The 16th Conference of the International Society of Indoor Air Quality & Climate (Indoor Air 2020)
COEX, Seoul, Korea | July 20 - 24, 2020

Paper ID xxx.xx ISBN: …0065…….

A benchmark test for the isothermal backward-facing step flow

Chen Zhang*, Peter V. Nielsen, Laura A. Bugenings, Markus Schaffer, Rasmus L. Jensen

Department of the Built Environment, Aalborg University, Denmark

Corresponding email: cz@civil.aau.dk

SUMMARY

CFD is one of the most important approaches for predicting and evaluating the airflow in the indoor environment. Although there has been a continuous improvement of computer performance and CFD technology in the past few decades, the uncertainty in CFD prediction remains high due to the user dependency on building meshes, selecting turbulence models, defining boundary conditions, and choosing numerical schemes. Benchmark tests are therefore an important approach to validate the CFD models and guide the selection of proper turbulence models under different flow regimes. This study aims to perform a benchmark test for the isothermal backward-facing step flow under different flow regimes. The benchmark test is conducted in a small-scale model and LDA is employed to identify airflow patterns. The benchmark results indicate that the SST *k-ω* model could be a good option to predict low turbulent flow while the Realizable *k-ε* and RSM models can be used for fully developed turbulent flow.

KEYWORDS

Benchmark test; Laser Doppler anemometry; Airflow pattern ; CFD

1 INTRODUCTION

CFD is one of the most important approaches for predicting and evaluating the airflow in the indoor environment. Even though there has been a continuous improvement of computer performance and CFD technology in the past few decades, the uncertainty in CFD prediction remains unneglectable due to the user dependency on building meshes, selecting turbulence models, defining boundary conditions and choosing numerical schemes(Peter V. Nielsen, 2015)(Peng et al., 2016)(van Hooff, Nielsen, & Li, 2018). A good example of the user-dependency in CFD prediction is the workshop held in ISHVAC-COBEE 2015, named 'To predict low turbulent flow'. In this workshop 19 professional teams simulated a typical flow scenario in the indoor environment, an isothermal backward-facing step flow, without benchmark test validation available. There were significant diversities in the simulated results among the teams and at different Reynolds numbers, where the largest deviation coefficient was more than 50%. The selection of the turbulence model seemed to be a very important issue and no agreement was reached between different teams on which turbulence model to use for different flow regimes (Peng et al., 2016).

This study aims to perform a benchmark test for the isothermal backward-facing step flow. The benchmark test is conducted in a small-scale model and a Laser Doppler Anemometry

(LDA) is employed to identify the airflow patterns in the space and to measure the velocity field. To validate the isothermal assumption the air temperature is measured at the inlet, exhaust and surrounding zone.. The benchmark test is carried out with Re=500 and Re=4000, in order to represent a low turbulent flow and a fully developed turbulent flow regime. The measured results could be used for further CFD validation and to guide the selection of proper turbulence models under different flow regimes.

2 FLOW PROBLEM DESCRIPTION

The flow problem investigated in this study is an isothermal supply airflow scenario in a deep room with ventilation opening in one end wall. The flow is similar to the backward-facing step flow in fluid dynamics (Chen, Asai, Nonomura, Xi, & Liu, 2018). This flow scenario is different from the conventional ventilated room with short sections, but it is relevant for elongated industrial buildings or deep tunnels.

