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Laboratory Report

Numerical Study of Turbulent Natural Convection Flow over a Backward-Facing Step

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The representation of the thermal boundary conditions of a fenestration surfaces has a major influence on the accuracy of predicting the thermal properties of a fenestration products. To represent internal surface heat-transfer rates of glazing are usually used average values of film coefficient for the entire surfaces. Because these values are averages, they are often not accurate for specific locations on the surface. Local surface heat-transfer film coefficients can be derived from data of numerical modeling of heat-mass transfer in testing chambers with fenestration specimens. Computational fluid dynamics (CFD) is being extensively used for this modeling.

Henkes and Hoogendroon [1] tested various turbulence models for the calculations of natural convection heat transfer from a vertical heated plate. They examined the next models: a standard k-ε model; a low-Reynolds-number (LRN) k-ε model; and an algebraic stress model. They found that the algebraic model calculates a low heat transfer coefficient whereas the standard k-ε model gives a high value compared with experimental data. They, therefore, concluded that the accurate prediction of surface heat transfer requires the use of a LRN k-ε model. That is why we used in our study LRN k-ε turbulence model.

The main aim of this study to assess the ability of a low-Reynolds-number (LRN) k-ε turbulence model to predict heat transfer and fluid flow along vertical heated flat plate with a backward-facing step. The existence of flow separation and subsequent reattachment due to a sudden change in flow geometry, such as a backward-facing step, plays an important role in distribution of heat transfer coefficient along fenestration surfaces. Numerical calculations have been performed for heated flat plate and for flat plate with backward-facing steps and are compared with experimental measurements taken by and Abu-Mulaweh and et al. [2].

1. Numerical model and method

In our study we used LRN k-ε turbulence model with variable coefficients described in details in [3] as VC LRN k-ε turbulence model. Therefore we do not give here the model equations that are available in ref. [3] and our report [4].

A computer code named FLU2TURB has been developed to solve the two-dimensional steady turbulent problem. The numerical discrete method is based on the upwind and fully implicit transient differencing control volume scheme used respectively for the convective, diffusive and time-dependent terms in the governing equations where the velocity control volumes are staggered with respect to the main control volumes. The resulting algebraic equations are solved iteratively using a line-by-line TDMA solution procedure and the SIMPLE algorithm formulated by Patankar [5]. Steady-state solutions are obtained using under-relaxation techniques.

We did not found more than 0.5 % difference in average Nusselt number and maximum velocities for various grids that we used for modeling.

2. The geometry and boundary conditions

To compare results of numerical modeling with experimental data [2] we defined the geometric dimensions and temperature conditions close to the conditions used in the experiment. Figure 1 shows geometry and boundary conditions of the air tunnel used for modeling flow along heated vertical flat plate. Geometry and boundary conditions of plate with backward-facing step are shown in Figure 2.

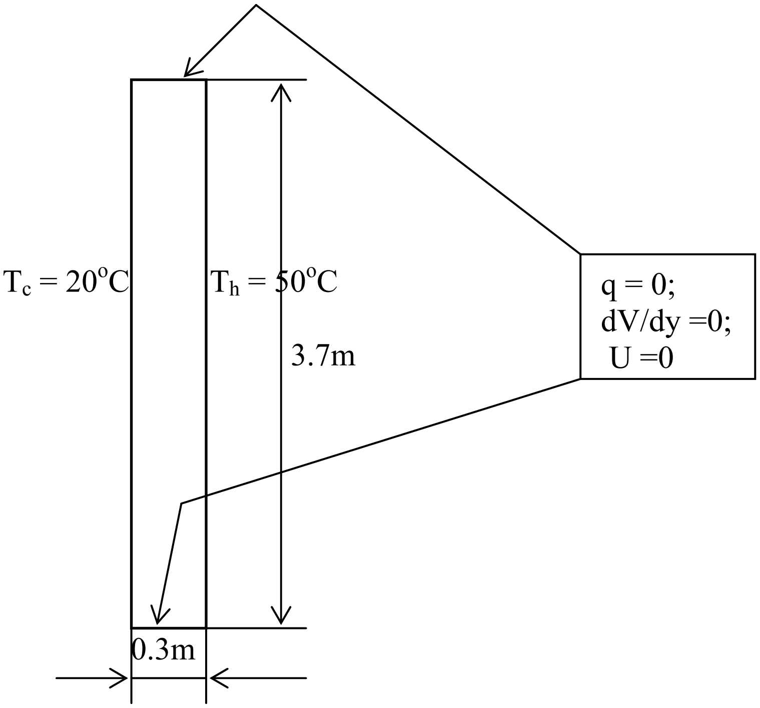


Figure 1. Geometry and boundary conditions used for modeling flow along heated flat plate

