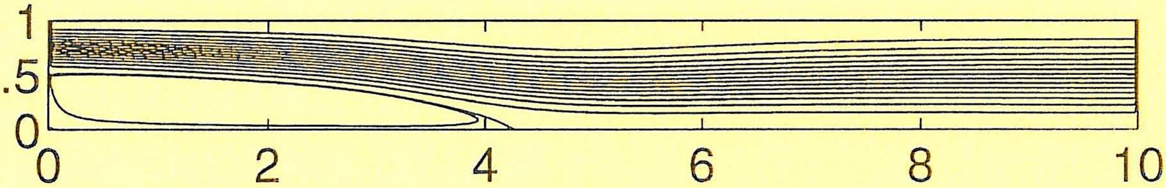
A Study of Laminar Backward-Facing Step Flow

Davidson, Lars; Nielsen, Peter V.

Publication date:
1998

Document Version
Publisher's PDF, also known as Version of record

INSTITUTTET FOR BYGNINGSTEKNIK
DEPT. OF BUILDING TECHNOLOGY AND STRUCTURAL ENGINEERING
AALBORG UNIVERSITET • AAU • AALBORG • DANMARK



INDOOR ENVIRONMENTAL ENGINEERING
PAPER NO. 83

L. DAVIDSON, P. V. NIELSEN
A STUDY OF LAMINAR BACKWARD-FACING STEP FLOW
FEBRUARY 1998 ISSN 1395-7953 R9802

Printed at Aalborg University

INSTITUTTET FOR BYGNINGSTEKNIK
DEPT. OF BUILDING TECHNOLOGY AND STRUCTURAL ENGINEERING
AALBORG UNIVERSITETET • AAU • AALBORG • DANMARK

INDOOR ENVIRONMENTAL ENGINEERING
PAPER NO. 83

L. DAVIDSON, P. V. NIELSEN
A STUDY OF LAMINAR BACKWARD-FACING STEP FLOW

FEBRUARY 1998 ISSN 1395-7953 R9802

A Study of Laminar Backward-Facing Step Flow

Lars Davidson*
Dept. of Thermo and Fluid Dynamics
Chalmers University of Technology
S-412 96 Gothenburg, Sweden
http://www.tfd.chalmers.se/~lada

Peter V. Nielsen
Dept. of Building Technology and Structural Engineering
Aalborg University
Sohngaardsholmsvej 57
DK-9000 Aalborg, Denmark
http://www.civil.auc.dk/i6/staff/navn/i6pvn.html

Abstract

The laminar flow for a backwards facing step is studied. This work was initially part of the work presented in [1]. In that work low-Reynolds number effects was studied, and the plan was also to include laminar flow. However, it turned out that when the numerical predictions of the laminar flow ($Re = 118$) was compared to the experiments of Restivo [2], we found a large discrepancy. We believe that there is something wrong in that experimental investigation. To support that conclusion, we present in this report prediction of other backward facing flow configurations, where we show that our predictions agree well with experimental data.

1 Configuration

The configuration is shown in Fig. 1. The Reynolds number is defined as

$$Re = \frac{U_{bulk}h}{\nu}.$$

The boundary conditions at all walls are $U = V = 0$. At the outlet we have used zero streamwise gradient for U, i.e.

$$\frac{\partial U}{\partial x} = 0$$

which, from continuity, gives $V = 0$. A parabolic inlet profile is used

$$U = 6U_{bulk}\bar{y}(1-\bar{y})$$
$$\bar{y} = \frac{y-(H-h)}{h} \qquad (1)$$

*This work was carried out during the author's stay at Dept. of Building Technology and Structural Engineering, Aalborg University in Autumn 1997.

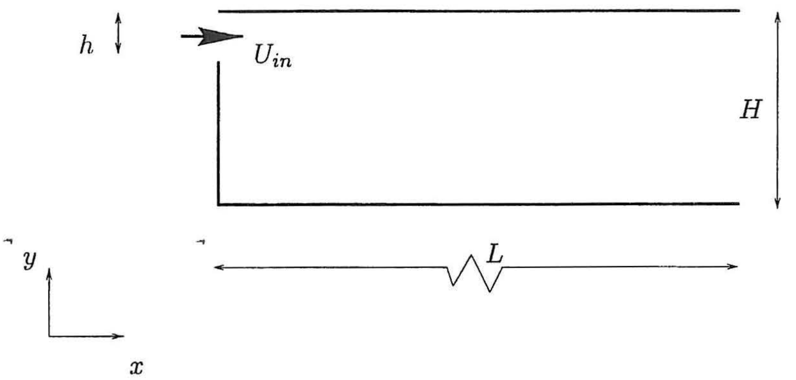


Figure 1: Configuration.

