Appendix CD contents A

This appendix contains a list of the material included on the attached CD.

A.1 Experimental data

Folder containing the results from experimental work. The folder contains following files.

Airflow_distribution.xlsx
Excel file containing air flow over time and velocity occurrences.

Data_treatment_2.5.xlsx
Excel-file containing data treatment of measurements at room height of 2.5 m. Results include velocity and temperature depiction, draught rate, vertical temperature gradients and radiant temperature asymmetry.

Data_treatment_2.5.xlsx
Excel-file containing data treatment of measurements at room height of 4.1 m. Results include velocity and temperature depiction, draught rate, vertical temperature gradients and radiant temperature asymmetry.

Data_treatment_2.5.xlsx
Excel-file containing data treatment of measurements at room height of 4.4 m. Results include velocity and temperature depiction, draught rate, vertical temperature gradients and radiant temperature asymmetry.

DCV_design_chart_cases_1.xlsx
Excel-file containing creation of design charts, similarity principle and pressure difference over ceiling.

A.2 CFD data

Folder containing the results from the CFD work. The folder contains following files and folders.

Case_a___low_room__low_flow (folder)
Folder containing CFD model. The entire folder should be opened in FloVENT to access the model.

Case_b___low_room__high_flow (folder)
Folder containing CFD model. The entire folder should be opened in FloVENT to access the model.

Case_c___high_room__slots (folder)

Folder containing CFD model. The entire folder should be opened in FloVENT to access the model.

Case_c___high_room__diffuse (folder)
Folder containing CFD model. The entire folder should be opened in FloVENT to access the model.

CFD_cases.xlsx
Excel-file containing data treatment of CFD cases including grid independence and comparisons between models.

Kinetic turbulent and dissipation rate.pdf
Calculation of kinetic turbulent energy and dissipation rate of turbulent energy input in CFD models.

B Drawings

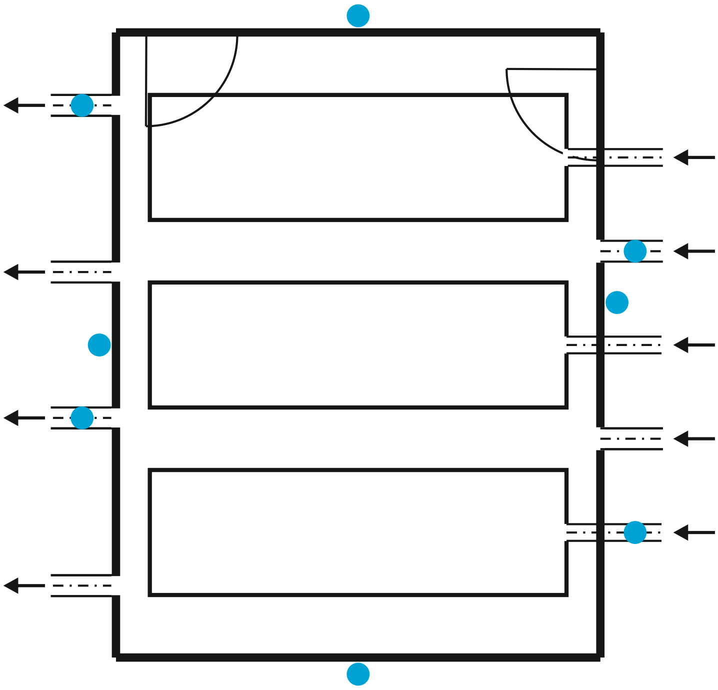


Figure B.1. Position of thermocouples outside test room.

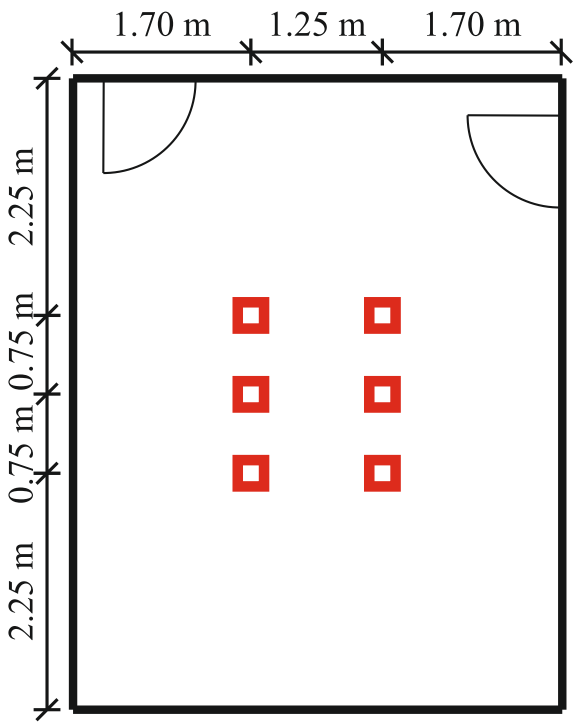


Figure B.2. Heat load distribution 1.

