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Turbulent mixed convection flow over a forward-facing step—the effect of step heights

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Abstract

Measurements of heat transfer and fluid flow of turbulent mixed convection boundary-layer air flow over an isothermal two-dimensional, vertical forward-facing step are reported. The upstream and downstream walls and the step itself were heated to a uniform and constant temperature. Air velocity and temperature distributions and their turbulent fluctuations are measured simultaneously by using, respectively, a two-component laser-Doppler velocimeter (LDV) and a cold wire anemometer. The present study examines the effect of forward-facing step heights on turbulent mixed convection flow along a vertical flat plate. The experiment was carried out for step heights of 0, 11, and 22 mm, at a free stream air velocity, u_∞, of 0.55 m·s^{-1}, and a temperature difference, ΔT, of 30 °C between the heated walls and the free stream air (corresponding to a local Grashof number $Gr_{xi} = 6.45 \times 10^{10}$). It was found that the turbulence intensity of the streamwise and transverse velocity fluctuations and the intensity of temperature fluctuations downstream of the step increase as the step height increases. Also, it was found that both the reattachment length and the heat transfer rate from the downstream heated wall increase with increasing step height.

Keywords: Mixed convection; Turbulent; Forward-facing step

1. Introduction

Convective heat transfer in separated–reattached flow fields is an interesting and important phenomenon. The existence of flow separation and subsequent reattachment caused by a sudden compression in flow geometry, such as a forward-facing step, greatly influences the mechanism of heat transfer. It is well established that there is a large variation of the local heat transfer rate within separated flow regions and substantial heat transfer enhancement may result in the reattachment zone. Thus, in thermal engineering applications where cooling or heating is required, it is essential to understand the basic mechanism of heat transfer in such flows. These heat transfer applications appear in cooling systems for electronic equipment, combustion chambers, chemical processes and energy systems equipment, high performance heat exchangers, 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 heat transfer devices, thus affecting their heat transfer performance. Backward-facing and forward-facing steps are the most simple and fundamental geometries where flow separation and subsequent reattachment occur. Owing to this fact, a large number of studies have been conducted in relation to these two step geometries.

The problem of turbulent flow over backward-facing step geometry in natural, forced, and mixed convection has been examined rather extensively in the past (see, for example, Vogel and Eaton [1], Abe et al. [2], Rhee and Sung [3], Inagaki [4], and Abu-Mulaweh et al. [5–7] and the references therein). On the other hand, the problem of turbulent flow over a forward-facing step has received very little attention. Recently, the effect of free stream velocity on turbulent natural convection flow over a vertical forward-facing step was examined by Abu-Mulaweh et al. [8]. To the best knowledge of the author, the effects of forward-facing step heights on the flow and heat transfer characteristics of turbulent mixed convection along a vertical flat plate have not been published

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Nomenclature

Gr_{xi}	local Grashof number, $= g\beta(T_w - T_\infty)x_i^3/\nu^2$	
g	gravitational acceleration	m·s^{-2}
h	local heat transfer coefficient, $= -k(\partial T/\partial y)_{y=0}/(T_w - T_\infty)$	W·m^{-2}·°C^{-1}
k	thermal conductivity	W·m^{-1}·°C^{-1}
Nu_{x^*}	local Nusselt number, $= hx^*/k$	
s	step height	mm
T	fluid temperature	°C
T_∞	free stream temperature	°C
T_w	wall temperature	°C
$\overline{t'^2}$	intensity of temperature fluctuations	°C^2
u	mean streamwise velocity	m·s^{-1}
u_∞	free stream velocity	m·s^{-1}
u^*	reference velocity, $= [g\beta(T_w - T_\infty)x_i]^{1/2}$	m·s^{-1}
$\overline{u'^2}$	intensity of streamwise velocity fluctuations	m^2·s^{-2}
U	dimensionless mean streamwise velocity, $= u/u^*$	
v	mean transverse velocity	m·s^{-1}
$\overline{v'^2}$	intensity of transverse velocity fluctuations	m^2·s^{-2}
V	dimensionless mean transverse velocity, $= v/u^*$	
x, y	streamwise and transverse coordinates measured from the downstream plate	m
x^*	$= x + x_i$	m
x_i	inlet length upstream of the step	m
x_r	reattachment length	m