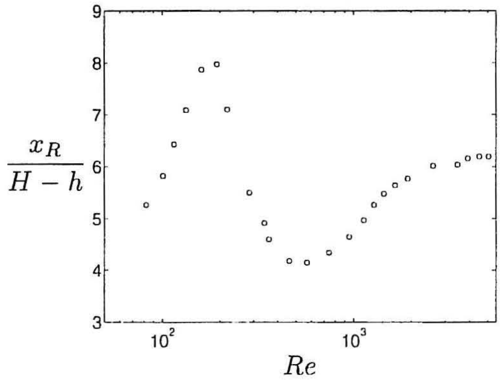


Figure 2: Experimental reattachment length x_R as a function of inlet Reynolds number Re [2].

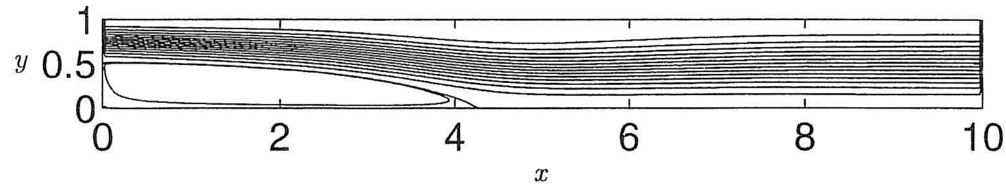


Figure 3: Contours of stream function. $Re = 195$. $h/H = 0.516$

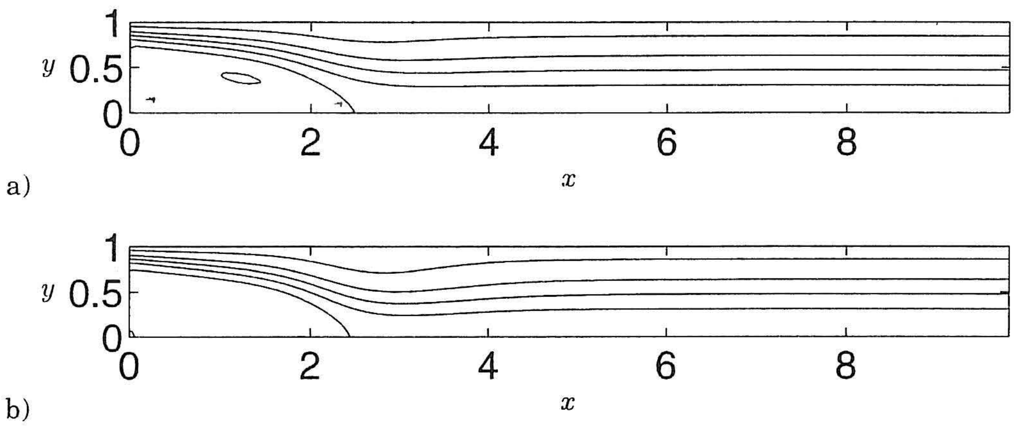


Figure 4: Contours of stream function. $Re = 50$. $h/H = 1/4$. a) Hybrid scheme, 80×40 cells. b) QUICK scheme, 160×80 cells.

2 Backward-Facing Flow with $h/H = 0.516$

Armaly *et al.* [3] have presented an experimental investigation of backward-facing flow. The ratio of the inlet height and the step is larger ($h/H = 0.516$) than in the Restivo configuration. They report that the flow is laminar up to $Re = 600$. For $600 < Re < 3000$ the flow is transitional, and for higher Re number the flow is fully turbulent. Even if the flow is laminar for $Re < 600$, they found it to be three-dimensional for $200 < Re < 3000$.

