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Turbulent mixed convection flow over a backward-facing step

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Abstract

Measurements of turbulent mixed convection flow over a two-dimensional, vertical backward-facing step are reported. Laser-Doppler velocimeter (LDV) and cold wire anemometer were used, respectively, to measure simultaneously the time-mean velocity and temperature distributions and their turbulent fluctuations. The experiment was carried out for a range of free stream air velocities 0 m/s $\leqslant u_\infty \leqslant$ 0.41 m/s for a step height of 22 mm, and a temperature difference, ΔT, of 30°C between the heated walls and the free stream air. The step geometry consists of an adiabatic backward-facing step, an upstream wall and a downstream wall. Both the upstream and downstream walls are heated to a uniform and constant temperature. The present results reveal that the introduction of a small free stream velocity causes a decrease in the turbulence intensity of both the streamwise and transverse velocity and temperature fluctuations. Also, it was found that the reattachment length increases while the heat transfer rate from the downstream heated wall decreases as the free stream velocity increases.

1. Introduction

The existence of flow separation and subsequent reattachment due to a sudden expansion in flow geometry, such as a backward-facing step, plays an important role in a wide variety of engineering applications where heating or cooling is required. These heat transfer applications appear in cooling systems for electronic equipment, combustion chambers, environmental control systems, high performance heat exchangers, chemical processes and energy systems equipment, and cooling passages in turbine blades. A great deal of mixing of high and low energy fluid occurs in the reattached flow region in these devices, thus affecting their heat transfer performance. The problem of laminar flow over a backward-facing step geometry in natural, forced, and mixed convection has been investigated rather extensively in the past, both numerically and experimentally (see, for example, [1–4] and the references cited therein). On the other hand, studies of turbulent flow over a backward-facing step have dealt mainly with forced and natural convection cases (see, for example, [5–12] and the references cited therein). To the best knowledge of the authors, measurements of the flow and heat transfer characteristics of turbulent mixed convection flow over a vertical backward-facing step have not been reported in the open literature. A lack of detailed measurements of the mean and fluctuating flow and thermal fields in turbulent mixed convection flow for such a step geometry has motivated the present study. Such detailed results are needed for optimizing the performance of heat transfer devices, and for developing or validating models for simulating their behaviors.

The present study extends the authors' earlier work [11,12] and treats buoyancy-dominated mixed convection over a vertical backward-facing step to examine the effect of small free stream velocities on turbulent natural convection. The step geometry consists of an adiabatic step and upstream and downstream walls that are heated to a constant and uniform temperature. Results of interests such as time-mean velocity and temperature, intensities of velocity and temperature fluctuations, reattachment lengths and local Nusselt number

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Nomenclature

g	gravitational acceleration
h	local heat transfer coefficient $(-k(\partial T/\partial y)_{y=0}/(T_w - T_\infty))$
k	thermal conductivity
Nu_{x^*}	local Nusselt number (hx^*/k)
s	step height
T	fluid temperature
T_∞	free stream temperature
T_w	wall temperature
$\overline{t'^2}$	intensity of temperature fluctuations
u	mean streamwise velocity
u_∞	free stream velocity
u^*	reference velocity $([g\beta(T_w - T_\infty)x_i]^{1/2})$
$\overline{u'^2}$	intensity of streamwise velocity fluctuations
U	dimensionless mean streamwise velocity (u/u^*)
v	mean transverse velocity
$\overline{v'^2}$	intensity of transverse velocity fluctuations
V	dimensionless mean transverse velocity (v/u^*)
x, y	streamwise and transverse coordinates measured from the downstream plate
x^*	$x + x_i$
x_i	inlet length upstream of the step
x_r	reattachment length
X_r^*	$(x - x_r)/x_r$
y^*	$y - s$

Greek symbols

β	coefficient of thermal expansion
ΔT	temperature difference $(T_w - T_\infty)$
θ	dimensionless temperature $((T - T_\infty)/(T_w - T_\infty))$

distributions are reported to illustrate the effect of small free stream velocities on turbulent natural convection downstream of a backward-facing step.

2. Experimental apparatus and procedure

The experimental investigation was performed in an existing low turbulence, open circuit air tunnel that was oriented vertically, with air flowing in the upward direction. Details of the air tunnel has been described by Abu-Mulaweh et al. [11,12] and a schematic is shown in Fig. 1. It has a smooth converging nozzle, a straight square test section, and a smooth diverging diffuser. Plastic honeycomb and stainless steel screens are placed at the inlet of the air tunnel to straighten the flow and to minimize the free stream turbulence in the test section. A variable-speed suction fan is attached to the end of the diffuser section. The tunnel is constructed from a 1.27 cm thick plexiglass plate and a 1.91 cm plywood with adequate steel frames and supports to provide a rigid structure. The test section, which is constructed from transparent plexiglass material, allows for flow visualizations and permits the use of a Laser-Doppler velocimeter (LDV) for velocity measurements. The step geometry is supported in the test section of the tunnel and spans its entire width (85.1 cm). A cross section of 63.5×85.1 cm is provided adjacent to the test surface in

