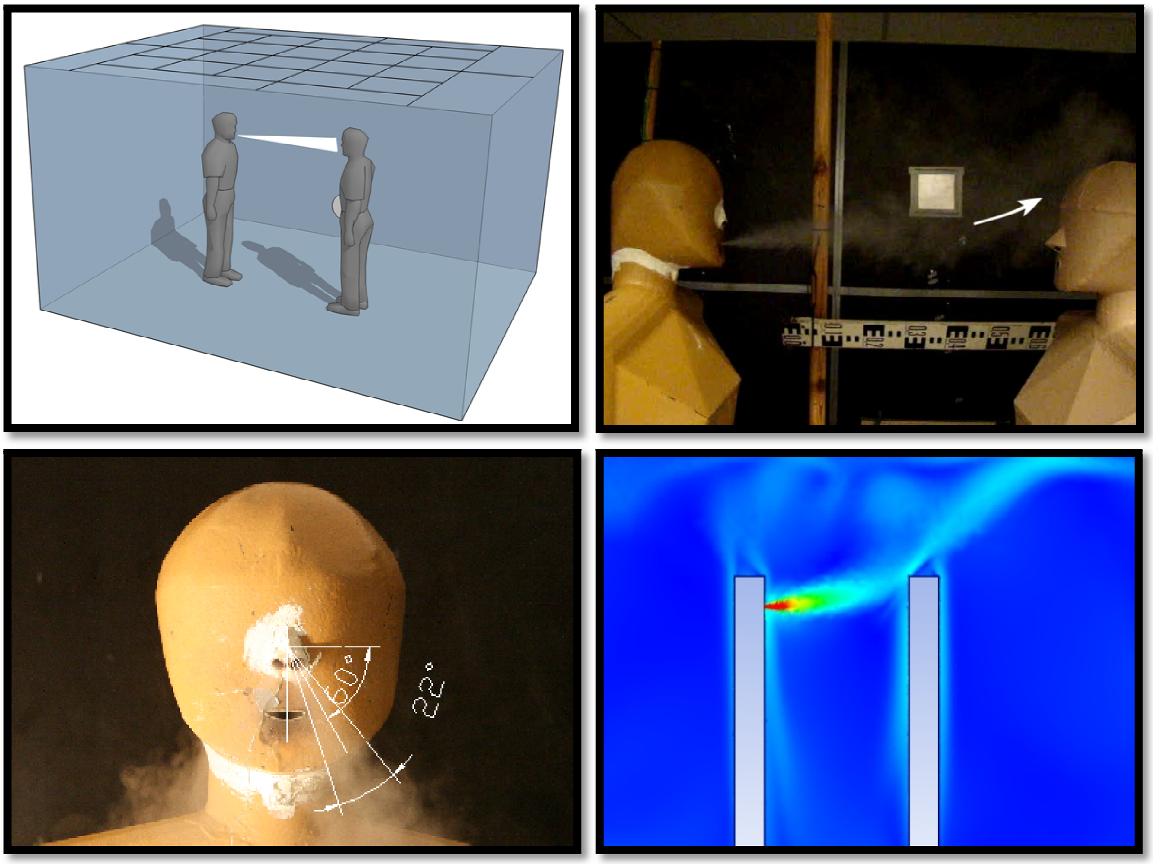
# MICROENVIRONMENT AROUND PEOPLE

## APPENDIX





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# Appendix A – equipment

## A.1. Breathing thermal Manikin

During this project the air quality manikins (AQM) were used

Figure A.1.1. Thermal manikin

Manikin simulates human breathing function so it was important to obtain conditions similar to actual ones i.e. temperature of the manikin surface, temperature of the exhalation air, dimension and shape of the mouths and nose. To obtain these conditions nearing to the real, manikin is equipped with:

- Built inside heater which allows to achieve required heat flux of the manikin. The range of potential used is 0 -220V, which change heat load between 35 W and 145 W and is regulated by a transformer.


Figure A.1.2. Erik Blichfeld type 11.36 transformer

- Additionally, built on the supply pipe air heater allows to achieve an adequate temperature of the exhalation air. The range of potential used is 0 -20V.