Greek symbols

β	coefficient of thermal expansion	K^{-1}
ΔT	temperature difference, $= (T_w - T_\infty)$	°C
θ	dimensionless temperature, $= (T - T_\infty)/(T_w - T_\infty)$	
ν	kinematic viscosity	m^2·s^{-1}

in the open literature. A lack of detailed measurements of time-mean and fluctuating flow and thermal fields in turbulent mixed convection flow for such step geometry has motivated the present study.

The present study extends the author's earlier work Abu-Mulaweh et al. [8] and examines the effect of forward-facing step height on turbulent mixed convection along a vertical flat plate. The upstream and downstream walls and the forward-facing step itself were heated to a uniform and constant temperature. Results of interests such as time-mean velocity and temperature, intensities of velocity and temperature fluctuations, reattachement lengths and local Nusselt number distributions are reported to illustrate the effect of forward-facing step heights on turbulent mixed convection along a vertical flat plate.

2. Experimental apparatus and procedure

The experimental investigation was performed in an existing low turbulence (less than 1%), open circuit air tunnel that was oriented vertically, with air flowing in the upward direction. Details of the air tunnel have been described by Abu-Mulaweh et al. [5] and a schematic of the tunnel 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 board with adequate steel frames and supports to provide a rigid structure. The test section, which is constructed from transparent plexiglass material, allows

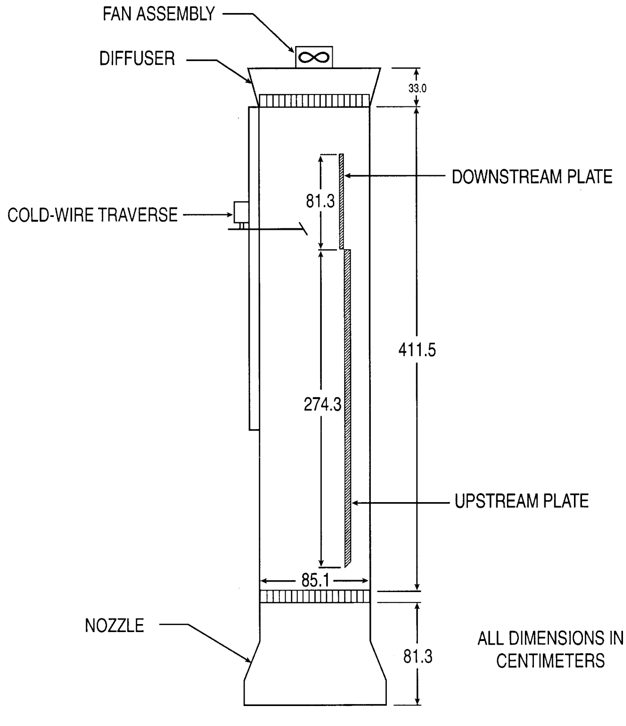

Fig. 1. Schematic of the air tunnel.

for flow visualizations and permits the use of a laser-Doppler velocimeter 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 the test section for the developing boundary layer air flow.

Fig. 2 shows a schematic diagram of the step geometry which consists of a forward-facing step (22 mm in height), an upstream wall (274.3 cm in length), and a downstream

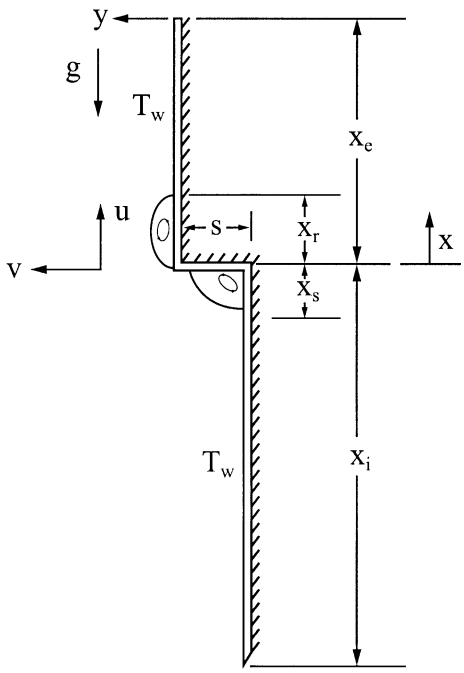

Fig. 2. Schematic of the step geometry.