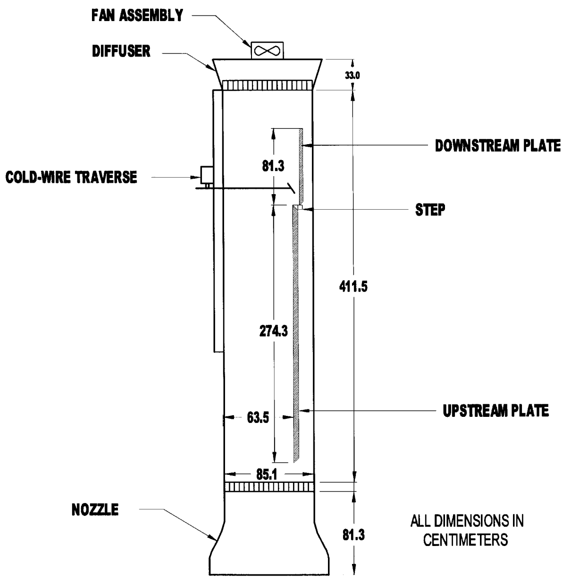

Fig. 1. Schematic diagram of the air tunnel.

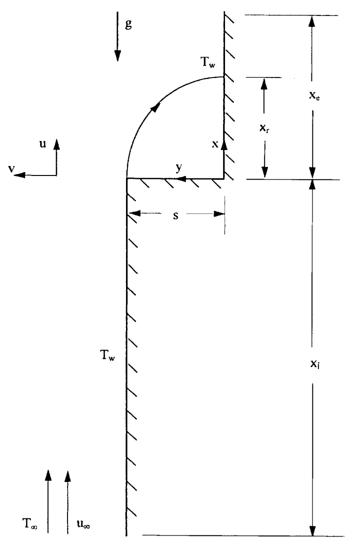

Fig. 2. Schematics diagram of the step geometry.

the test section for the developing boundary layer air flow.

Fig. 2 shows a schematic diagram of the step geometry which consists of an adiabatic backward-facing step (22 mm in height), an upstream wall (274.3 cm in length), and a downstream wall (81.3 cm in length). Both the upstream and the downstream walls can be heated to a constant and uniform temperature. The heated walls are made of three composite layers that are held together by screws. The upper layer is an aluminum plate (85.1 cm wide, and 1.27 cm thick) instrumented with several thermocouples that are distributed in the axial direction along its entire length. Each thermocouple is inserted into a small hole from the backside of the plate and its measuring junction is flush with the test surface. The middle layer consists of several heating pads that can be controlled individually for electrical energy input. By controlling the level of electrical energy input to each of the heating pads, and monitoring the local temperature of the heated walls with the imbedded thermocouples, the temperature of the heated surface can be maintained constant and uniform to within 0.2°C. The bottom layer of the heated walls is a 1.91 cm thick plywood board serving as backing and support for the heated wall structure. The backward-facing step is made of Plexiglass to simulate an adiabatic surface. The front edge of the upstream plate is chamfered to insure a proper development of the boundary layer flow. The edges of the upstream and downstream walls which are in contact with the step, are also chamfered to minimize the contact area, and hence the conduction heat transfer, between the heated walls and the adiabatic step, as shown in Fig. 1.

Air velocity and temperature were measured simultaneously by using a two-component LDV and a cold-wire anemometer, respectively. The LDV system is equipped with an automated three-dimensional traverse system for positioning the measuring LDV probe volume at any desired point in the flow domain. The cold wire probe with a separate traverse system is placed within 2 mm behind the measuring LDV volume. The outputs from both the LDV and the cold wire anemometer are then processed through an A/D converter and a suitable software on an IBM personal computer to determine the local instantaneous velocity and temperature. These measurements were then used to determine the time-mean velocity and temperature, intensities of velocity and temperature fluctuations, and local Nusselt number distributions.

It was established, through repeated LDV measurements, that 1024 acceptable LDV samples of the local instantaneous fluctuating velocity component were sufficient to repeatedly and accurately determine the local mean velocity and temperature in the flow domain. The acceptable sampling rate for these measurements varied between 10 and 100 sample/s. All of the reported data in this study resulted from taking the average of two separate measurements taken back to back, each of which having a sample of 1024 instantaneous measurements.

The repeatability of the mean velocity measurements was determined to be within 4%, and that of the temperature measurements was within 0.25°C (0.5%). The uncertainties in the measured results were estimated (at the 95% confidence level) according to the procedure outlined by Moffat [13] and they are reported in the appropriate section of this paper.

Flow visualizations were also performed to verify the boundary-layer development and its two-dimensional nature. These flow visualizations were carried out by using a 15 W collimated white light beam, 2.5 cm in diameter. Glycerin smoke particles, 2–5 μm in diameter, which are generated by immersing a 100 W heating element into a glycerin container, are added to the inlet air flow and used as scattering particles for flow visualization and for LDV measurements.