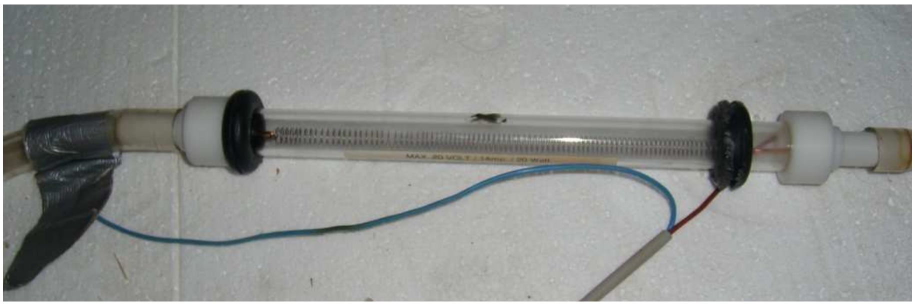

Figure A.1.3. Heater

- Shape and dimensions of the mouths and nose are given as a standard and those values are: field of the mouth is 100mm², field of one nostril is 50mm².
  Manikin have also a possibility to set respiration either through the nose or through the mouth.
- Artificial lungs, which are used to obtain desired expired volume i.c. certain amount of air for an exhalation and respiration frequency. Piston controls volume of exhaled air. Travel of piston can be regulated to change the volume of expired air.

Figure A.1.4. Artificial lungs

## A.2 Temperature

One of aims of this project was to measure temperature gradient inside the house during experiments.

To measure temperatures inside the test room thermocouples were used. Thermocouples allow to measure temperature in the exhaled air, outlet, inlet, surface temperature and temperature gradient.

### A.2.1. Thermocouples

Thermocouples are one of the most widely used temperature sensors and one of the easiest to use as well. Thermocouples are pairs of dissimilar metal wires, which are joined at least at one end.  When the junction of two metals is heated or cooled a voltage is produced that can be correlated back to temperature.

There are many types of thermocouples. Different kind means different combination of metals. However only four, identified by letters K, J, T, E, are mostly used.

In our measurements thermocouples type K (Chrome (+) – Alumel(-)) were used. K-type thermocouple is most commonly used for general purposes as it is inexpensive and available in a range of -40°C to 375°C. Table B.2.5. Shows different colour codes for K-type thermocouples wires.

| Colour code | Chrome (+) | Alumel (-) |
|---|---|---|
| IEC | Green | White |
| DIN | Red | Green |
| BS | Purpule | Blue |
| ANSI | Yellow | Red |

Figure A.2.1. Colour codes for K-type thermocouples wires.

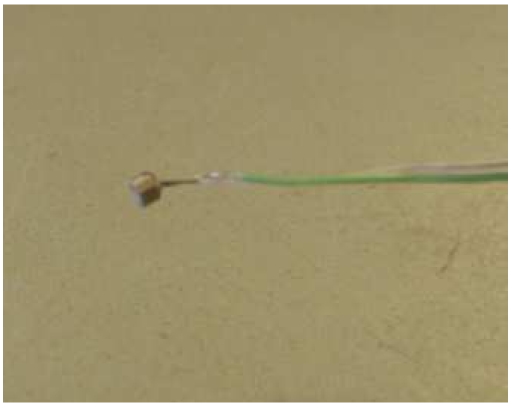

Figure A.2.2. K-type Thermocouple (DIN)

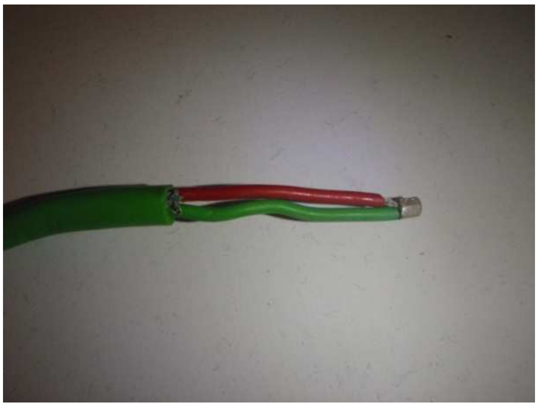

Figure A.2.3. K-type Thermocouple (IEC)

### A.2.2 Data loggers

#### Fluke Helios Plus 2287A data logger

The Helios Plus 2287A is a modular data acquisition system for measuring voltage, current, resistance, temperature etc. 100 channels is available at Helios data logger. The resolution of the data logger is 0.488 μV. Using type K thermocouples this corresponds to about 0.012 K. For all experiments, the data logger was configured to measure with intervals of 60 seconds.