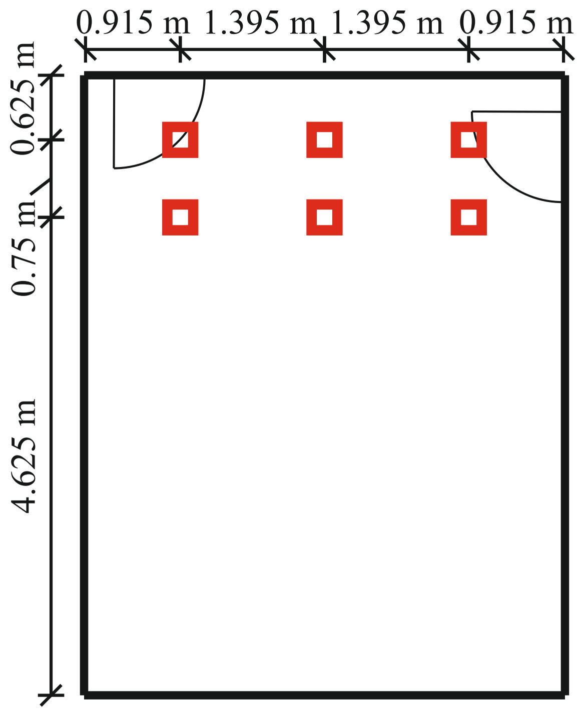


Figure B.3. Heat load distribution 2.

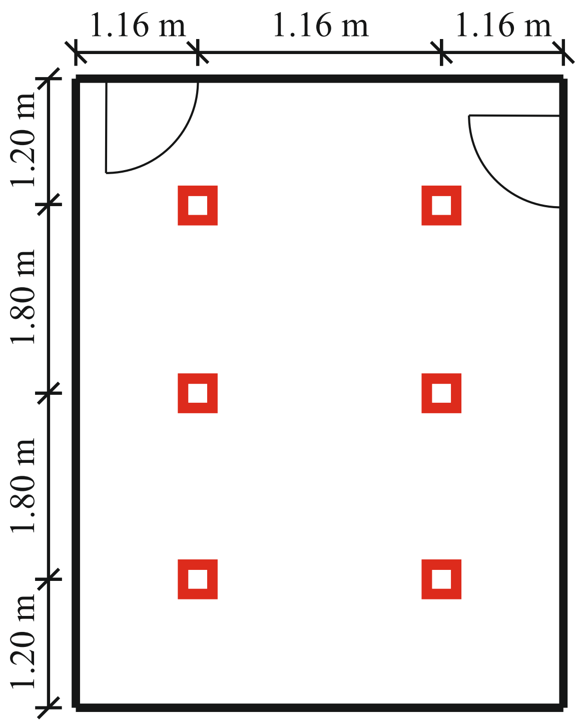


Figure B.4. Heat load distribution 3.

Calibration of anemometers C

This appendix contains a description of the anemometers used to measure air velocity in the experiment. Anemometers of the type Dantec 54R10 were calibrated in a wind tunnel and the process is described in the following.

C.1 Equipment

Following equipment was used for calibrating anemometers:

- Dantec 54R10 hot-sphere anemometers
- Wind tunnel including different orifices
- Micro manometer

C.1.1 Dantec 54R10 hot-sphere anemometers

Hot-sphere anemometers are used to measure velocities in the room during measurements. A picture of an anemometer is shown in figure C.1.

Figure C.1. Dantec hot-sphere anemometer.

The anemometers can be used in the interval 0 to 5 m/s, but for the case of these measurements, only values from 0 to 1 m/s are calibrated, and therefore also a very fine calibration in especially the low regions (<0.2 m/s) is performed. The anemometers are positioned at the end of a wind tunnel in horisontal position, since this is how the velocities are measured in the experiment.

C.1.2 Wind tunnel including different orifices

The wind tunnel which can be controlled by a frequency converter is shown in figure C.2.

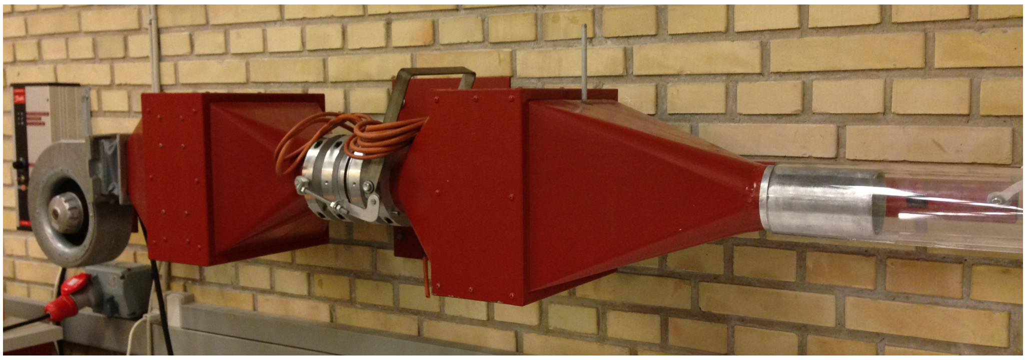


Figure C.2. Wind tunnel.

Dependent on the type of orifice, different equations for velocity was used, see table C.1.

Orifice size [mm]	Δp requirement [mbar]	Velocity [m/s]
10	< 0.5	$v = 14.663 \cdot \Delta p^{0.3878}$
10	> 0.5	$v = 0.157 \cdot \Delta p^{0.485}$
23	–	$v = 0.744 \cdot \Delta p^{0.4516}$

Table C.1. Equations used with different orifices.

When calculating the velocity, the density of the air is taken into consideration, the corrected velocity is calculated from equation C.1.

$$v_{\text{corrected}} = v \cdot \sqrt{\frac{1.2}{\rho}} \tag{C.1}$$

Where ρ is the density of the air calculated from the air temperature, humidity and pressure in the laboratory.

C.1.3 Micro manometer

To measure the pressure difference over the orifices, a micro manometer was used. The same micro manometer was used to measure pressure over the orifices in the large air distribution system when performing measurements. A picture is shown in figure C.3 on the facing page.