wall (81.3 cm in length). Both the upstream and the downstream walls and the step itself were heated to a constant and uniform temperature. The heated walls were made of three composite layers that were held together by screws. The upper layer was an aluminum plate (85.1 cm wide and 1.27 cm thick) instrumented with several thermocouples that were 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 front edge of the upstream plate is chamfered to insure a proper development of the boundary layer flow.

Air velocity and temperature were measured simultaneously by using a two-component laser-Doppler velocimeter (LDV) and a cold wire anemometer, respectively. Details of the measuring systems and their level of accuracy are given by Ramachandran et al. [9] and Baek et al. [10]. 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 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·sec^{-1}. All of the reported data in this study resulted from taking the average of two separate measurements taken back to back, each 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 (0.8%). The uncertainties in the measured results were estimated (at the 95% confidence level) according to the procedure outlined by Moffat [11] 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 to 5 microns 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 (65 cm, or about 80% of the width of the heated wall around its center $z = 0$) where the air flow velocity distribution, in the z direction at a fixed distance from the heated wall, could be approximated (to within 5%) as uniform and two-dimensional flow. 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. [5]. 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.

In this experimental study, the flow and the thermal fields are measured to examine the effect of forward-facing step heights ($s = 11$ and 22 mm, corresponding to Reynolds number, $Re_s = u_\infty s/\nu$, of 373.5 and 746.9) on turbulent mixed convection flow ($u_\infty = 0.55\ \mathrm{m{\cdot}s^{-1}}$ and $\Delta T = 30\,^\circ\mathrm{C}$, corresponding to a local Grashof number $Gr_{xi} = 6.45 \times 10^{10}$) along a vertical flat plate. To examine the effect of step heights on the flow and thermal fields of turbulent mixed convection flow, measurements of the flow and thermal fields were carried out at five different streamwise locations: one location is at the step itself ($x = 0$ cm) and at four locations downstream of the step ($x = 3, 6, 10$, and 25 cm).

The effects of forward-facing step heights on the time-mean streamwise and transverse velocity and temperature distributions of turbulent mixed convection along a vertical flat plate are illustrated in Figs. 3–5, respectively. Fig. 3 shows that at the streamwise locations of $x = 3$ and 6 cm for case of forward-facing step heights of $s = 11$ and 22 mm, the time-mean velocity distributions have negative streamwise velocity component near the heated wall. This indicates that these distributions are inside the recirculation region that develops downstream of the forward-facing step. This clearly indicates that the introduction of the forward-facing step significantly affects the flow characteristics in the recirculation region downstream of the forward-facing step. On the other hand, the streamwise velocity distributions at 10 and 25 cm do not exhibit any negative velocity component, indicating that these velocity distributions are located outside the recirculation region that develops downstream of the forward-facing step. From flow visualization, it was determined that, for the experimental conditions in Fig. 3, a shallow recirculation region downstream of the forward-facing step develops with a reattachment length of $x_r = 7.1$ cm or 6.45 step heights and 9.7 or 4.41 step heights for the cases of forward-facing step heights of $s = 11$ and 22 mm, respectively. Also, as can be seen from the figure, the effect of the forward-facing step on the flow field continues to be present even at large distances downstream from the step. The uncer-