3. Results and discussion

The boundary layer development in the experimental set up, along with its two-dimensional nature, was verified through flow visualization and through measurements of velocity across the width of the tunnel, at various heights above the heated wall. These measurements showed a wide region (about 80% of the width of the heated wall around its center) where the air flow velocity is almost constant (to within 5%) at a fixed distance from the heated surface, thus justifying the two-dimensional flow approximation. In addition, velocity measurements in the free stream were performed (up to 200 mm from the edge of the boundary layer) and showed that the free stream velocity is uniform and constant (to within 2%). The operation of the air tunnel, its instrumentation, and the accuracy and the repeatability of the measurements were validated by performing measurements of turbulent natural convection boundary-layer flow adjacent to a vertical heated flat plate at a uniform temperature in the air tunnel for different levels of heating conditions. Both the measured flow and thermal fields compared well with other previously measured and predicted results, as was reported by Abu-Mulaweh et al. [11]. All reported measurements were taken along the midplane ($z = 0$) of the plate's width, and only after the system had reached steady-state conditions.

To examine the effect of small free stream velocities on turbulent natural convection over a backward-facing step, measurements of the flow and thermal fields were carried out at one streamwise location upstream of the step ($x = -5$ cm) and four different streamwise locations downstream of the step ($x = 3.5, 6, 10,$ and 25 cm), for a step height of 22 mm, a temperature difference of 30°C between the heated walls and the free stream air, and three different free stream velocities: $u_\infty = 0$ m/s (i.e., natural convection) and $u_\infty = 0.23$ and 0.41 m/s (i.e., mixed convection).

The distributions of the dimensionless time-mean streamwise and transverse velocity and temperature distributions upstream of the step ($x = -5$ cm) are shown in Figs. 3(a)–(c), respectively. These figures illustrate the effect of free stream velocity on the turbulent natural convection adjacent to the upstream wall of the step (i.e., vertical flat plate). Figs. 3 (a) and (c) clearly show that both the momentum and thermal boundary layer thicknesses are smaller for the turbulent mixed convection flow ($u_\infty = 0.23$ and 0.41 m/s) than that of turbulent natural convection flow ($u_\infty = 0$ m/s). The maximum streamwise velocity is higher for the turbulent mixed convection and it increases as the free stream velocity increases. The effect of free stream velocity on the temperature distribution is to decrease the heat transfer rate from the heated wall with increasing free stream velocity. This is because the introduction of free stream velocity on the turbulent natural convection flow reduces the level of turbulence intensity inside the boundary layer. This results in a suppressed turbulent mixed convection regime. These trends are similar to those reported by Hattori et al. [14] and Abu-Mulaweh et al. [15]. The uncertainties in these measurements are ± 0.1 mm in y^*, $\pm 4\%$ in U and V, and $\pm 2\%$ in θ.

The distributions of the dimensionless turbulent intensities of streamwise and transverse velocity and temperature fluctuations upstream of the step ($x = -5$ cm) are shown in Figs. 4(a)–(c), respectively. The magnitudes of the intensities of the streamwise and transverse velocity fluctuations are much larger for natural convection than for mixed convection. Also, it can be seen from these figures that the magnitude of the in-