Figure C.3. Micro manometer.

C.2 Method

Calibration was carried out using 16 different velocities in the range from 0 to 1 m/s. After a stabilisation time of 60 s, average velocity and corresponding voltage reading from the data logger connected to the anemometer was measured over 60 s. The true velocity was calculated on the basis of the pressure drop over the orifice plate put into the wind tunnel. The calibration values can be found on the Appendix CD.

Calibration of thermocouples D

In order to measure temperature in the experiment, type-k thermocouples are used. They consist of two cables of dissimilar metals. The cables are welded together in one end and exactly in this point the temperature is measured. A schematic drawing of a thermocouple is shown in figure D.1.

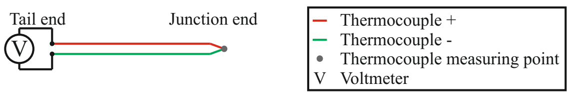


Figure D.1. Scheme of thermocouple.

Due to a temperature difference between the junction and the tail end of the thermocouple a voltage occurs. When the junction end of the thermocouple is either heated or cooled, the voltage difference changes.

D.1 Equipment

Following equipment is used in the calibration of thermocouples:

- Type K thermocouples (both thin and thick)
- Kaye K170 Ice Point Reference
- Compensation box
- Fluke Helios Plus 2287A data logger
- Isocal 6 Venus 2140B
- Precision Thermometer F200

The equipment is described in the following sections.

D.1.1 Type K thermocouples

Two different types of type K thermocouples are used in the experiments. First thin thermocouples which have very low thermal mass. They react very fast to temperature changes and are good for measuring surface temperatures because they are easily connected to a surface with thermal paste. Thick thermocouples are less fast in reacting to temperature changes and also more sensitive to radiative influence for which reason they are polished in silver to reflect as much radiation as possible.

D.1.2 Kaye K170 Ice Point Reference

An ice point reference is an instrument that keeps a reference temperature of 0 °C which is used to have a suitable difference between measured temperatures and a reference. The instrument is shown in figure D.2 on the following page.

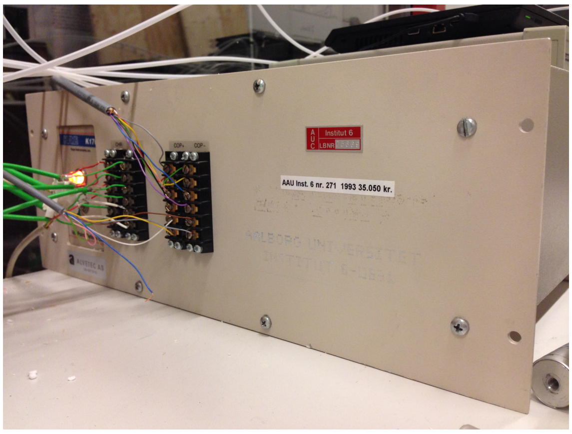


Figure D.2. Kaye K170 ice point reference.

The thermocouples can be used without a compensation box but then all thermocouples have to be connected directly to the ice point reference. When more thermocouples are added, a compensation box is included which acts as an intermediary between the ice point reference and thermocouples.

D.1.3 Compensation box

A compensation box is a box of aluminium where thermocouples are connected to copper cables. A picture of a large compensation box with 100 channels is shown in figure D.3. In this project two small compensation boxes are used.

Figure D.3. Compensation boxes.

The compensation boxes are well insulated to keep the temperature inside as even as possible. This way the thermocouples connected to the ice point reference measures the temperature difference between ice point reference and compensation box, while the thermocouples in the compensation box measure the temperature difference between compensation box and the point in which the junction end of the thermocouple is positioned.

D.1.4 Fluke Helios Plus 2287 A data logger

The data logger is connected to a computer where measured data is logged. Data logger is shown in figure D.4.

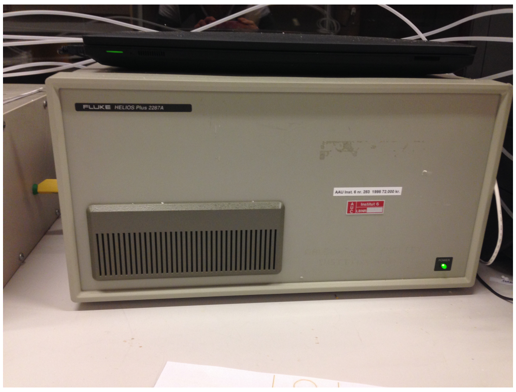


Figure D.4. Fluke Helios data logger.

D.1.5 Isocal 6 Venus 2140B

Isocal 6 is an instrument that is able to keep a very constant temperature over time. The Isocal is shown in figure D.5 and is used to keep the different temperature, at which calibrations are made, constant before measuring.

Figure D.5. Isocal.

Even though the Isocal can keep a constant temperature, it does not measure this temperature very accurately. Therefore a precision thermometer is used.

D.1.6 Precision Thermometer F200

The precision thermometer returns a very accurate temperature and is used to measure the temperature in the Isocal. The precision thermometer is shown in figure D.6 on the following page.

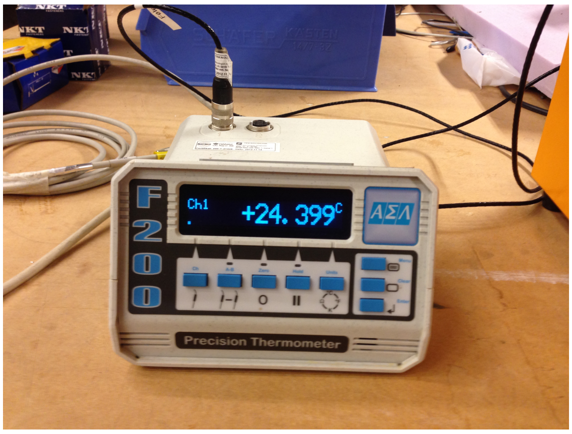


Figure D.6. Precision thermometer.