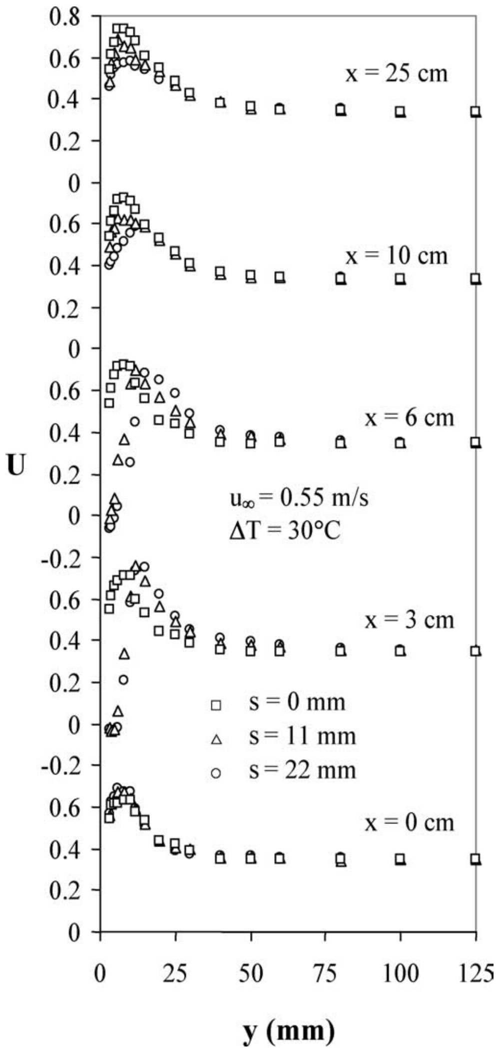

Fig. 3. Mean streamwise velocity distributions downstream of the step.

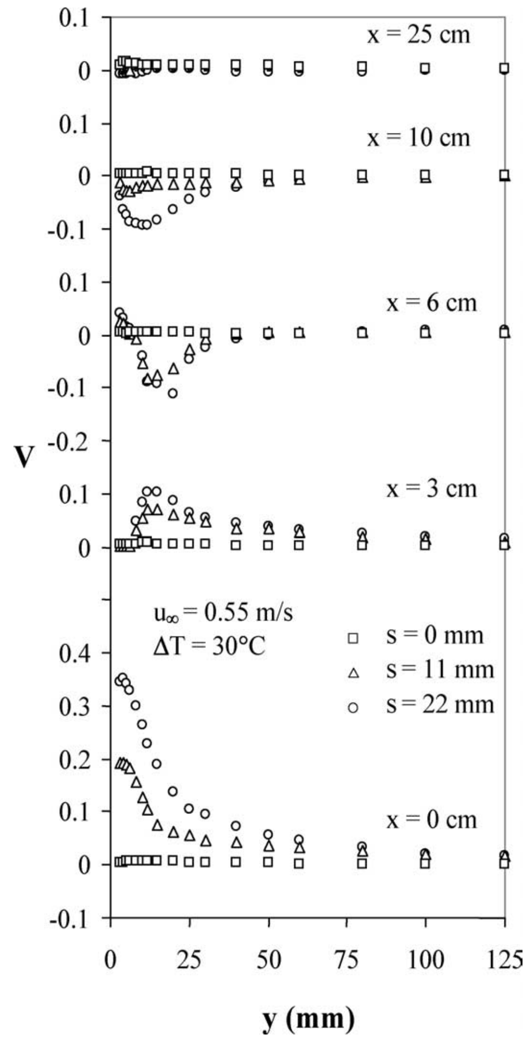

Fig. 4. Mean transverse velocity distributions downstream of the step.

tainty in the measurements is ±0.1 mm in y, ±1 mm in x, and ±4% in U.

The effects of forward-facing step heights on the time-mean transverse velocity distributions downstream of the step are illustrated in Fig. 4. As can be seen from the figure, the largest magnitude of maximum mean transverse velocity is attained at the forward-facing step ($x = 0$ cm) and it increases with increasing step height. In the region downstream of the forward-facing step ($x = 6$, 10, and 25 cm), the transverse velocity distributions for the cases of step heights of $s = 11$ and 22 mm exhibit negative time-mean transverse velocity component in the region near the heated wall. This is because the forward-facing step causes the streamlines to curve outward from the upstream heated wall near the step and then the streamlines are forced to curve towards the downstream heated wall causing a shallow recirculation region to develop downstream of the step. The magnitude of the negative mean transverse velocity component increases with increasing step height. On the other hand, at the streamwise location $x = 3$ cm for the cases of step heights of $s = 11$ and 22 mm, the mean transverse velocity is positive in the region near the heated wall. This is because the streamlines are still curving outward at this streamwise location. The figure also shows that magnitude of the mean transverse velocity at $x = 3$ cm increases as the step height increases. Also, it can be seen from the figure that the magnitude of the negative transverse velocity component in the flow region near the heated downstream wall decreases as the streamwise distance increases downstream from the step, indicating that the effect of the forward-facing step somewhat diminishes as the streamwise distance increases downstream from the step. This behavior is similar to that of the effect of backward-facing step on turbulent mixed convection flow along a vertical flat plate reported by Abu-Mulaweh et al. [7]. The uncertainty in the measured values for V is ±4%.