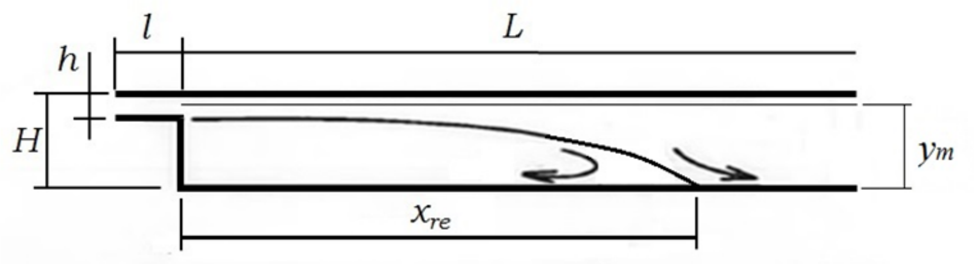
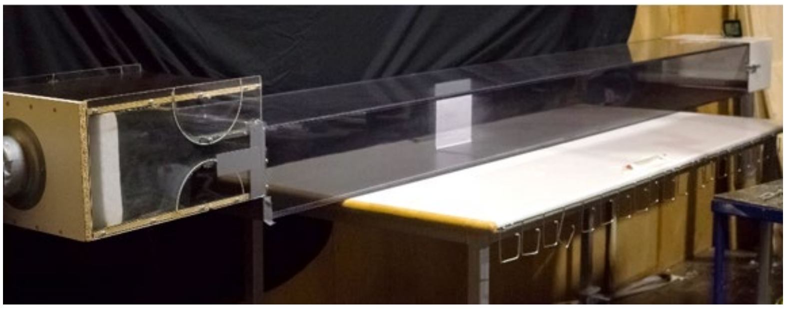


Figure 1. Backward-facing step flow model presented in ISHVAC-COBEE workshop

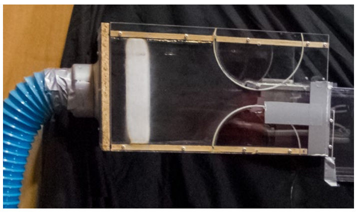
Figure 1 illustrates the backward-facing step flow model introduced in the ISHVAC-COBEE workshop (Peng et al., 2016). The model has the following dimensions: $h/H = 1/5 = 0.2$, $l/H = 4$, width $W = 2H$. In ISHVAC-COBEE workshop, the penetration length x_{re} is selected as one of the parameters to compare CFD prediction results, which is the distance from the front wall to the location of the flow reattached point. Due to the large uncertainty in the measurement of the separated flow area, another variable is used in this benchmark, which is the velocity profile along a horizontal line in the height of y_m above the floor, as shown in Figure 1.

3 EXPERIMENTAL INVESTIGATIONS

A small-scaled physical model is used to investigate the backward-facing step flow, as shown in Figure 2. The physical model is built with the geometrical similarity to the theoretical model, where h=0.04 m, H= 0.2, l= 0.16 m and L= 3m. The inlet is a slot opening located at the top of the front wall and is connected to a supply chamber Figure 2 (b). A layer of fibre insulation is placed in the supply chamber to uniform the supply airflow. The exhaust is located at the bottom of the back wall and is connected to an exhaust fan through the exhaust chamber, Figure 2 (c).



(a)



(b)

(c)

Figure 2. Small-scaled model in the laboratory (a) Physical model (b) Inlet chamber (c) Exhaust chamber

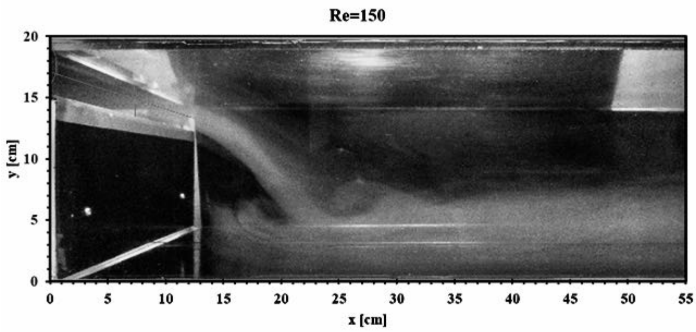
Laser Doppler anemometry (LDA) is used to measure the velocity distribution in the small-scale model, due to its non-intrusive and directional-sensitive features. The 2D velocity (x-y direction) is measured in the central cross-section along the length of the model. LDA is a point measurement technique; therefore, the whole flow filed is evenly divided into small grids with a spacing of 57 mm, as shown in Figure 3 (a). The resulting grid has 4*53 points.