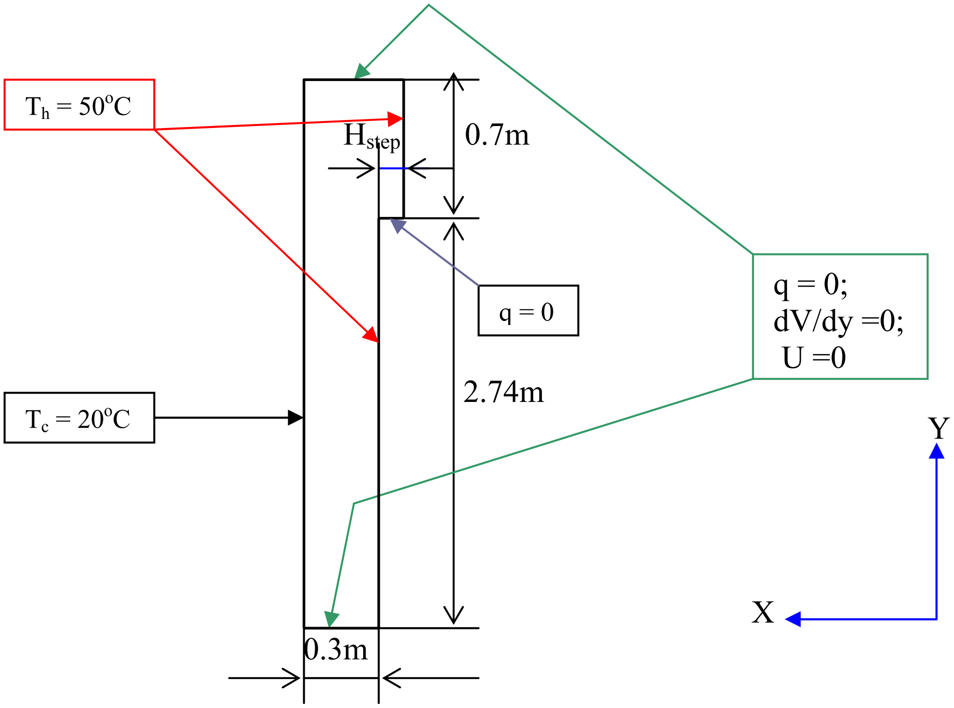


Figure 2. Geometry and boundary conditions used for modeling flow along heated flat plate with backward-facing step.

3. Comparison of experimental and numerical modeling results and discussion

3.1. The convective heat transfer rate of heated flat plate.

In work [2] is not pointed what reference temperature was used for definition air properties needed for calculation local Nusselt number Nu_y and local Grashof number Gr_y where y is distance from leading edge of flat plate. Our calculation of these values based on average temperature (35°C) between ambient temperature (20°C) and plate temperature (50°C) and air properties from [6]. In Figure 3 is shown comparison between predicted local Nusselt number along flat plate and empirical correlation reported in literature [2,7] as

$$Nu_y = 0.11\ Gr_y^{1/3}. \qquad (1)$$

Also we give here available data obtained by Abu-Mulaweh and et al. [2] for case of flat plate.

