the same order, Fig 2.

Laminar heat transfer augmentation by a maximum of 10-15% was reported for FSTI varied from 6% to 7% [2]. However, up to 30% enhancement has been achieved in turbulent boundary layer when FSTI variations in the range of 8-10% [2]. The greater influence of FSTI on turbulent heat transfer can be explained by considering the following relations:

$$O(Nu)\approx O\left(\int_0^1\left(\hat{\bar{U}}\cdot\nabla\hat{\bar{T}}\right)d\hat{y}\right)+O\left(v'T'\right)$$

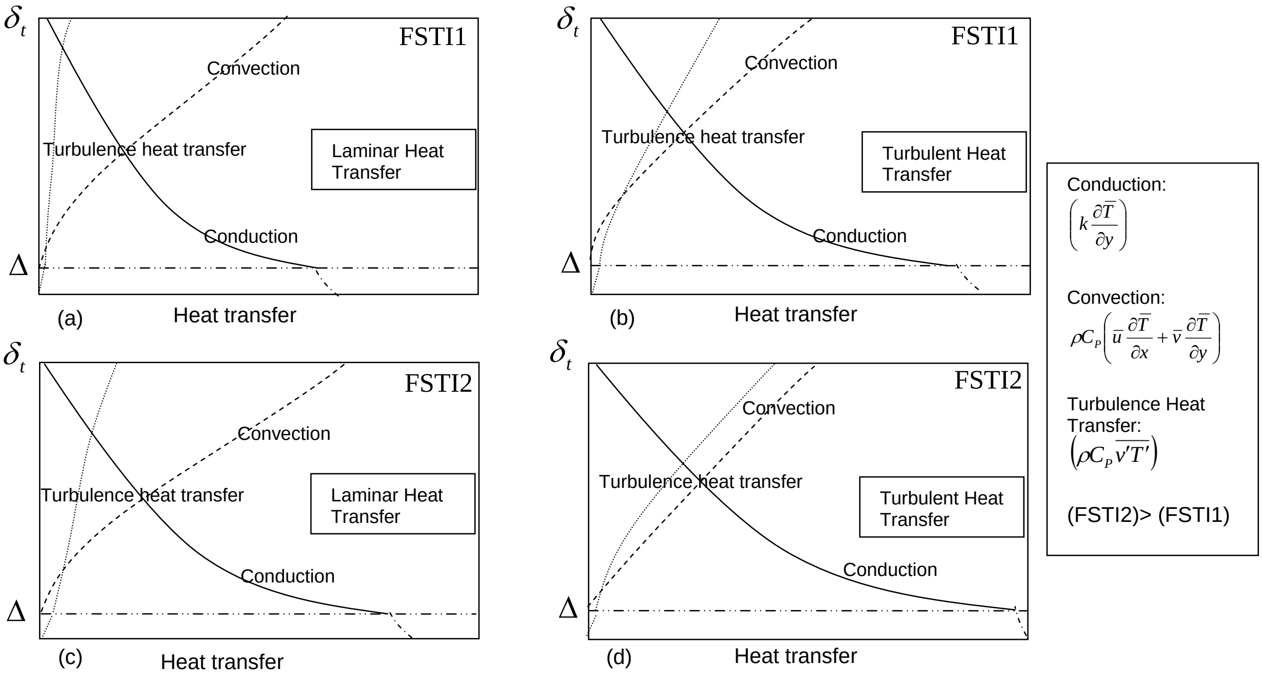

Fig. 2. Schematic shows the effect of FSTI on heat transfer in different flow regimes

and,

$$\begin{cases} O\left(\int_0^1 \left(\hat{\overline{U}} \cdot \nabla \hat{\overline{T}}\right) d\hat{y}\right)_{lam} >> O(v'T')_{lam} \\ O\left(\int_0^1 \left(\hat{\overline{U}} \cdot \nabla \hat{\overline{T}}\right) d\hat{y}\right)_{tur} >\approx O(v'T')_{tur} \end{cases}$$

The experimental results suggest that free stream fluctuations affect the turbulent heat transfer more than the laminar heat transfer. This is in agreement with the above mentioned scale-analysis between the influence of convection and turbulence on heat transfer, in different flow regimes.

4. Conclusion

A sensitivity analysis was performed to predict the effect of free stream fluctuations on heat transfer. The analogy between conduction and convection heat transfer was applied to show that conduction at the wall is the same as the summation of the convection and turbulence heat transfer at the edge of the thermal boundary layer.

The simplified time-average two-dimensional energy equation was integrated over the thermal boundary layer, and the conduction at the wall was put equal to the part of the conductive and turbulent terms in heat transfer. Moreover, it was discussed that how FSTI affect the heat transfer rate according to the parameters such as laminar and turbulent flow regimes, fluid type, and the direction of temperature gradient.

Some part of the discussion made in this work has already been experimentally proven through the literature. However, the importance of this work can be explained through the explaining the experimental results by simplified theoretical discussions, which need to be confirmed in future works.

The remarks of this study can be stated as followings:

- Temperature and velocity fluctuations enhance the heat transfer rate when plate is warming up by a free stream flow
- As far as $\overline{\hat{v}'\hat{T}'}\big|_{\hat{y}=\Delta}$ concerns, fluctuations depreciate heat transfer rate. However, implicitly they amplify the magnitude of the convective terms, which plays a prominent role in laminar and turbulent heat transfer
- The part of $\overline{\hat{v}'\hat{T}'}\big|_{\hat{y}=\Delta}$ is less significant in high conductive fluid flows with circulation zones
- The convective term dominate the turbulent heat transfer component in a laminar flow. They are approximately of the same order of magnitude in a turbulent regime although the convective terms are still dominating.

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