To verify if the airflow is isothermal during the test, the air temperature is measured at the inlet, exhaust and ambient air using PT-100 sensors. However, the measured results indicate the isothermal condition is not always guaranteed due to the limitations of the measurement set up. First of all, the physical model is located in a laboratory without precise temperature control, consequently there are heat gains/losses through the model's surface. Second, a haze machine is applied to generate seeding particles in the airflow for the LDA measurement. The haze machine produces a small amount of heat during the particle generation, which results in the fact that the inlet air temperature increases slightly during the operation. The air temperature difference between inlet and exhaust is up to 0.5 K during the measurement and the effect on the flow pattern may thus be relevant at low Reynolds numbers.

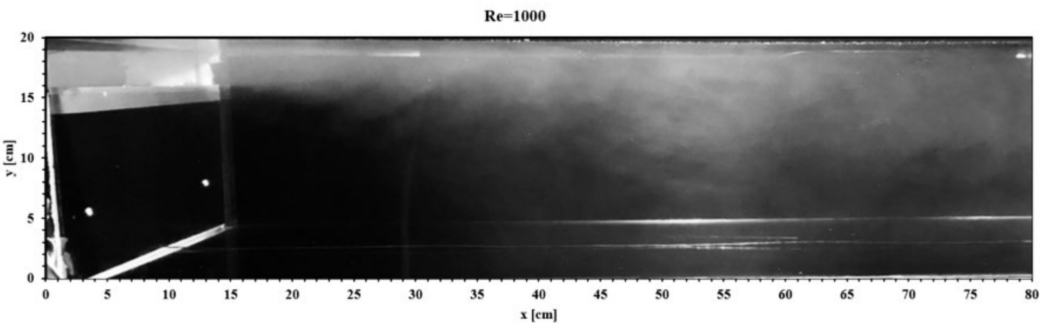
Besides the above-mentioned measurements, smoke tests are conducted to visualize the flow development at different Reynolds numbers.

4 RESULTS

Figure 3 shows the flow pattern of the backward-facing step flow under different Reynold numbers by smoke visualization. In the case of Re=150, the flow shows the laminar feature. The flow is smooth and unperturbed, and the separation point can be seen around x=20 ~ 25 cm. When the Re increased to 1000, the flow shows the transitional feature, where the flow presents an unsteady complex structure and shows several regions of flow separation and reattachment, therefore, it is hard to observe the separation point by eye.



(a)



(b)

Figure 3. Smoke visualization of the backward-facing step flow (a) Re=150; (b) Re=1000

Figure 4 illustrates the velocity field in the central cross-section measured by LDA with Re=4000. The inlet flow develops into a wall jet with a high initial velocity. The wall jet detaches the ceiling at dimensionless length around 4. The flow further develops and re-attaches to the floor at dimensionless length around 5 ~ 6, and separates into a reverse recirculated flow entrainment into the wall jet and a forward flow towards the exit. Small vortexes occur near the front wall corner and below the ceiling after the wall jet detachment.