This flow has been computed using a 160×80 equidistant mesh and a QUICK scheme. The extent of the computation domain in the x direction is $10H$. The streamlines for $Re = 195$ are shown in Fig. 3 and the predicted re-attachment point is located at $x_R = 4.3$ which is in agreement with experiments [3] ($X_{R,exp} = 4.3$) and other computations (see Ref. [4]). In the present computations a small recirculation bubble was found along the upper wall for $4 < x/H < 5.2$; it was very thin however (only one or two cells).

3 Backward-Facing Flow with $h/H = 1/4$

In Fig. 4 the contours of the predicted streamlines are shown. Two equidistant meshes have been used. A 80×40 mesh using the Hybrid scheme gives $x_R/H = 2.55$ and a 160×80 mesh employing QUICK gives $x_R/H = 2.47$. This agrees well with the predicted value reported by Thangam and Knight [5] who report $x_R/H \simeq 2.5$.

4 Backward-Facing Flow with $h/H = 1/6$

For this configuration the grids are equidistant in the x direction. In the y direction cells with a constant spacing dy_1 is used for the inlet, and dy_2 is used below the inlet. Seven and fourteen cells are used to cover the inlet for the coarse and fine mesh, respectively.

In Fig. 5 the streamline contours are shown for $Re = 50$. The extent of the the recirculation region is similar to that in Fig. 4. When the Re number is increased, the recirculation region grows larger, Figs 6 and 7.

For $Re = 50$ the difference between the predictions obtained with the different grids is small. For $Re = 100$ the size of the predicted recirculation bubble near the ceiling is larger with the finer grid. The size of the bubble below the inlet, however, does not differ that much. For $Re = 118$ the extent of the computation domain is increased to $12H$. As can be seen from Fig. 7 the size of the recirculation bubble near the ceiling and of the bubble near the floor increases slightly, compared to $Re = 100$. In Fig. 9 the sensitivity to the inlet velocity profile is investigated. A parabolic inlet profile is compared to the experimentally measured profile (see Fig. 8), and as can be seen from Fig. 9 the difference is rather small.

Using the fine grid the predicted length of the recirculation region in Figs. 7 and 9 ($x_R/H = 3.92$ and 3.76, respectively) is considerably shorter than that reported by Restivo [2, 6], whose experimental value x_R/h is between 30 and 45, i.e $6 < x_R/(H-h) < 9$ ($5 < x_R/H) < 7.5$). The value shown in Fig. 2 (taken from Ref. [2]) is $x/(H-h) = 6.42$.

The predicted velocity profiles are compared with experiments in Fig. 11. They agree fairly well up to $x/h = 15$, but then there is a large discrepancy. It can be seen that at $x/h = 20$ a recirculation bubble appears near the ceiling in the predictions, which is not present in the experiments. Such a separation bubble is indeed present in the predictions in Fig. 3 and also in the measurements [3].

In Fig. 10 the predicted streamlines for $Re = 160$ are presented. A slightly longer computations domain was used ($14H$). No convergence was obtained with QUICK on the fine mesh, which probably indicates that the flow starts to get transitional and/or three-dimensional. As can be seen both the recirculation bubble at the floor and at the ceiling gets slightly larger.

5 Conclusions

We have computed laminar flow in a backward-facing step for different configurations. Good agreement with experiments is obtained for $h/H = 0.516$. Good agreement is also obtained with other predictions in the literature for $h/H = 1/4$. However, for $h/H = 1/6$ the agreement with experiments of Restivo [2] is very poor. Thus we believe that the experiments are in error. One reason could be that the configuration in the experimental setup was too small. The streamwise extent was $9H$ and the predicted extent of the recirculation bubble near the ceiling is approximately $6H$ at $Re = 118$ and $7H$ at $Re = 100$.