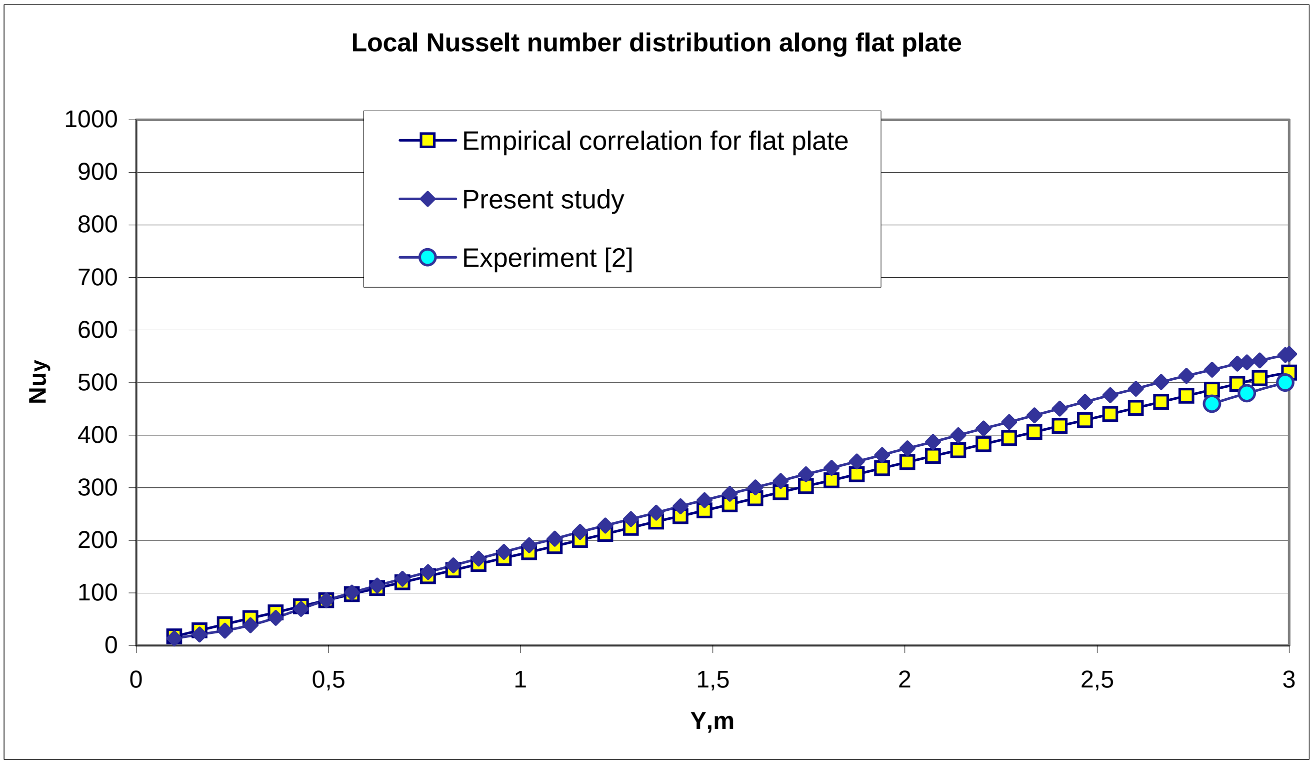
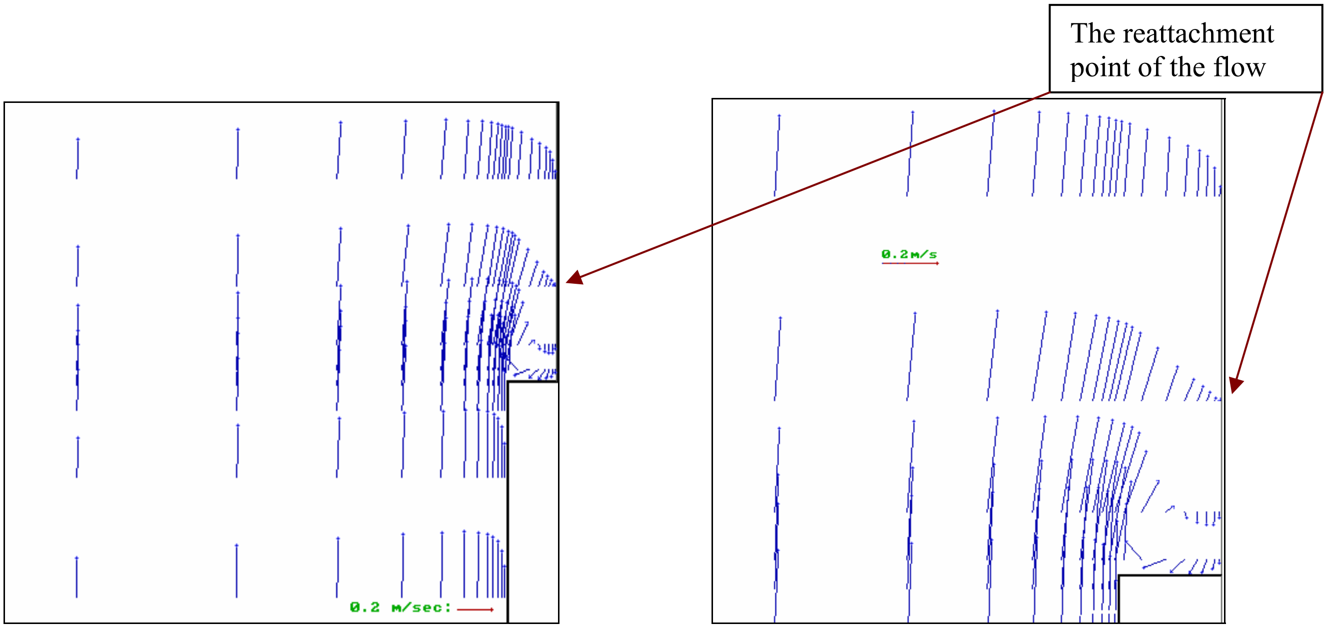


Figure 3. Comparison of local Nusselt number Nu_y along flat plate.