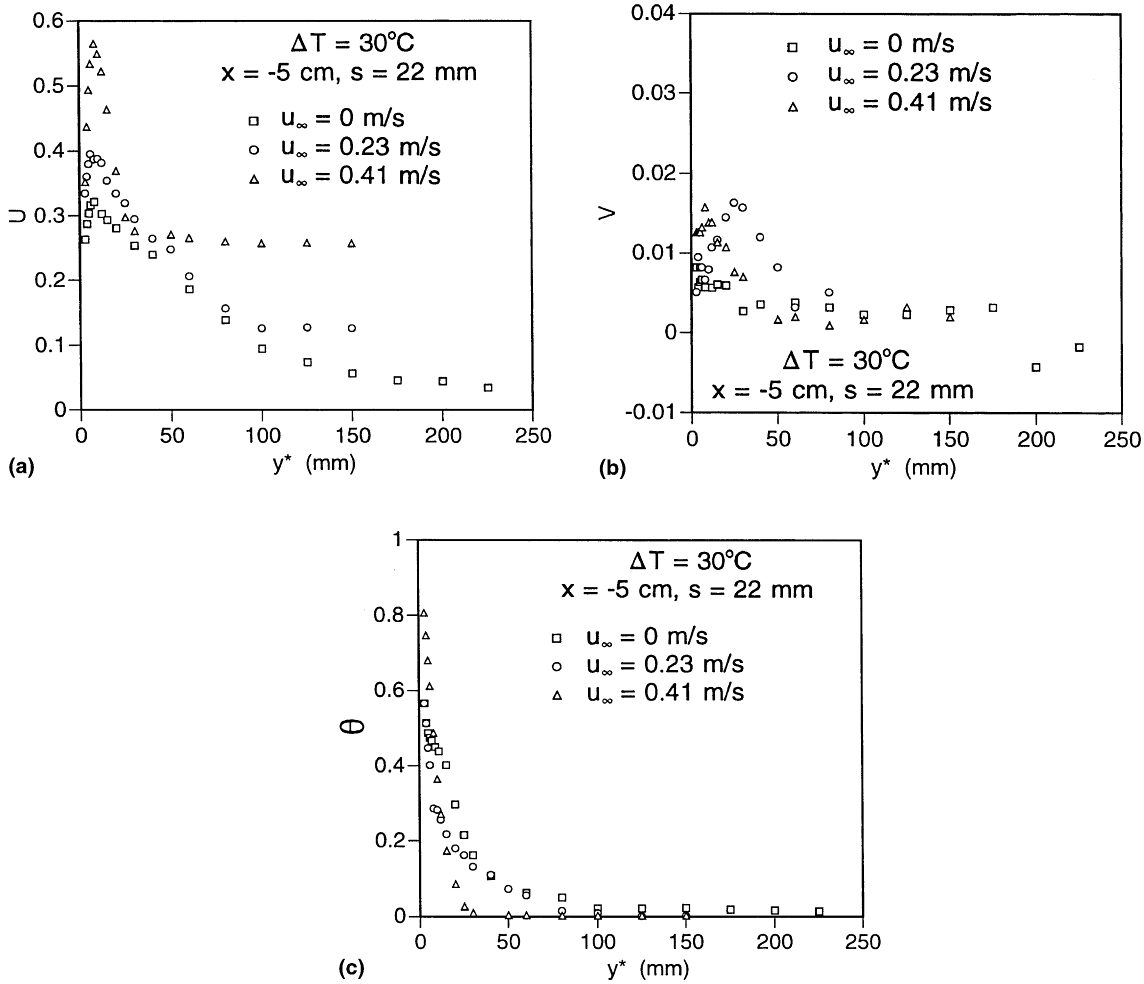

Fig. 3. (a) Dimensionless mean streamwise velocity distributions upstream of the step. (b) Dimensionless mean transverse velocity distributions upstream of the step. (c) Dimensionless mean temperature distributions upstream of the step.