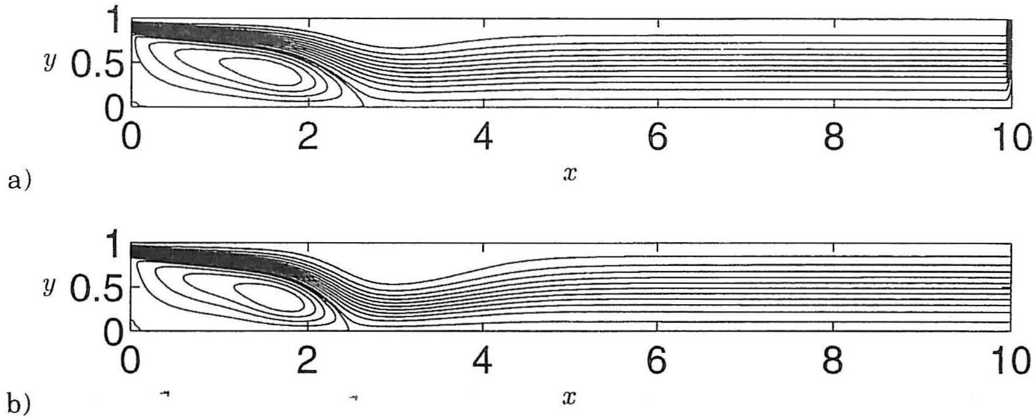


Figure 5: Contours of stream function. $Re = 50$. $h/H = 1/6$. a) Hybrid scheme, 80×42 cells. b) QUICK scheme, 160×84 cells.

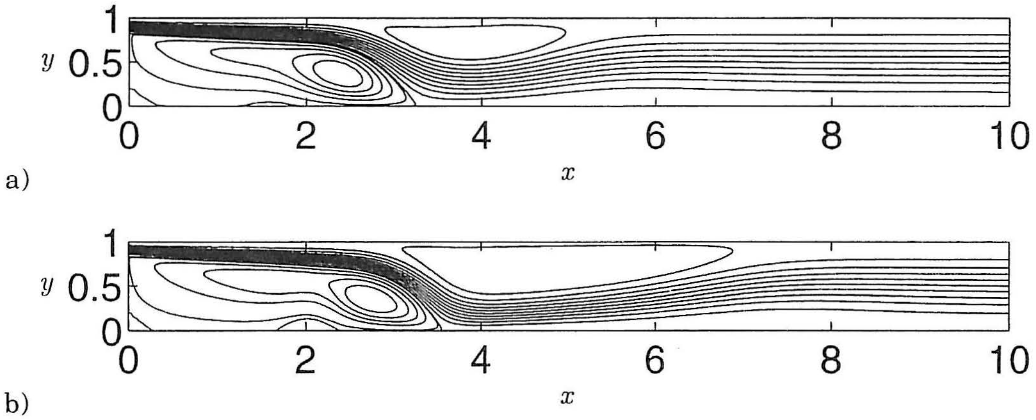


Figure 6: Contours of stream function. $Re = 100$. $h/H = 1/6$. a) Hybrid scheme, 80×42 cells. b) QUICK scheme, 160×84 cells.

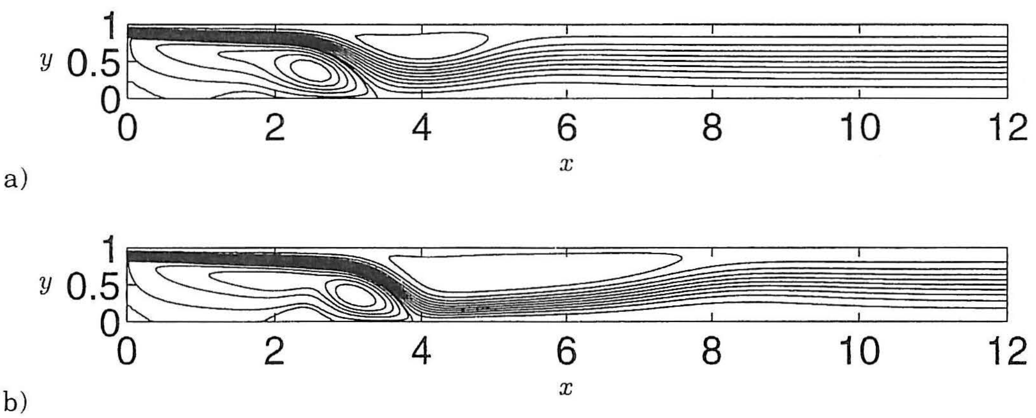


Figure 7: Contours of stream function. $Re = 118$. $h/H = 1/6$. a) Hybrid scheme, 80×42 cells. b) QUICK scheme, 160×84 cells.