It should be noted that the predicted results of the Nusselt number compare well (within 5%) with empirical correlation for heated flat plate.

3.2. The flow and convective heat transfer rate of heated flat plate with backward-facing step.

The predicted velocity distribution at the backward-facing step is shown in Figure 4. A turbulent boundary layer in two dimensional plane flow is shown approaching the step beyond which a separated shear layer is formed. Part of the fluid in the shear layer is in a region of recirculation near the step while the remaining fluid continues downstream. The location where velocity vector nearby wall changes his direction on opposite one is called the reattachment point. In this point shear stress is minimum and the heat transfer is maximum.



The reattachment point of the flow

Figure 4. The fluid flow vector plot along plate with backward-facing step height of 11 mm .

For step heights of 11 mm and 22 mm the LRN k-ε turbulence model predicted location of the reattachment point at 2 step heights downstream of the step. The measured averaged values the reattachment point location for these cases reported by [2] are 3.2 and 2.7. So increasing step heights decreases under-prediction of the LRN k-ε turbulence model.

The predicted vertical velocity profiles downstream of the step height of 22 mm are given in Figure 5. The reference velocity V_{ref} is buoyancy velocity defined as $V_{ref} = [g\beta H(Th-Tc)]^{1/2}$ and in our case is equal to 1.86 m/s. LRN k-ε model predicted the same velocity change and position to wall as in experimental work [2] but peak velocity less than measured about 20% .

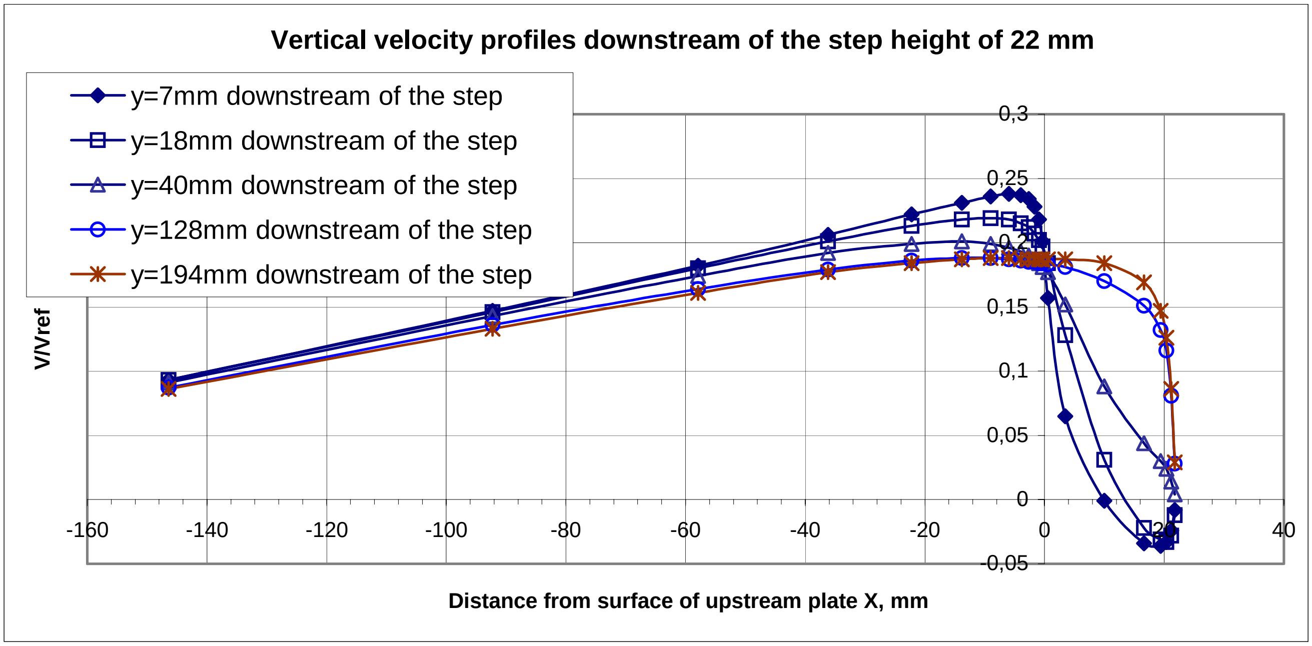


Figure 5. Predicted vertical velocity profiles downstream of the step height of 22 mm .