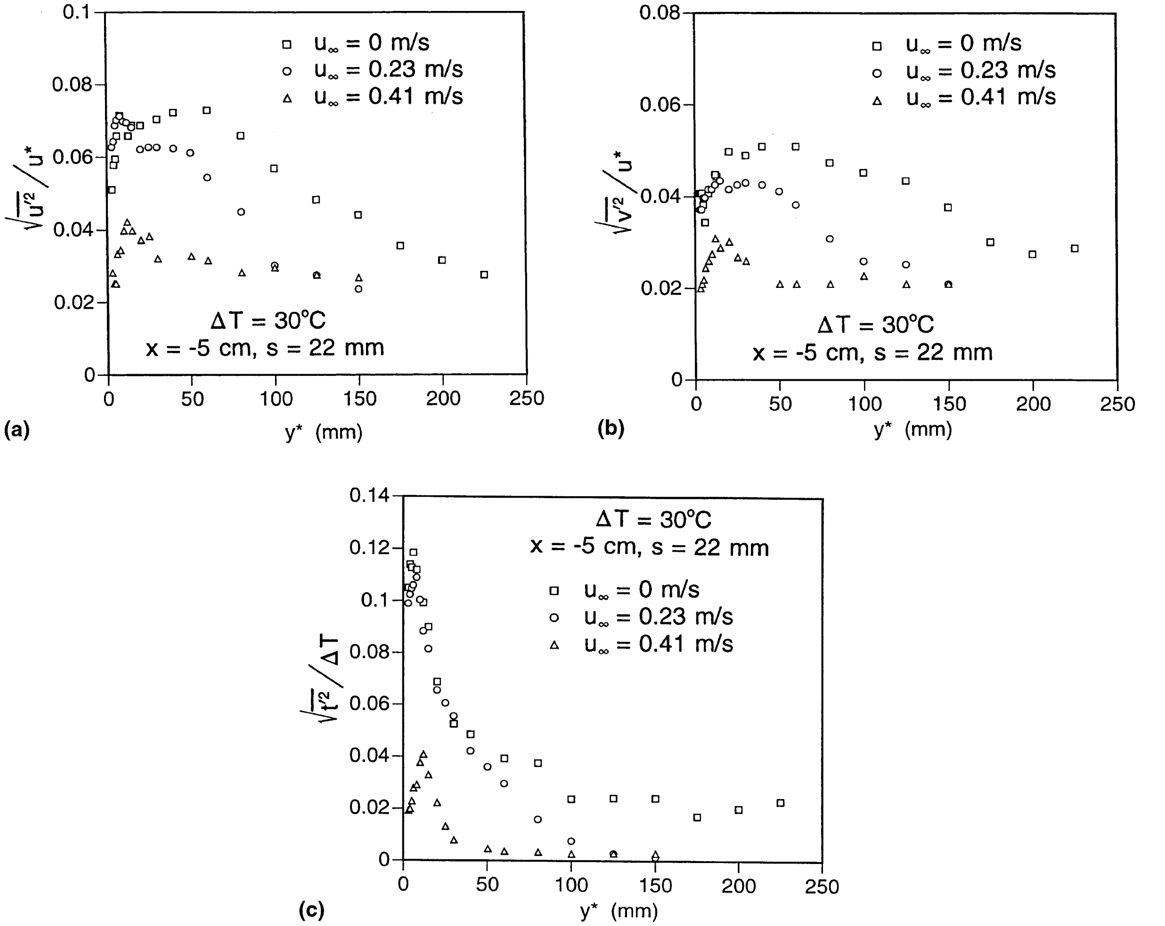

Fig. 4. (a) Distributions of dimensionless streamwise velocity fluctuation upstream of the step. (b) Distributions of dimensionless transverse velocity fluctuation upstream of the step. (c) Distributions of dimensionless temperature fluctuation upstream of the step.

tensities of turbulent fluctuations decreases rapidly for mixed convection flow, giving a smaller maximum value as the free stream velocity increases. This causes the flow to relaminarize. These trends are similar to those reported by Abu-Mulaweh et al. [15]. The uncertainty in $\sqrt{\overline{u'^2}}/u^*$ and $\sqrt{\overline{v'^2}}/u^*$ is ±6% and in $\sqrt{\overline{t'^2}}\Delta T$ is ±5%.

The dimensionless time-mean streamwise and transverse velocity and temperature distributions downstream of the step ($x = 3.5, 6, 10,$ and 25 cm) are presented in Figs. 5–7, respectively. These figures illustrate the effect of free stream velocity on the turbulent natural convection downstream of a backward-facing step. Similar to the case upstream of the step, the momentum boundary layer thickness downstream from the step, as shown in Fig. 5, is smaller for the turbulent mixed convection flow ($u_\infty = 0.23$ and 0.41 m/s) than that of turbulent natural convection flow ($u_\infty = 0$ m/s), and the maximum velocity is higher for the turbulent mixed convection and it increases as the free stream velocity increases. The figure shows that at the streamwise location $x = 3.5$ cm the velocity profiles of the three different cases have negative mean streamwise velocity component near the wall, indicating that these profiles are inside the recirculation region downstream of the step. It can be seen that turbulent mixed convection velocity profile ($u_\infty = 0.41$ m/s) at the streamwise location $x = 6$ cm exhibits a negative mean streamwise velocity component; that is, the profile is inside the recirculation region. This indicates that the free stream velocity significantly affects the flow characteristics in the recirculation region downstream of the step. The introduction of the free stream velocity tends to increase the size of the recirculation region and hence the reattachment length. It was observed that for the experimental conditions of turbulent natural convection ($u_\infty = 0$ m/s), the recirculation region was not steady and the reattachment point oscillated between 5.5 and 6.5 cm downstream of the step. Measurements reported

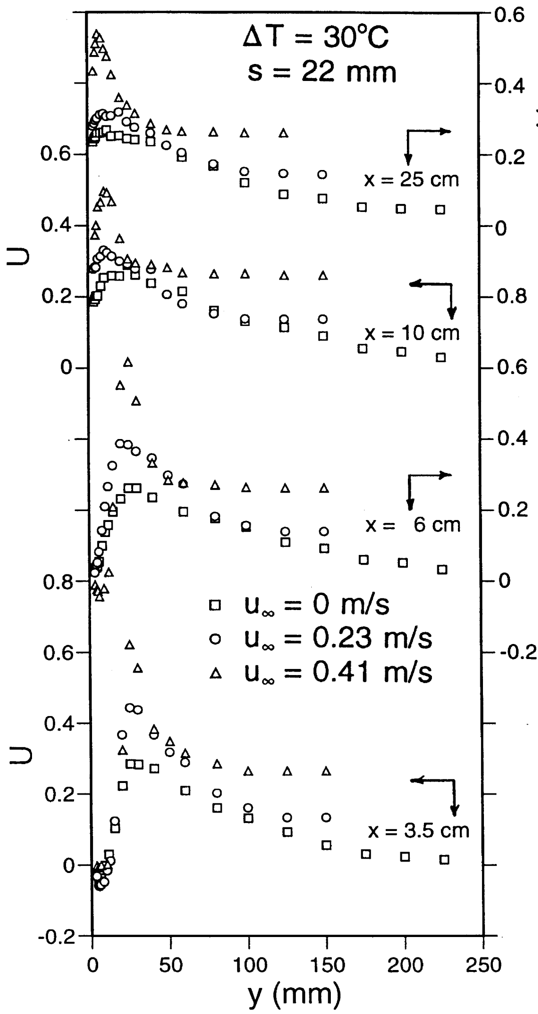

Fig. 5. Dimensionless mean streamwise velocity distributions downstream of the step.