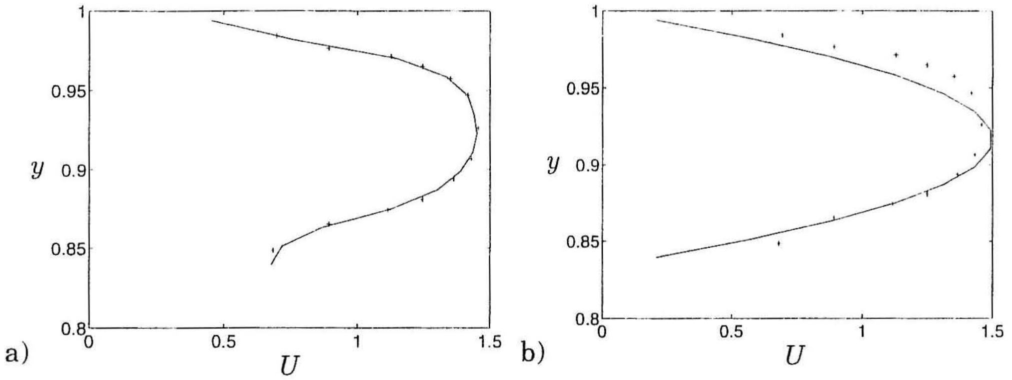


Figure 8: Inlet profiles. Solid lines: prescribed inlet U profiles in the predictions; markers: experiments. $Re = 118$. $h/H = 1/6$. 160×84 cells. a) Interpolated profile from experiments. b) Parabolic profile.

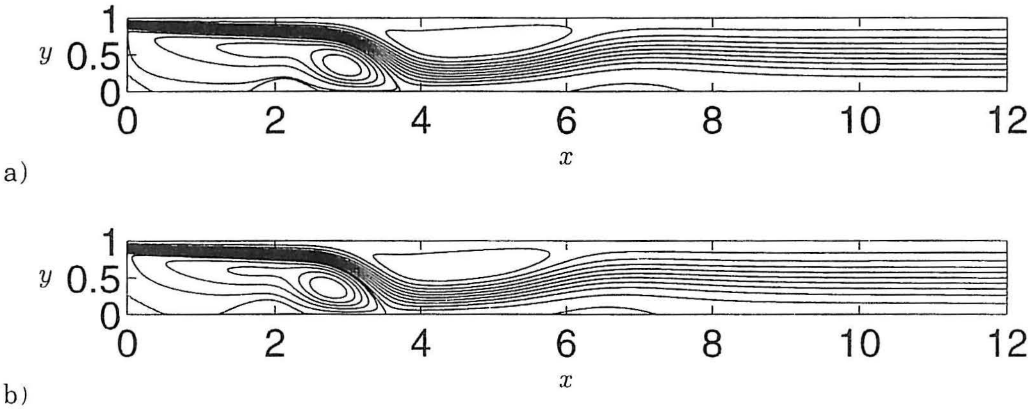


Figure 9: Contours of stream function. $Re = 118$, $h/H = 1/6$, Hybrid scheme, 160×84 cells. a) Prescribed inlet profiles according to experiments (see Fig. 8 a). b) Parabolic inlet profile (see Fig. 8 b).

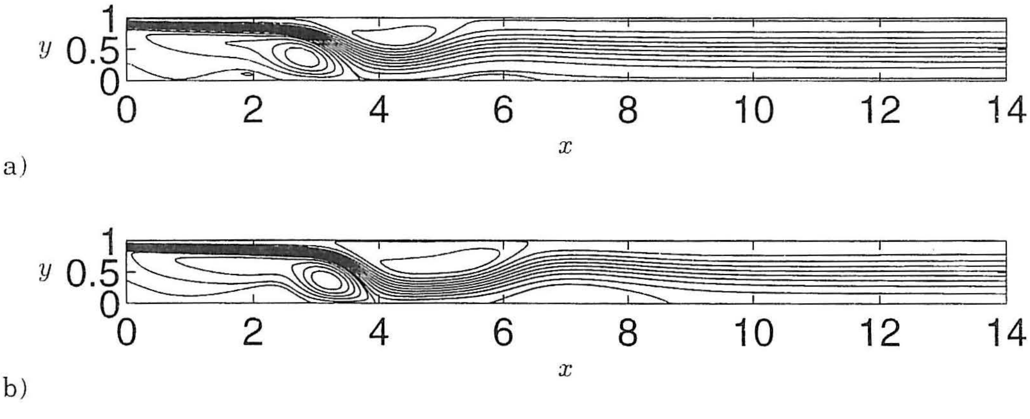


Figure 10: Contours of stream function. $Re = 160$, $h/H = 1/6$. Hybrid scheme. a) 85×42 cells. b) 169×84 cells.