The effect of forward-facing step on the dimensionless mean temperature distributions downstream from the

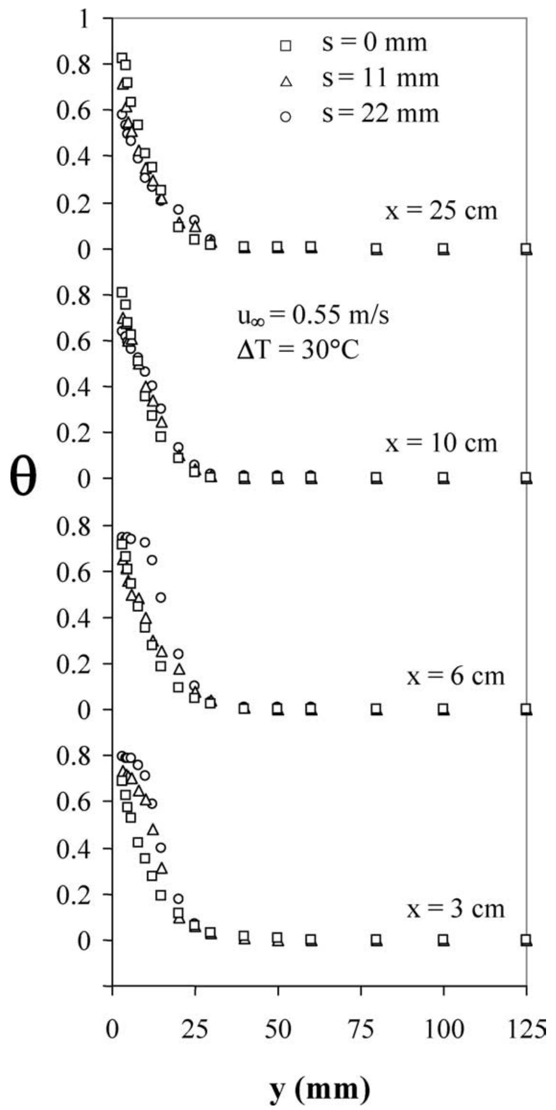

Fig. 5. Mean temperature distributions downstream of the step.