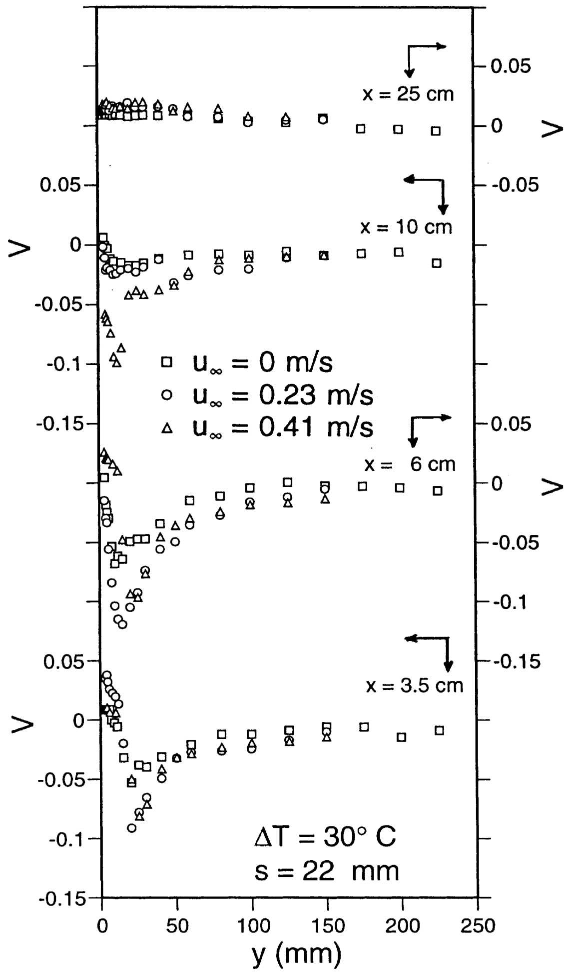

Fig. 6. Dimensionless mean transverse velocity distributions downstream of the step.

in that region represent the average value that results from these oscillations. On the other hand, in the case of turbulent mixed convection the recirculation region was almost steady. It was determined that for the conditions shown in Fig. 5, the reattachment lengths are $x_r = 8$ cm and 9.5 cm for the turbulent mixed convection cases of $u_\infty = 0.23$ and 0.41 m/s, respectively. It should be noted that the velocity profile for the turbulent mixed convection with a free stream velocity of 0.23 m/s at the streamwise location $x = 6$ cm is inside the recirculation region ($x_r = 8$ cm). The reason for the velocity profile not to exhibit negative velocity component is that the thickness of the recirculation region is very thin at this streamwise location, where the first measured experimental data point is at 3 mm from the heated wall.

Fig. 6 shows that, for all cases, the mean transverse velocity in the flow region that is very close to the heated surface is always positive. Also, it can be seen that the distributions at $x = 3.5, 6$, and 10 cm exhibit negative mean transverse velocity component in the region near the heated surface and it is higher in the negative sense for the turbulent mixed convection than the turbulent natural convection. The reason for the negative mean transverse velocity component is because of the sudden expansion in the flow geometry which causes the streamlines to curve towards the downstream heated surface. On the other hand, the profiles at $x = 25$ cm do not exhibit any negative mean transverse velocity component near the heated surface; that is, the effect of the step has diminished and the flow beyond that region can be treated as boundary layer flow. The effect of free stream velocity on the mean temperature distributions is illustrated in Fig. 7. The figure clearly shows that the surface temperature gradient at the heated downstream wall decreases (i.e., the heat transfer rate from the

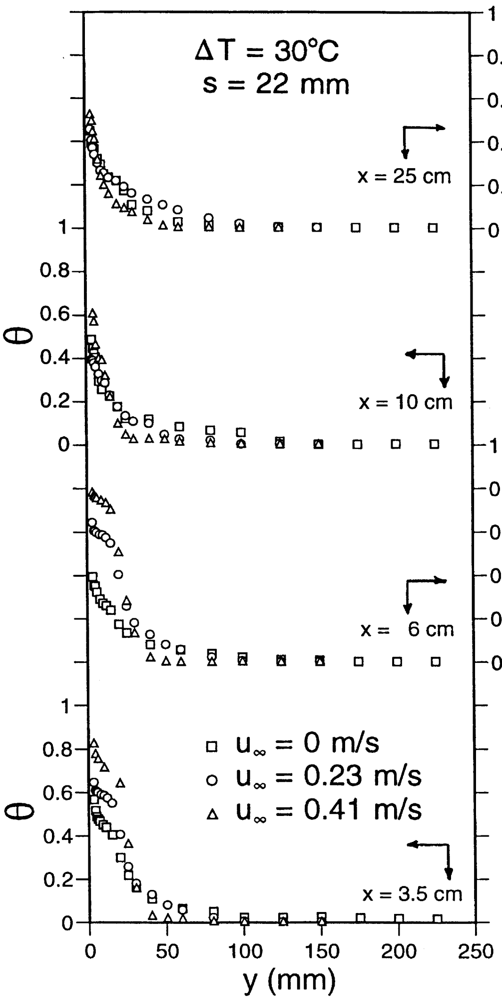

Fig. 7. Dimensionless mean temperature distributions downstream of the step.