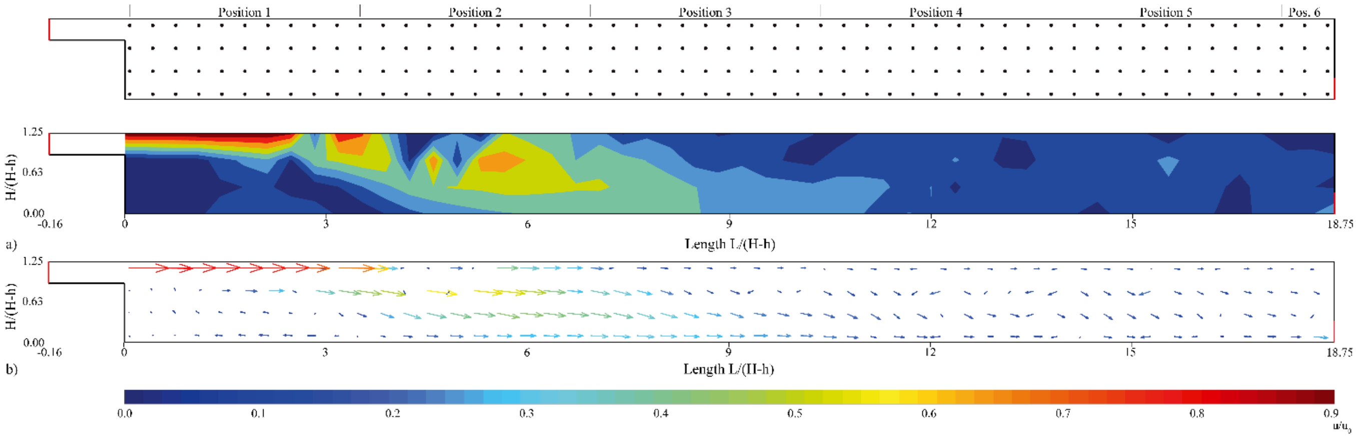
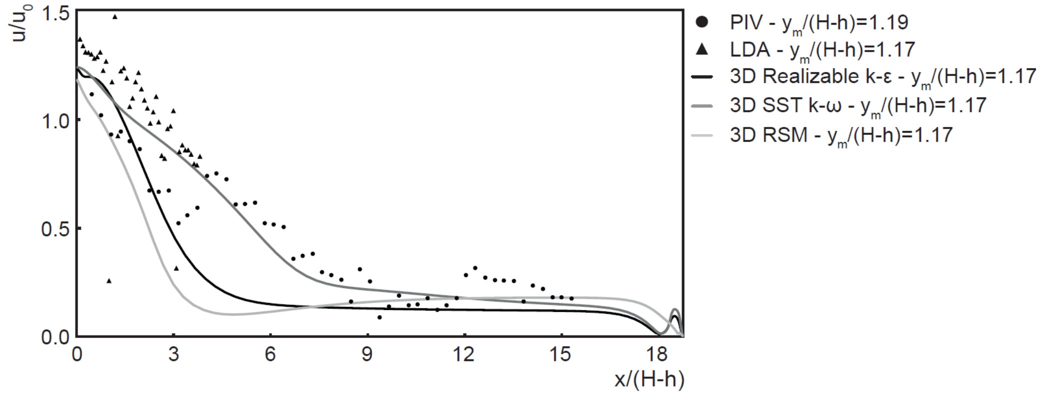
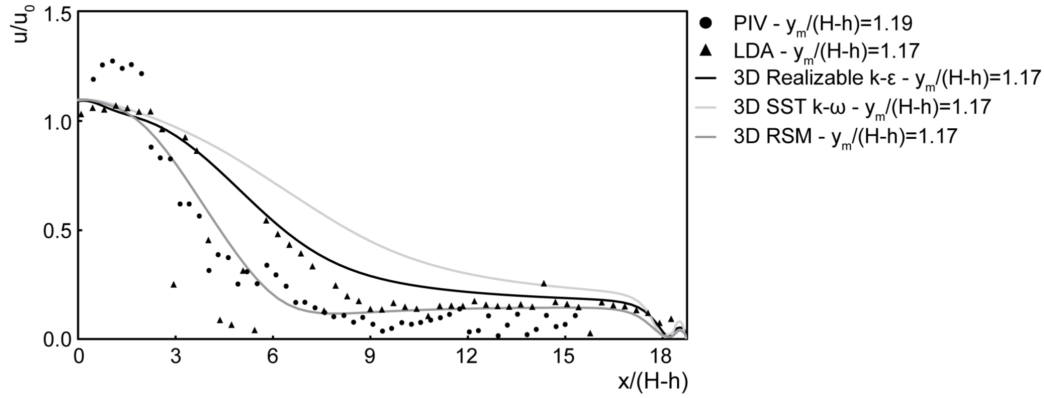


Figure 4. LDA measured velocity distribution in the cross-section, Re=4000. (a) Measurement grid (b) velocity contour plot (c) velocity vector plot

The velocity profile along the horizontal line at the dimensionless height of $y_m/(H-h)$=1.17 are compared between LDA measured results and CFD predicted results, see Figure 5. Three sets of CFD predictions are made where only the turbulence model is changed between Realizable k-ε, SST k-ω and RSM. For a detailed description of CFD models and discussion of turbulence models it is referred to Nielsen et al. (Peter V Nielsen, Zhang, Bugenings, & Schaffer, 2020). The velocity profile measured by PIV (Particle Image Velocimetry) in the previous study (P. V. Nielsen et al., 2019) is also presented here and compared with the other velocity profiles. Even though the PIV measurement was conducted at a height slightly different from the other methods, the difference is very small (3mm) and it can be neglected.