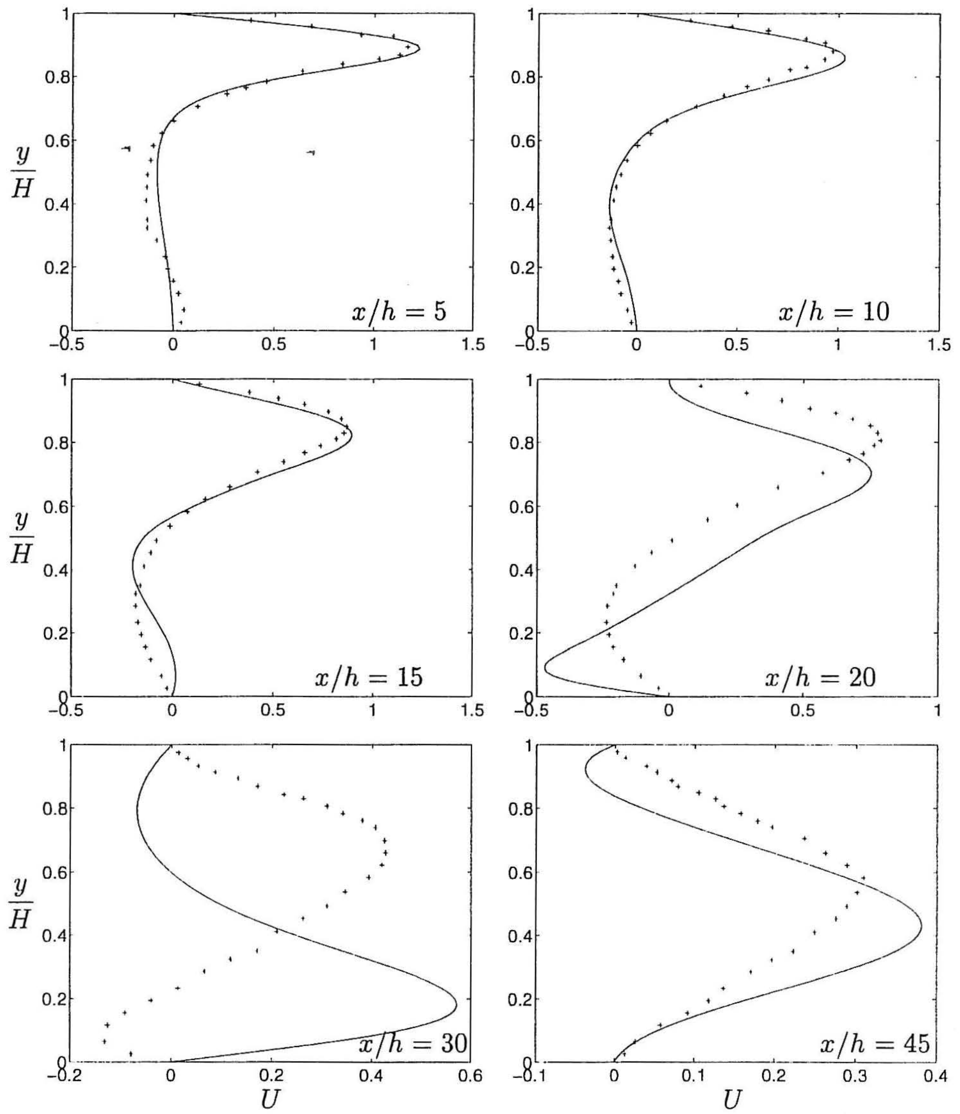


Figure 11: U velocity profiles. QUICK scheme, 160 × 84 cells. Prescribed inlet profiles according to experiments (see Fig. 8 a). Solid lines: predictions; markers: experiments [2]

References

[1] L. Davidson and P. Nielsen. A study of low-Reynolds number effects in backward-facing step flow using large eddy simulations. In *6th Int. Conf. on Air Distributions in Rooms, ROOMVENT'98*, Stockhom, Sweden, 1998. to be presented.