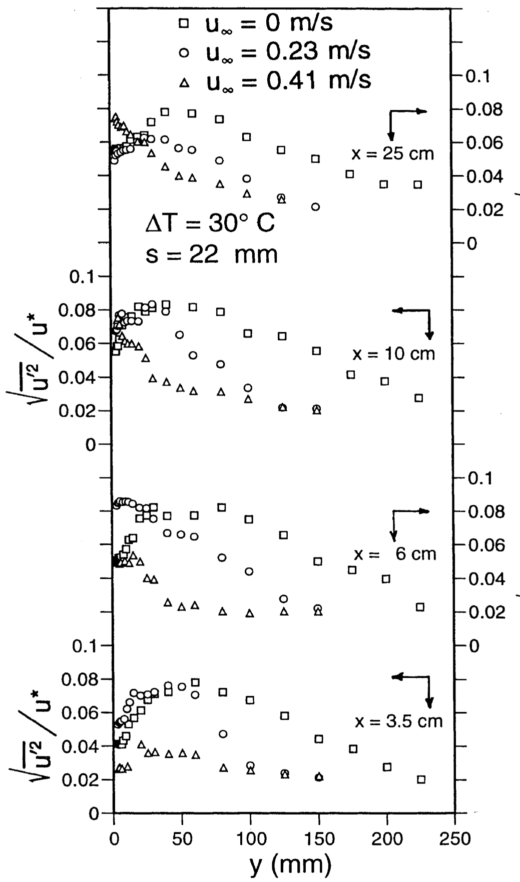

Fig. 8. Distributions of dimensionless streamwise velocity fluctuation downstream of the step.

heated downstream wall decreases) with increasing free stream velocity. This is due to the fact that introduction of free stream velocity on the turbulent natural convection flow over a backward-facing step tends to reduce the level of turbulence intensity inside the boundary layer.

The dimensionless turbulent intensities of streamwise and transverse velocity and temperature fluctuations downstream from the step are presented in Figs. 8–10, respectively. As can be seen from these figures, the values of the streamwise and transverse velocity and temperature fluctuations increase to a maximum as the distance from the heated wall increases, start to decrease as the distance from the heated wall continues to increase, and then reach a minimum value at the edge of the boundary layer, for both turbulent natural and mixed convection flows. The magnitudes of the intensities of both velocity and temperature fluctuations are smaller for mixed convection than for natural convection. This trend is similar to the flat plate results reported by Hattori et al. [14] and Abu-Mulaweh et al. [15] and to those distributions upstream of the step (Figs. 4(a)–(c)). But the reduction in the magnitudes of these fluctuations downstream of the step is not as large as that occurs in the flat plate case (or upstream of the step). This is because for the case of the backward-facing step there exists two opposite effects: the free stream velocity tends to suppress the turbulence, while the step, acting as a trigger, tends to enhance the turbulence.

The convective heat transfer coefficients for the heated downstream wall were determined from the measured temperature distributions (temperature gradients) in the laminar sublayer near the heated wall. For a given free stream velocity, the air temperature was measured at four different locations within 0.5 mm from the heated wall in order to establish the temperature gradient at the heated wall. The temperature distributions in the laminar sublayer near the heated wall were

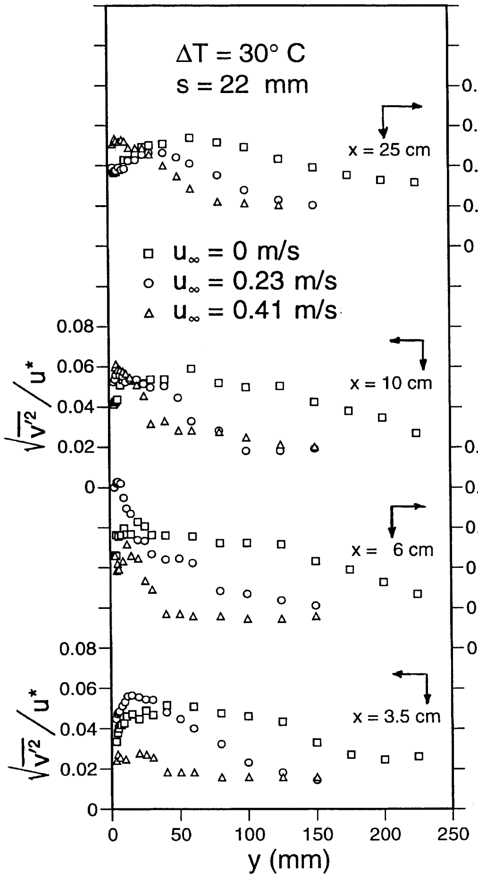

Fig. 9. Distributions of dimensionless transverse velocity fluctuation downstream of the step.