D.2 Method

The practical method is that the thermocouples are positioned in the Isocal, and the temperature is returned from the precision thermometer. When the temperature is stable, the voltages of the thermocouples measured in the datalogger are logged, so the relationship between voltage and temperature is saved. A principle sketch of the setup is shown in figure D.7

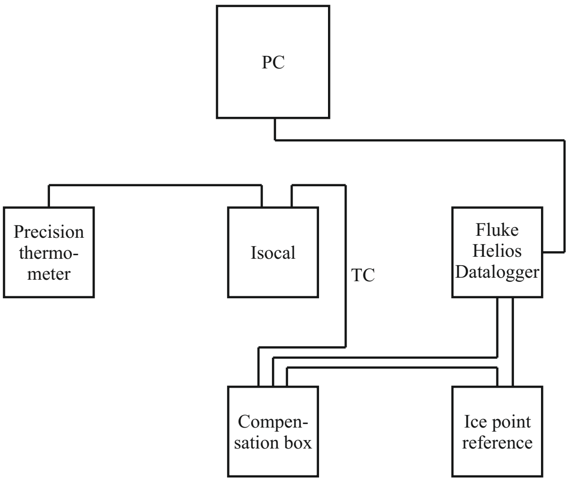


Figure D.7. Principle sketch.

The thermocouples are calibrated in the interval of 5 - 50 °C in five different steps, which are 5.00, 16.25, 27.50, 38.75 and 50.00 °C. At each step the temperature is stabilised for approximately 30 min before measuring the resulting voltages and temperatures. For each thermocouple, a 2$^{\text{nd}}$ order interpolation polynomial is created, which go through all five points.

D.3 Calibration polynomials for thermocouples

The calibration polynomials for references and thin thermocouple are shown in table D.1, while polynomials for thick thermocouples are shown in table D.2.

Channel	Name	Calibration polynomial
0	Ref1a	$(-324955.8714)x^2 + 25431.7735x - 0.3201$
1	Ref1b	$(-299207.2636)x^2 + 25318.4245x - 0.2317$
2	Ref2a	$(-317748.4055)x^2 + 25396.4664x - 0.3170$
3	Ref2b	$(-297732.2983)x^2 + 25302.8949x - 0.2134$
4	01	$(-283213.7342)x^2 + 24954.3914x + 0.0093$
5	02	$(-281017.1540)x^2 + 24974.7207x + 0.0182$
6	03	$(-273810.1080)x^2 + 24968.3561x - 0.0014$
7	04	$(-272590.0592)x^2 + 25028.5170x - 0.0139$
8	05	$(-267888.6485)x^2 + 24933.0907x + 0.0028$
9	06	$(-266230.7269)x^2 + 24956.4811x - 0.0189$
10	07	$(-278226.8756)x^2 + 24965.9996x + 0.0022$
11	08	$(-268534.4287)x^2 + 24995.5143x - 0.0080$
12	09	$(-230039.9559)x^2 + 25036.3169x + 0.0926$
13	10	$(-204561.2028)x^2 + 25100.3472x + 0.1024$
14	11	$(-265969.7981)x^2 + 24865.9509x - 0.0199$
15	12	$(-273132.4881)x^2 + 24861.4062x + 0.0159$
16	13	$(-286323.4788)x^2 + 24988.2489x + 0.0561$
17	14	$(-284084.3480)x^2 + 24827.7474x + 0.0317$
18	15	$(-278484.5210)x^2 + 24938.4786x + 0.0063$
19	16	$(-277323.8041)x^2 + 24846.5339x - 0.0059$
20	17	$(-280658.6949)x^2 + 24953.9615x - 0.0167$
21	18	$(-284842.1185)x^2 + 24950.8754x - 0.0157$
22	19	$(-286858.0319)x^2 + 24966.4716x - 0.0113$
23	20	$(-287751.5833)x^2 + 24954.2016x - 0.0136$
24	21	$(-279071.5754)x^2 + 24987.1463x - 0.0137$
25	22	$(-264133.9302)x^2 + 24928.7735x - 0.0331$
26	23	$(-275303.2652)x^2 + 24970.3966x - 0.0163$

Table D.1. Calibration polynomials for references and thin thermocouples.