(a)



(b)

Figure 5. Velocity profiles with different methods (a) Re=500; (b) Re=4000.

Figure 5 shows that the CFD simulation with SST *k-ω* model generated a velocity profile in good accordance with the LDA and PIV measurement results at a Re=500. However, when the Re is increased to 4000, the Realizable *k-ε* and RSM models provide better predictions of the velocity field, and the SST *k-ω* model seems to overestimate the velocity magnitude.

5 DISCUSSIONS AND CONCLUSIONS

A benchmark test for the isothermal backward-facing step flow is conducted in a small-scale model using Laser Doppler Anemometry (LDA). The difficulties associated with the measurement of backward-facing step flow was discussed in the previous studies (Häggmark et al., 2000)(Havlica & Šimc, 2012). The separation flow is highly sensitive to various perturbations, such as mean flow variations, freestream turbulence, noise disturbances, and surface vibrations and roughness. In addition, a small variation in the inlet flow condition can cause unsteadiness and a significant movement of the separation point in the streamwise direction. The structure of the separation flow also depends on the flow history, such as the initial variation in pressure gradient and Reynolds number at the start-up of the experiment. All these factors result in an extremely challenging to use separation length as an indicator to compare experimental results with CFD prediction ones. Therefore, the velocity profile in the high-velocity area is selected as a parameter to validate the CFD model. The benchmark results indicate that the SST *k-ω* model could be a good option to predict low turbulent flows while the Realizable *k-ε* and RSM models can be used for fully developed turbulent flow.

The benchmark documented in this article is presented on the home page: www.cfd-benchmarks.com.

6 REFERENCES

Chen, L., Asai, K., Nonomura, T., Xi, G., & Liu, T. (2018). A review of Backward-Facing Step (BFS) flow mechanisms, heat transfer and control. *Thermal Science and Engineering Progress*, *6*(April), 194–216. https://doi.org/10.1016/j.tsep.2018.04.004

Häggmark, C. P., Bakchinov, A. A., & Alfredsson, P. H. (2000). Experiments on a two-dimensional laminar separation bubble. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *358*, 3195–3205.

Havlica, J., & Šimc, M. (2012). *The transitional backward-facing step flow in a water channel with variable expansion geometry*. *40*, 112–125. https://doi.org/10.1016/j.expthermflusci.2012.02.006

Nielsen, P. V., Zhang, C., Kjær, C. T., Leiria, D., Nørholm, H., Ramstad, T., … Jensen, R. L. (2019). A benchmark test for room air distribution: The backward facing step flow. *IOP Conference Series: Materials Science and Engineering*, *609*(3). https://doi.org/10.1088/1757-899X/609/3/032017

Nielsen, Peter V. (2015). Fifty years of CFD for room air distribution. *Building and Environment*, *91*, 78–90. https://doi.org/10.1016/j.buildenv.2015.02.035

Nielsen, Peter V, Zhang, C., Bugenings, L. A., & Schaffer, M. (2020). THE DEVELOPMENT OF A BENCHMARK FOR ROOM AIR DISTRIBUTION : THE BACKWARD FACING STEP FLOW. *Roomvent 2020*.

Peng, L., Nielsen, P. V, Wang, X., Sadrizadeh, S., Liu, L., & Li, Y. (2016). Possible user-dependent CFD predictions of transitional fl ow in building ventilation. *Building and Environment*, *99*, 130–141. https://doi.org/10.1016/j.buildenv.2016.01.014

van Hooff, T., Nielsen, P. V., & Li, Y. (2018). Computational fluid dynamics predictions of non-isothermal ventilation flow—How can the user factor be minimized? *Indoor Air*, *28*(6), 866–880. https://doi.org/10.1111/ina.12492