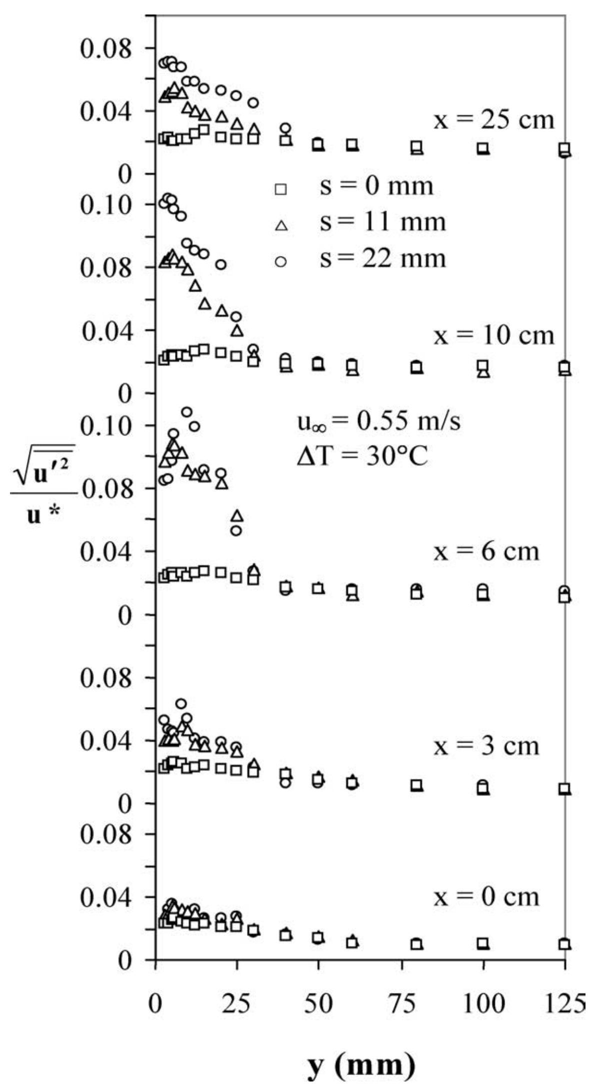

Fig. 6. Distributions of streamwise velocity fluctuation downstream of the step.

forward-facing step is shown in Fig. 5. For all cases, the temperature distribution asymptotically approaches the mainstream temperature as the distance from the heated wall increases. This figure shows that the forward-facing step height affect the characteristics of the thermal field downstream of the step. The uncertainty in the measured values for θ is ±2%.

The distributions of the dimensionless turbulent intensities of streamwise and transverse velocity and temperature fluctuations are presented, respectively, in Figs. 6–8. As can be seen from these figures, the values of turbulent intensities fluctuations, at a streamwise location, increase to a maximum as the distance from the heated wall increases, then start to decrease as the distance from the heated wall continues to increase, reaching a minimum value at the edge of the boundary-layer. The maximum turbulent intensities of both the streamwise and the transverse velocity fluctuations at a streamwise location appear to occur at the same distance from the heated wall. The magnitudes of the turbulent intensities of streamwise velocity fluctuations are higher than those of the transverse velocity fluctuations. Abu-Mulaweh et al. [12] and Hattori et al. [13] reported that the introduction of small free stream velocity on turbulent natural convection flow along a vertical flat plate ($s = 0$ mm) causes laminarization (i.e., turbulent suppression). This is because the introduction of small free stream velocity on turbulent natural convection restricts the large-scale vortex motions in the outer edge of the boundary layer that serve to maintain in the outer layer, and the large-scale structure in the outer layer plays a major role in turbulence generation. These figures clearly show that the introduction of forward-facing step enhances the turbulence intensity. The introduction of forward-facing step tends to trigger transition from the relaminarized flow upstream of the step to turbulent flow downstream of the step. The figures also show that the magnitudes of the turbulent intensities of both velocity (stream-