Channel	Name	Calibration polynomial
27	24	$(-104583.1790)x^2 + 24536.3312x - 0.0098$
28	25	$(-151731.8937)x^2 + 24871.9057x - 0.0220$
29	26	$(-130510.9248)x^2 + 24712.7907x - 0.0350$
30	27	$(-152119.9869)x^2 + 24819.1528x - 0.0344$
31	28	$(-139681.3498)x^2 + 24726.8008x - 0.0218$
32	29	$(-116160.8609)x^2 + 24544.6057x - 0.0163$
33	30	$(-55679.3865)x^2 + 24548.4516x - 0.0269$
34	31	$(-78928.7207)x^2 - 24718.2339x + 0.1067$
35	32	$(-60134.8349)x^2 - 24529.1617x + 0.1023$
36	33	$(-124839.0786)x^2 - 24700.6782x + 0.1169$
37	34	$(-139331.7226)x^2 - 24706.4808x + 0.1056$
38	35	$(-106598.4454)x^2 + 24550.3214x + 0.0027$
39	36	$(-142001.2769)x^2 - 24712.1861x + 0.1239$
40	37	$(-120387.2070)x^2 - 24694.0838x + 0.1186$
41	38	$(-115785.1065)x^2 - 24679.7626x + 0.1103$
42	39	$(-142854.1286)x^2 + 24585.8078x + 0.0050$
43	40	$(-173008.8856)x^2 + 24911.2908x - 0.0281$
44	41	$(-167765.7031)x^2 - 24663.5694x + 0.1117$
45	42	$(-150674.2987)x^2 - 24740.9617x + 0.1527$
46	43	$(-133275.0058)x^2 - 24721.9730x + 0.1267$
47	44	$(-186670.9144)x^2 + 24842.5514x + 0.0050$
48	45	$(-105167.9735)x^2 - 24658.8728x + 0.1235$
49	46	$(-103329.3067)x^2 + 24536.3447x - 0.0826$
50	47	$(-110133.1943)x^2 - 24840.2102x + 0.1579$
51	48	$(-180141.8847)x^2 - 24608.8724x + 0.1370$
52	49	$(-273052.8079)x^2 - 24949.8639x + 0.1507$
53	50	$(-16554.1537)x^2 + 24578.2102x - 0.0604$

Table D.2. Calibration polynomials for thick thermocouples.

Air distribution system E

The system distributing air to the room through the ceiling is controlled by two frequency converters shown in figure E.1.

Figure E.1. Frequency converters used to control supply and extract flow.

To measure the flow rates two different types of orifices are used, dependent on which parts of the ceiling is used in the air supply. Figure E.2 show for which type of air supply the individual orifices can be used.

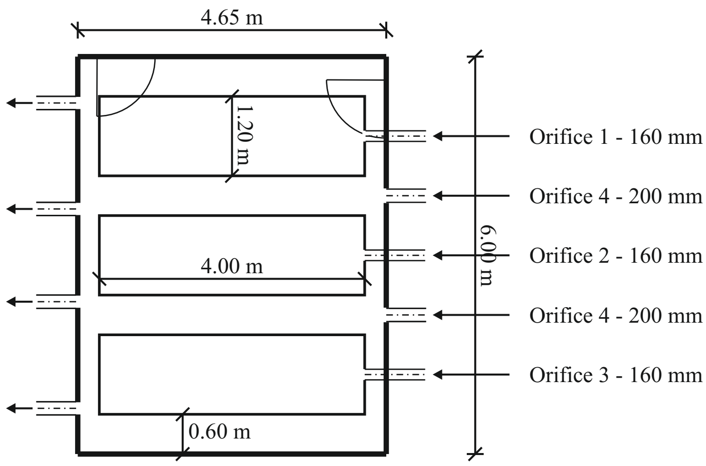


Figure E.2. Two different types of orifices used for measuring the supply flow rate.

The two inlets called “4” meet into one duct so the flow rate only needs to be measured in one position. The equations for the two types of orifices are shown in table E.1 on the following page. Pressure is in Pa.

Orifice size [mm]	Flow rate [m^3/h]
160	$q_v = 33.591 \cdot \Delta p^{0.492}$
200	$q_v = 105.02 \cdot \Delta p^{0.4839}$

Table E.1. Equations used with different orifices.

CFD in FloVENT F

All info in this section comes from [Mentor Graphics, 2012].

Solution method
The differential equations and their associated boundary conditions do not have a general analytical solution and must be solved by use of numerical integration. A typical way for CFD programs including FloVENT is to divide the solution domain into a set of finite control volumes for which the conservation equations are expressed in a purely algebraic form. The finite volumes are generally referred to as grid cells.

Termination residual
Convergence processes in FloVENT is monitored by the residual history of the different variables such as temperature, pressure, x-, y- and z-velocity. The solution will not be converged before all of the variables reach a certain satisfactory value. All residual criteria are from default set to 1 and they are kept this way.

For pressure, velocities and temperature the convergence tolerance, that is, the acceptable total error in a solution for a variable, can be automatically calculated by FloVENT. The acceptable errors are:

- For pressure: 0.5% estimated typical mass flow
- For velocities: 0.5% estimated typical momentum
- For temperature: 0.5% of fixed heat sources

An example of the residual error is the one for temperature. The residual error, RT, is defined as the sum for all grid cells of the absolute values of the error, rT, of the temperature equation for each grid cell, namely:

$$RT = \sum |rT| \tag{F.1}$$

The grid cell error, rT, is the extent to which the temperature in a cell is not satisfied:

$$\begin{aligned} rT = (&C_0T_0 + C_1T_1 + C_2T_2 + C_3T_3 + C_4T_4 + C_5T_5 + C_6T_6 + S) \\ &- ((C_0 + C_1 + C_2 + C_3 + C_4 + C_5 + C_6) \cdot T) \end{aligned} \tag{F.2}$$

When using the entire sum of errors as the total error, when making the grid more dense, likely the individual error on each cell will be smaller, but the sum of errors could be higher. Therefore convergence problems can occur even when making the model more precise.

Turbulence modeling

Turbulence model used is LVEL K-ϵ. The model is described below in the following. This turbulence model defines the turbulent viscosity at each point from two additional variables, the turbulent kinetic energy and turbulent dissipation rate.