[2] A. Restivo. *Turbulent Flow in Ventilated Rooms*. PhD thesis, University of London, Imperial College of Science and Technology, Mechanical Engineering Department, 1979.

[3] B.F. Armaly, F. Durst, J.C.F. Pereira, and B. Schönung. Experimental and theoretical investigation of backward-facing step flow. *Journal of Fluid Mechanics*, 127:473–496, 1983.

[4] P.T. Williams and A.J. Baker. Incompressible computational fluid dynamics and the continuity constraint method for the three-dimensional Navier-Stokes equations. *Numerical Heat Transfer. Part B*, 29:137–272, 1995.

[5] S. Thangam and D.D. Knight. A computational scheme in generalized coordinates for viscous incompressible flows. *Computers & Fluids*, 18:317–327, 1990.

[6] A. Restivo and J.H. Whitelaw. Instabilities in sudden expansion flows of relevance to room ventilation. In *2nd Int. Symp. on Turbulent Shear Flow, London*, 1979.

PAPERS ON INDOOR ENVIRONMENTAL ENGINEERING

PAPER NO. 49: Kjeld Svidt & Per Heiselberg: *CFD Calculations of the Air Flow along a Cold Vertical Wall with an Obstacle.* ISSN 0902-7513 R9510.

PAPER NO. 50: Gunnar P. Jensen & Peter V. Nielsen: *Transfer of Emission Test Data from Small Scale to Full Scale.* ISSN 1395-7953 R9537.

PAPER NO. 51: Peter V. Nielsen: *Healthy Buildings and Air Distribution in Rooms.* ISSN 1395-7953 R9538.

PAPER NO. 52: Lars Davidson & Peter V. Nielsen: *Calculation of the Two-Dimensional Airflow in Facial Regions and Nasal Cavity using an Unstructured Finite Volume Solver.* ISSN 1395-7953 R9539.

PAPER NO. 53: Henrik Brohus & Peter V. Nielsen: *Personal Exposure to Contaminant Sources in a Uniform Velocity Field.* ISSN 1395-7953 R9540.

PAPER NO. 54: Erik Bjørn & Peter V. Nielsen: *Merging Thermal Plumes in the Indoor Environment.* ISSN 1395-7953 R9541.

PAPER NO. 55: K. Svidt, P. Heiselberg & O. J. Hendriksen: *Natural Ventilation in Atria - A Case Study.* ISSN 1395-7953 R9647.

PAPER NO. 56: K. Svidt & B. Bjerg: *Computer Prediction of Air Quality in Livestock Buildings.* ISSN 1395-7953 R9648.

PAPER NO. 57: J. R. Nielsen, P. V. Nielsen & K. Svidt: *Obstacles in the Occupied Zone of a Room with Mixing Ventilation.* ISSN 1395-7953 R9649.

PAPER NO. 58: C. Topp & P. Heiselberg: *Obstacles, an Energy-Efficient Method to Reduce Downdraught from Large Glazed Surfaces.* ISSN 1395-7953 R9650.

PAPER NO. 59: L. Davidson & P. V. Nielsen: *Large Eddy Simulations of the Flow in a Three-Dimensional Ventilated Room.* ISSN 1395-7953 R9651.

PAPER NO. 60: H. Brohus & P. V. Nielsen: *CFD Models of Persons Evaluated by Full-Scale Wind Channel Experiments.* ISSN 1395-7953 R9652.

PAPER NO. 61: H. Brohus, H. N. Knudsen, P. V. Nielsen, G. Clausen & P. O. Fanger: *Perceived Air Quality in a Displacement Ventilated Room.* ISSN 1395-7953 R9653.

PAPER NO. 62: P. Heiselberg, H. Overby & E. Bjørn: *Energy-Efficient Measures to Avoid Downdraft from Large Glazed Facades.* ISSN 1395-7953 R9654.