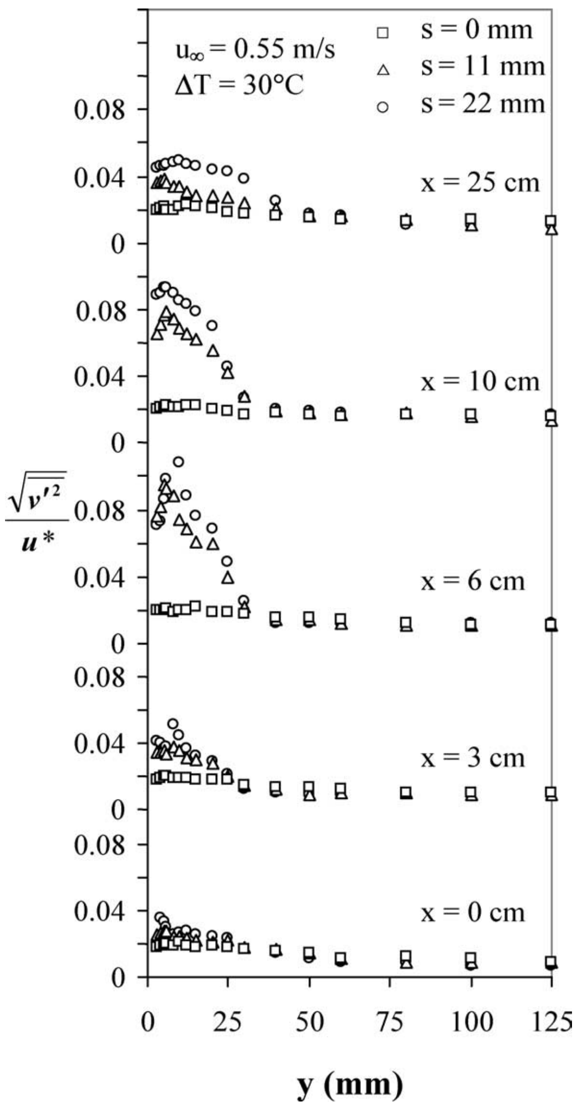

Fig. 7. Distributions of transverse velocity fluctuation downstream of the step.

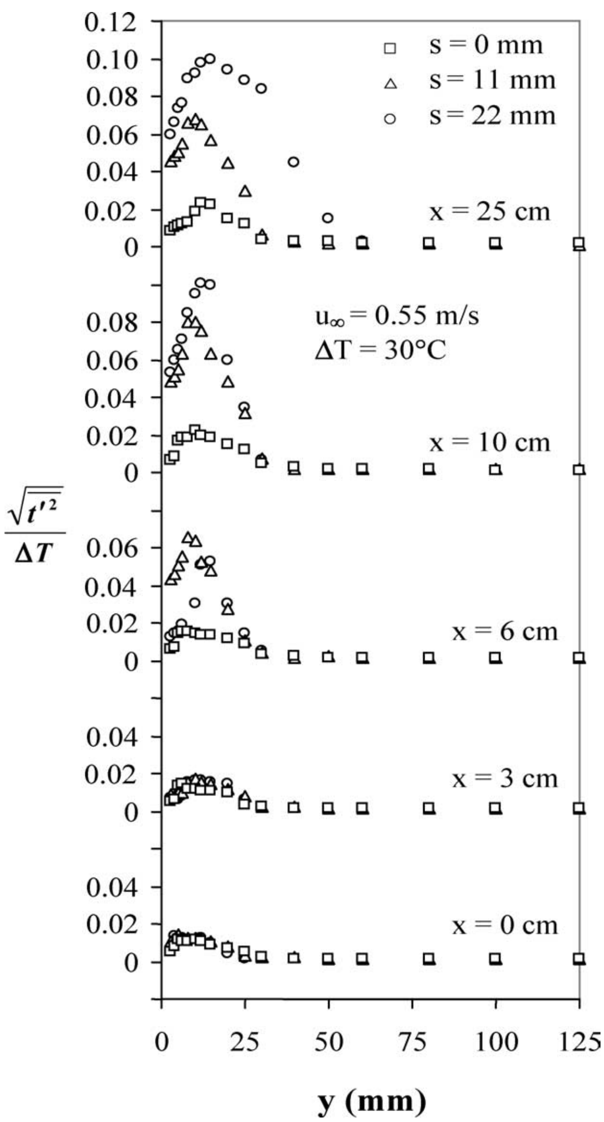

Fig. 8. Distributions of temperature fluctuation downstream of the step.

wise and transverse) and temperature fluctuations increase as the forward-facing step height increases. This is because of the larger impact angle of the upstream flow toward the heated plate downstream of the step as a result of the larger step height. It should be noted that this increase in the intensities of turbulent fluctuations is in the neighborhood of the reattachment region. The uncertainties in these measurements are ±6% in $\sqrt{\overline{u'^2}}/u_\cdot^*$, ±6% in $\sqrt{\overline{v'^2}}/u_\cdot^*$, and ±5% in $\sqrt{\overline{t'^2}}/\Delta T$.