The turbulent kinetic energy is calculated from equation F.3.

$$k = 10^{-3} \cdot (u_{\mathrm{avg}})^2 \tag{F.3}$$

Where:

k	Turbulent kinetic energy [J/kg]
u_{avg}	Mean inlet velocity [m/s]

The turbulent dissipation rate is estimated from the turbulent length scale and calculated from equation F.4. [Mentor Graphics, 2012]

$$\epsilon = \frac{0.1643 \cdot k^{3/2}}{l_i} \tag{F.4}$$

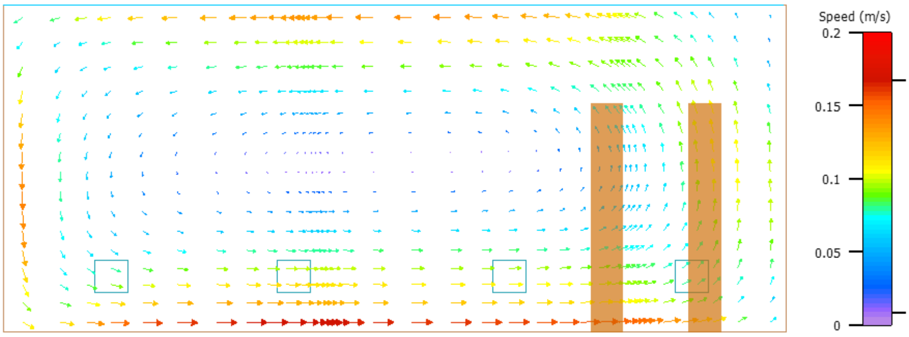
Where:

ϵ	Turbulent dissipation rate [W/kg]
l	Turbulent length scale. $l = 0.1 \cdot (\text{nominal inlet area})^{1/2}$

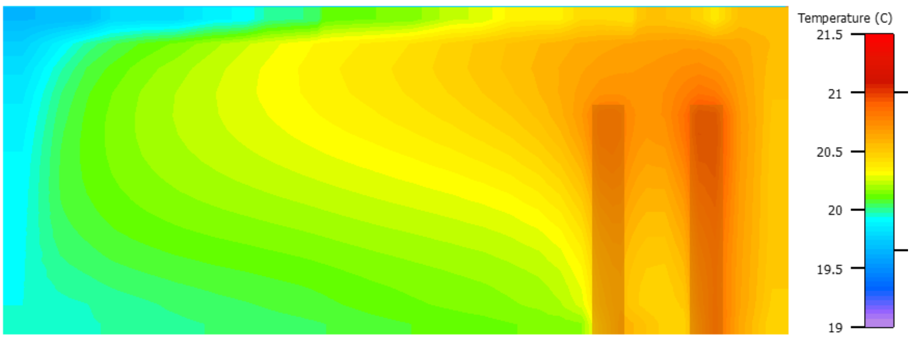
The calculation of each can be found on Appendix CD.

CFD - Grid independence G

Various grid density is tested to see when the model is grid independent. All of the shown solutions converge in steady-state with the error-requirements specified in Appendix F. Figures with different grid density to ensure a grid independent solution are shown in the following. All models are based on the reference model described in section 6.2 on page 60 with applied boundary conditions. The only difference is the grid.

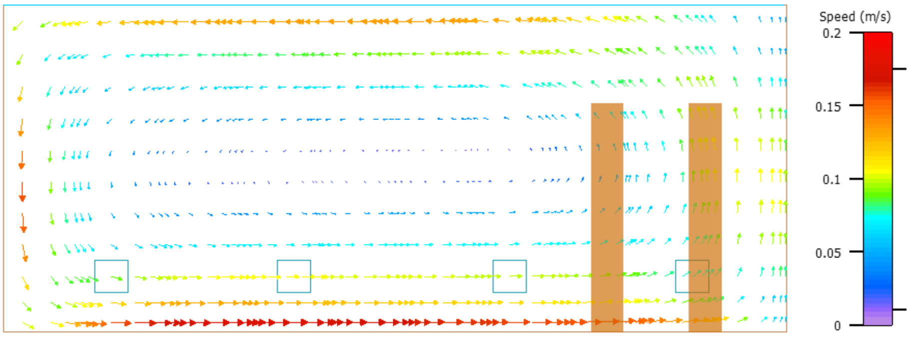


(a) Section, velocity, 19456 cells.

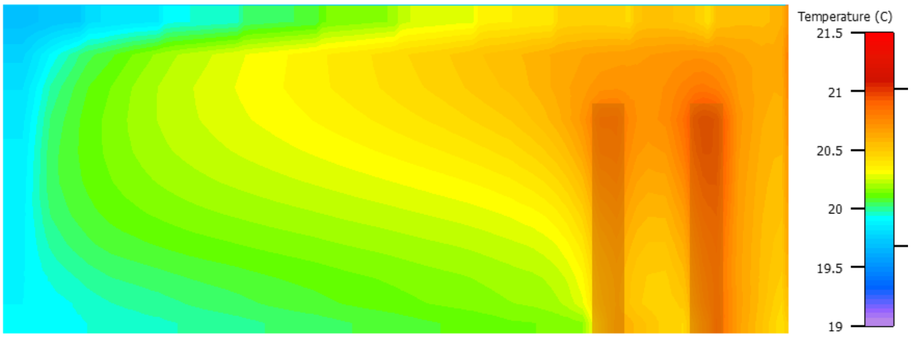


(b) Section, temperature, 19456 cells.

Figure G.1.