PAPER NO. 63: O. J. Hendriksen, C. E. Madsen, P. Heiselberg & K. Svidt: *Indoor Climate of Large Glazed Spaces.* ISSN 1395-7953 R9655.

PAPER NO. 64: P. Heiselberg: *Analysis and Prediction Techniques.* ISSN 1395-7953 R9656.

PAPER NO. 65: P. Heiselberg & P. V. Nielsen: *Flow Element Models.* ISSN 1395-7953 R9657.

PAPER NO. 66: Erik Bjørn & P. V. Nielsen: *Exposure due to Interacting Air Flows between Two Persons.* ISSN 1395-7953 R9658.

PAPERS ON INDOOR ENVIRONMENTAL ENGINEERING

PAPER NO. 67: P. V. Nielsen: *Temperature Distribution in a Displacement Ventilated Room.* ISSN 1395-7953 R9659.

PAPER NO. 68: G. Zhang, J. C. Bennetsen, B. Bjerg & K. Svidt: *Analysis of Air Movement Measured in a Ventilated Enclosure.* ISSN 1395-7953 R9660.

PAPER NO. 69: E. Bjørn, P. V. Nielsen: *Passive Smoking in a Displacement Ventilated Room.* ISSN 1395-7953 R9714.

PAPER NO. 70: E. Bjørn, M. Mattsson, M. Sandberg, P. V. Nielsen: *Displacement Ventilation - Effects of Movement and Exhalation.* ISSN 1395-7953 R9728.

PAPER NO. 71: M. Mattsson, E. Bjørn, M. Sandberg, P. V. Nielsen: *Simulating People Moving in Displacement Ventilated Rooms.* ISSN 1395-7953 R9729.

PAPER NO. 72: H. Brohus: *CFD-Simulation of Personal Exposure to Contaminant Sources in Ventilated Rooms.* ISSN 1395-7953 R9734.

PAPER NO. 73: H. Brohus: *Measurement of Personal Exposure using a Breathing Thermal Manikin.* ISSN 1395-7953 R9735.

PAPER NO. 74: H. Brohus, C. E. Hyldgaard: *The Use of Tracer Gas Measurements in Detection and Solution of Indoor Air Quality Problems in a Danish Twon Hall.* ISSN 1395-7953 R9736.

PAPER NO. 75: C. E. Hyldgaard, H. Brohus: *Detection and Solution of Indoor Air Quality Problems in a Danish Twon Hall.* ISSN 1395-7953 R9737.

PAPER NO. 76: C. Topp, P.V. Nielsen, P. Heiselberg: *Evaporation Controlled Emission in Ventilated Rooms.* ISSN 1395-7953 R9739.

PAPER NO. 77: P. Lengweiler, P.V. Nielsen, A. Moser, P. Heiselberg, H. Takai: *Deposition and Resuspension of Particles.* ISSN 1395-7953 R9740.

PAPER NO. 78: J. Richter Nielsen, P.V. Nielsen. K. Svidt: *Air Distribution in a Furnished Room Ventilated by Mixing Ventilation.* ISSN 1395-7953 R9742.

PAPER NO. 79: P.V. Nielsen: *Design of Local Ventilation by Full-Scale and Scale Modelling Techniques.* ISSN 1395-7953 R9743.

PAPER NO. 80: P. Heiselberg, K. Svidt, H. Kragh: *Application of CFD in Investigation of Ventilation Strategies for Improvement of Working Environment in a Waste Incineration Plant.* ISSN 1395-7953 R9745.

PAPER NO. 81: P. Heiselberg, C. Topp: *Removal of Airborne Contaminants from a Surface Tank by a Push-Pull System.* ISSN 1395-7953 R9746.

PAPER NO. 82: P. Heiselberg: *Simplified Method for Room Air Distribution Design.* ISSN 1395-7953 R9747.

PAPER NO. 83: L. Davidson, P. V. Nielsen: *A Study of Laminar Backward-Facing Step Flow.* ISSN 1395-7953 R9802.

Department of Building Technology and Structural Engineering
Aalborg University, Sohngaardsholmsvej 57. DK 9000 Aalborg
Telephone: +45 9635 8080 Telefax: +45 9814 8243