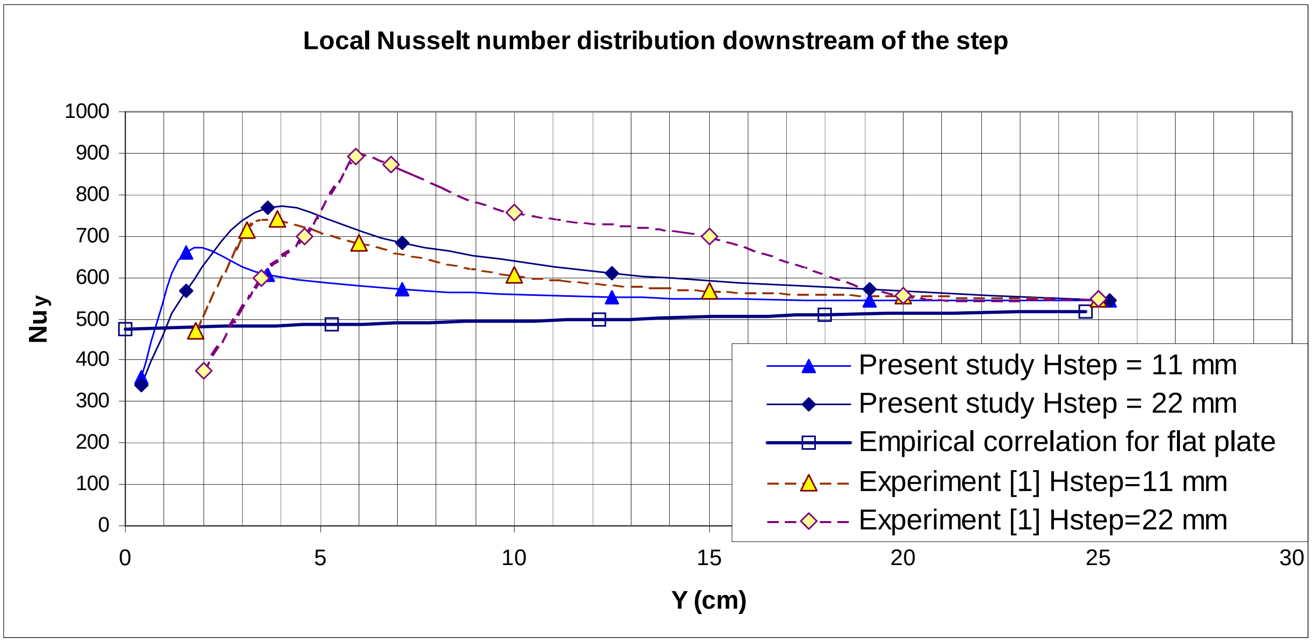


Figure 6. Comparison local Nusselt number Nu_y along flat plate downstream of the step.

The effect of the step height on local Nusselt number is illustrated in Figure 6 where is given comparison between predicted and measured local Nusselt number downstream of the step. For a given backward-facing step height, the local Nusselt number at the heated wall increases with increasing distance from the step, to a maximum value at some distance near the vicinity of the reattachment point, and then decreases slowly as the distance continues to increase in the stream-wise direction. The figure also shows that the location of the maximum local Nusselt number moves away from the step as the step height increases.

As can be seen from Figure 6, the LRN k-ε turbulence model under-predicted maximum of the local Nusselt number about 12% for both step heights and under-predicted location of maximum of the local Nusselt number and attachment length accordingly but this difference between predicted and measured values decreases with increasing of step height.

CONCLUSIONS

The low-Reynolds-number k-ε turbulence model was used to predict heat transfer and fluid flow along vertical heated flat plate with a backward-facing step for two different step heights of 11 mm and 22 mm and Grashof number range of $7.0 \times 10^{10} \le Gr_y \le 8.3 \times 10^{10}$.

For the case of heated flat plate the predicted results of the Nusselt number compare well (within 5%) with known empirical correlation for heated flat plate in air.

For the case of heated flat plate with a backward-facing step LRN k-ε model under-predicted maximum of the local Nusselt number (about 12%) and attachment length but this difference decreases with increasing of step height. When compared to the experimental results of Abu-Mulaweh and et al. [2], this model predicted the velocity profiles well but maximal velocity values under-predicted to 20%.

From the foregoing results, it is concluded that the LRN k-ε model does a satisfactory job of predicting natural convection flow and heat transfer along vertical heated flat plate with a backward-facing step and can be recommended for modeling of heat-mass transfer and air flows along glazing surfaces of fenestrations.

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