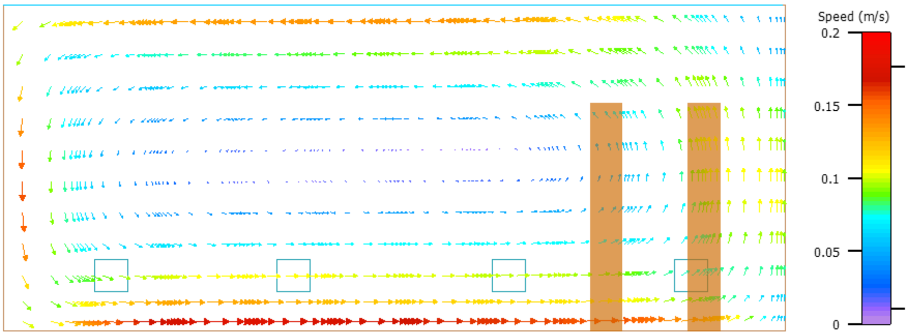


(a) Section, velocity, 35200 cells.

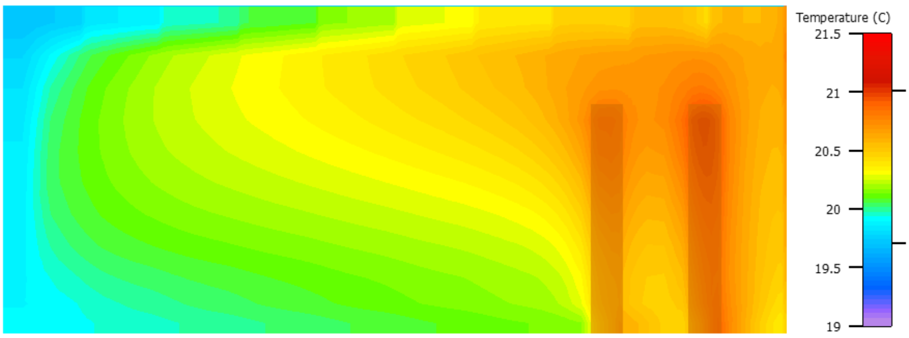


(b) Section, temperature, 35200 cells.

Figure G.2.

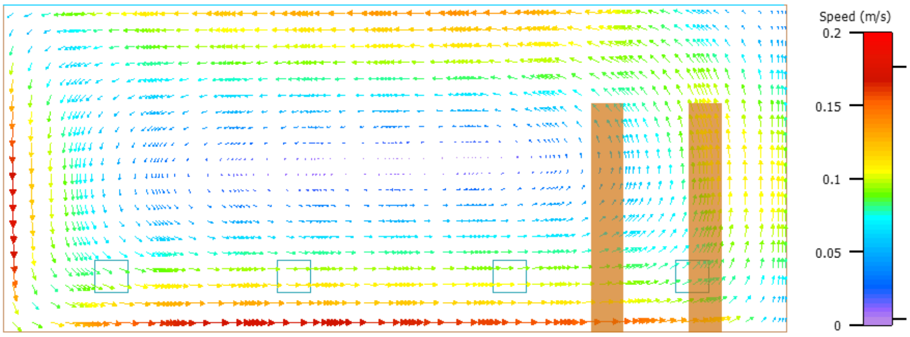


(a) Section, velocity, 64119 cells.

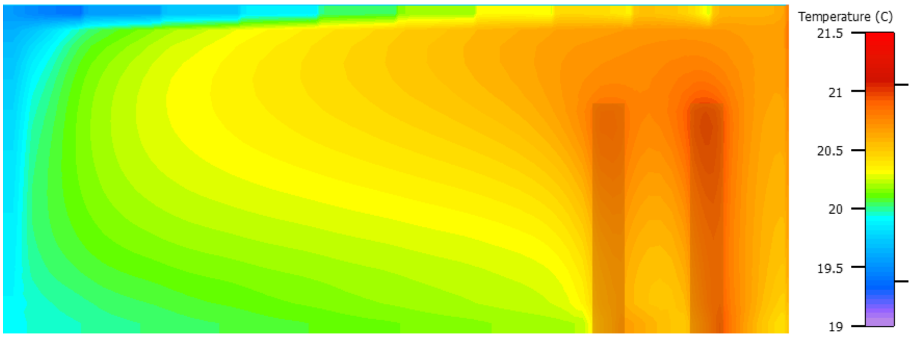


(b) Section, temperature, 64119 cells.

Figure G.3.

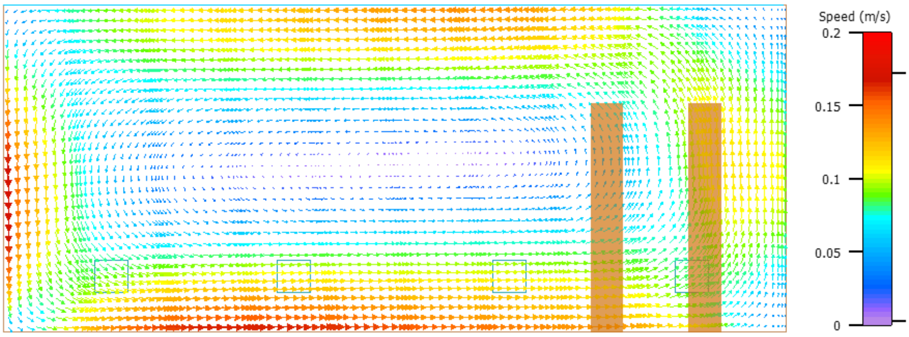


(a) Section, velocity, 126380 cells.