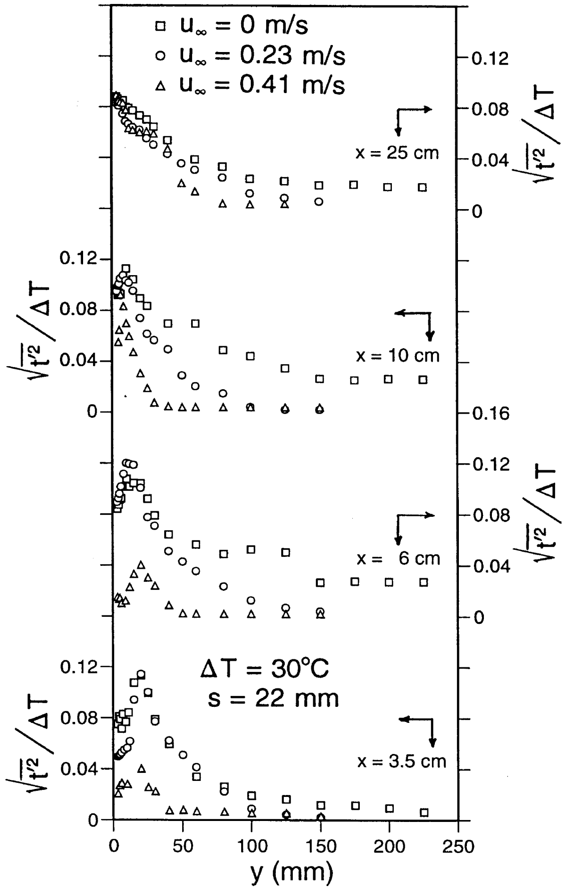

Fig. 10. Distributions of dimensionless temperature fluctuation downstream of the step.

linear and the temperature fluctuations in that region were very small (near zero). This technique for determining the surface temperature gradient and the convective heat transfer coefficient in turbulent flow was utilized and validated by Tsuji and Nagano [16,17], Qiu et al. [18], and Abu-Mulaweh et al. [11,12,15]. The effect of the free stream velocity on the local Nusselt number is illustrated in Fig. 11. As can be seen from the figure, the measured local Nusselt number downstream of the step (i.e., heat transfer rate from the heated downstream wall) decreases with increasing free stream velocity. This is because the introduction of a free stream velocity on turbulent natural convection flow suppresses turbulence (as shown in Figs. 8–10) and results in a decrease in the heat transfer rate. The the maximum heat transfer rate (i.e., the local Nusselt number) occurs in the vicinity of the reattachment region where the velocity and temperature fluctuations are maximum and a higher free stream velocity is associated with a larger reattachment length. The uncertainty in x is ± 1 mm and in the measured Nusselt number is $\pm 6\%$.

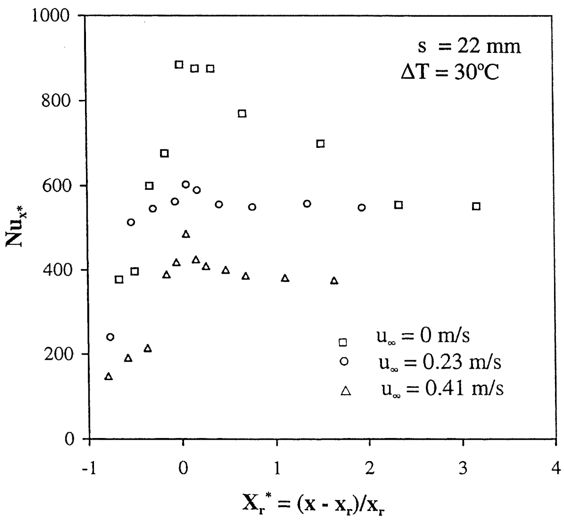

Fig. 11. Local Nusselt number variation downstream of the step.

4. Conclusion

Detailed measurements of the flow and thermal fields in turbulent natural and mixed convection flows adjacent to a vertical, two-dimensional backward-facing step are reported. The present results reveal that the existence of a small free stream velocity causes a decrease in the turbulence intensity of both streamwise and transverse velocity fluctuations and the intensity of temperature fluctuations. But this reduction is not as large as that occurs in the flat plate case. This is because for the case of a backward-facing step there exists two opposite effects: the free stream velocity tends to suppress the turbulence, while the backward-facing step, acting as a trigger, tends to enhance the turbulence. It was found that the reattachment length increases while the heat transfer rate from the downstream heated wall decreases as the free stream velocity increases. Also, it was noticed that as a result of the increase in the reattachment length, the location of the maximum heat transfer rate moves away from the step as the free stream velocity increases.

Acknowledgements

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