The convective heat transfer coefficients for the heated downstream wall were obtained from the measured temperature distributions (temperature gradients) in the laminar sublayer near the heated wall. For a given streamwise location downstream from the step, the air temperature was measured at four different heights within 0.5 mm from the heated wall in order to determine the temperature gradient at the heated wall. The temperature distributions in the laminar sublayer near the heated wall were linear and the temperature fluctuations in that region were near zero. This technique for determining the surface temperature gradient and the convective heat transfer coefficient in turbulent flow was used and validated by Tsuji and Nagano [14], Qiu et al. [15], and Abu-Mulaweh et al. [6–8]. The effect of forward-facing step heights on the local Nusselt number downstream of the forward-facing step is illustrated in Fig. 9. For a given forward-facing step height ($s = 11$ or 22 mm), the figure shows the local Nusselt number increases with increasing distance from the step, reaching a maximum value in the vicinity of the reattachment region. The impact of the relatively cooler fluid from the shear layer on the heated wall and the deflection of cooler fluid into the recirculating flow region downstream of the step cause this rapid increase in the Nusselt number. The magnitude of the local Nusselt number decreases as the distance continues to increase in the streamwise direction. As can be seen from the figure, the measured local Nusselt number downstream of the forward-facing step (i.e., heat transfer rate from the heated downstream wall) increases with increasing step height. This is because the introduction of a forward-facing step triggers transition from the relaminarized flow upstream of the step to turbulent flow downstream of the step. Increasing the forward-facing step height greatly enhances the turbulence intensity of both velocity and temperature fluctuations (as shown in Figs. 6–8) and results in an increase in the heat transfer rate. The figure also shows that the location of the maximum local Nusselt number (i.e., the local heat transfer rate) moves away from the forward-facing step as the step height increases. This is because the maximum heat transfer rate occurs in the vicinity of the reattachment zone where the velocity and temperature fluctuations are maximum and a larger forward-facing step is associated with a larger reattachment length. A similar trend was reported by Abu-Mulaweh et al. [7] for the case of backward-facing step. The uncertainty in x is ±1 mm and in the measured Nusselt number is ±6%.

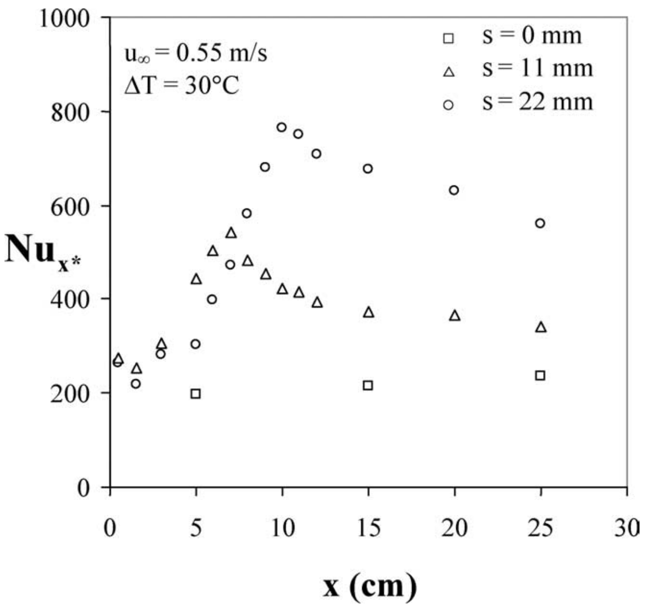

Fig. 9. Local Nusselt number variation downstream of the step.

4. Conclusion

Detailed measurements of the flow and thermal fields in turbulent mixed convection flow adjacent to a vertical, two-dimensional forward-facing step are reported. The effect of forward-facing step heights on time-mean streamwise and transverse velocity and temperature distributions, turbulent intensities of the distributions of velocity and temperature fluctuations, and local Nusselt number distributions are reported. The present results reveal that the introduction of a forward-facing step enhances and increases the turbulence intensity, which causes the relaminarized flow upstream of the step to become turbulent downstream of the step. This is due to the fact that in the case of a forward-facing step there are two opposite effects exist: the small free stream velocity tends to reduce and suppress turbulence, while the forward-facing step, acting as a trigger, enhances the turbulence. As the forward-facing step height increases, the turbulence intensity of velocity and temperature fluctuations, and the heat transfer rate downstream of the step were found to increase. The reattachment length was also found to increase as the forward-facing step height increase. 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 forward-facing step height velocity increases.

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