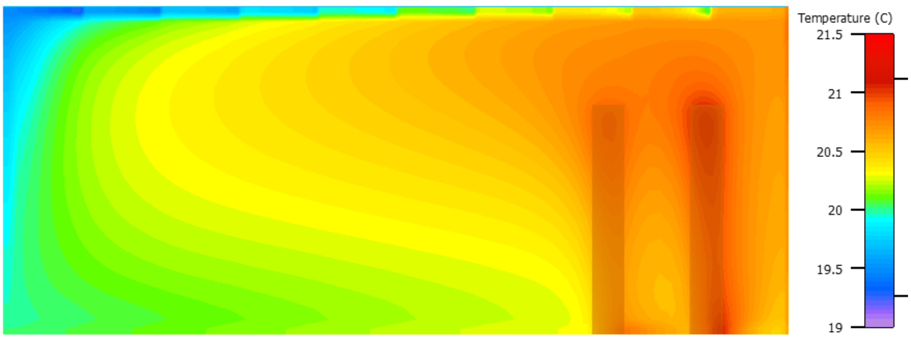


(b) Section, temperature, 126380 cells.

Figure G.4.

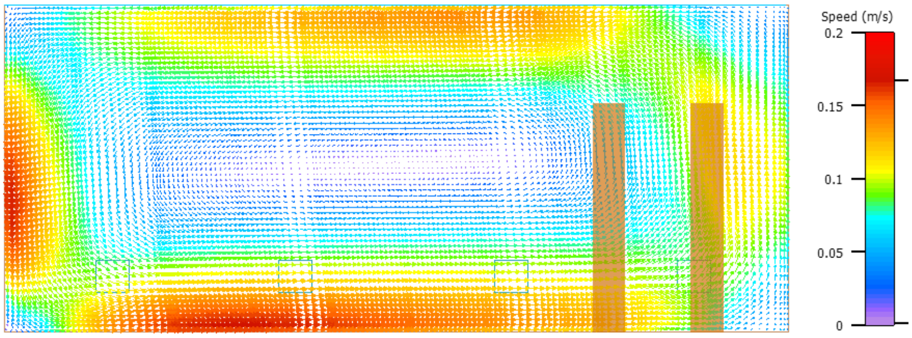


(a) Section, velocity, 247296 cells.

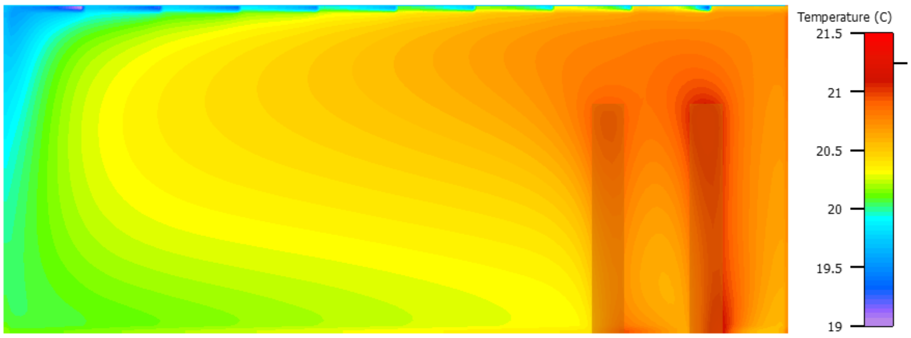


(b) Section, temperature, 247296 cells.

Figure G.5.

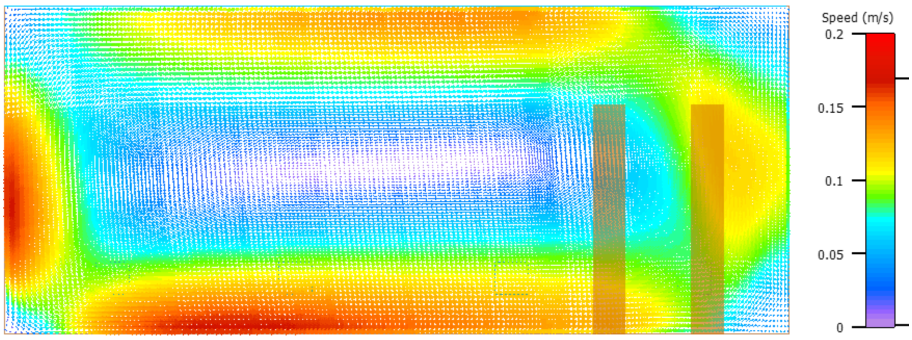


(a) Section, velocity, 617400 cells.

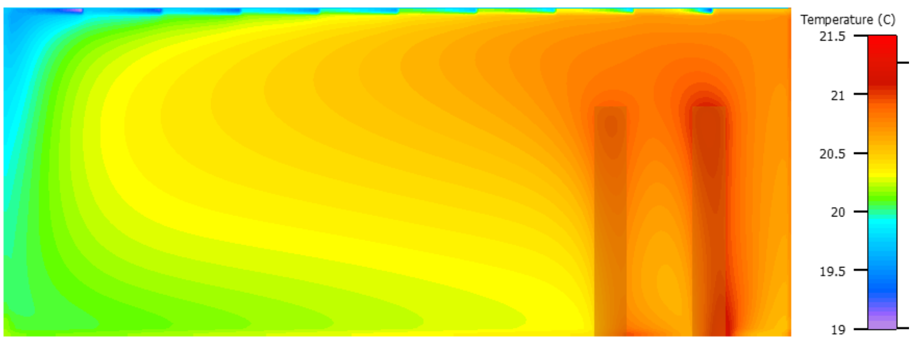


(b) Section, temperature, 617400 cells.

Figure G.6.



(a) Section, velocity, 1289472 cells.



(b) Section, temperature, 1289472 cells.

Figure G.7.