Figure A.2.4. Fluke Helios Plus 2287A data logger     Figure A.2.5. KAYE K170-6 ice point

Instead of using the temperature of the input terminals measured by the thermocouple as reference, an ice point reference can be applied. By definition the temperature of an ice bath made of finely crushed ice and air saturated water is 0 °C, the reference point for most thermocouple tables. In these case KAYE K170-6 ice point was used.

During all experiments, we constantly needed to control exhalation temperature in order to keep it at desired level. Therefore we needed to constantly measure those values. For that purpose a temperature sensor was used.


Figure A.2.6. Temperature sensor

**A.2.3. Calibration**

The temperature measurement were carried out using type K thermocouples. In order to obtain get correct temperature value in the measurements, calibration of thermocouples had to be done.

To calibrate the thermocouples two devices were used:

- Precision thermometer - to obtain real value of temperature

- Temperature calibrator (ISOCAL 6) - this device generates a constant temperature and keeps it at a stable level

Each device is shown in the figure A.2.7:


Figure A.2.7: Temperature calibrator (left), Precision thermometer (right)

The calibration was carried out for three different temperatures ( 10; 20; 30°C). The aim of the calibration was to get calibration curves for thermocouples which corrects the result of the measurements and check if the sensors had linear properties. All sensors were placed in temperature calibrator (maximum 3-4 thermocouples during each calibration). The objective with the use of temperature calibrator is to get constant temperature everywhere near the thermocouple. Temperature inside was measured by precision thermometer and compared with result from the datalogger. With both results a linear expression was made to correct future results.

## A.3. Velocity

### A.3.1. Instruments

**To measure velocity profile of exhalation**

Hot sphere anemometer

Velocity measurements of exhaled air were carried out by hot sphere anemometer DANTEC 54R50 and Dantec Low Velocity Analyzer.


Figure A.3.1. Dantec 54R50 – hot sphere anemometer(left). Dantec 54R50 – Low Velocity Analyzer (right)

Results of measurements are logged by  Lem Servogor 124 pen writer. It records the data as time dependent voltage graph, which is later converted to velocity using calibration curves.

It has two channels . Both of them have 2V range and speed of paper movement can be changed between 1 m/h to 120cm/min.


Figure A.3.2: Lem Servogor 124 pen writer

**To measure velocity distribution in the test room**

Velocity measurements in the test room were made with the use of hot sphere anemometers. There were 14 hot sphere anemometers installed on three stands. Anemometers were connected to Dantec data logger which is shown below.

Figure A.3.3: Dantec datalogger.

### A.3.2. Calibration

According to standards, anemometers were calibrated before velocity measurements.

Calibration was carried out in a wind tunnel. Voltmeter and micro manometer were also used. The voltage was compared to real velocity which is defined by pressure difference over the orifice placed in wind tunnel.

Figure A.3.4.. Debro micro manometer

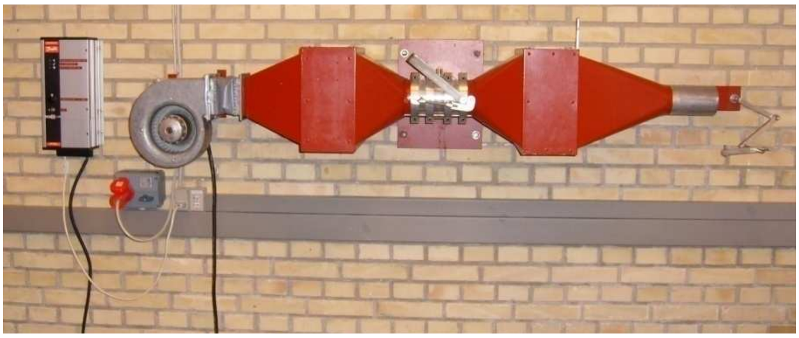

Figure A.3.5. Wind Tunnel


Figure A.3.6. Voltmeter Digimess DM100

## A.4. Smoke visualizations

To show thermal plume and exhalation jet smoke generators were used. An oil-based smoke creates very persistent fog suitable for large applications and it is also safe and non-toxic. Smoke generator is controlled by pilot.

Smoke is supplied to a metal sheet tank. Tubes are then connected between the tank and thermal manikin.

Figure A.4.1. Smoke generator. Figure A.4.2. Metal sheet tank

## A.5. Concentration equipment

During the concentrations measurements special equipment were used to supply tracer gas and to check its concentration in the test room. The concentration equipment is shown below.

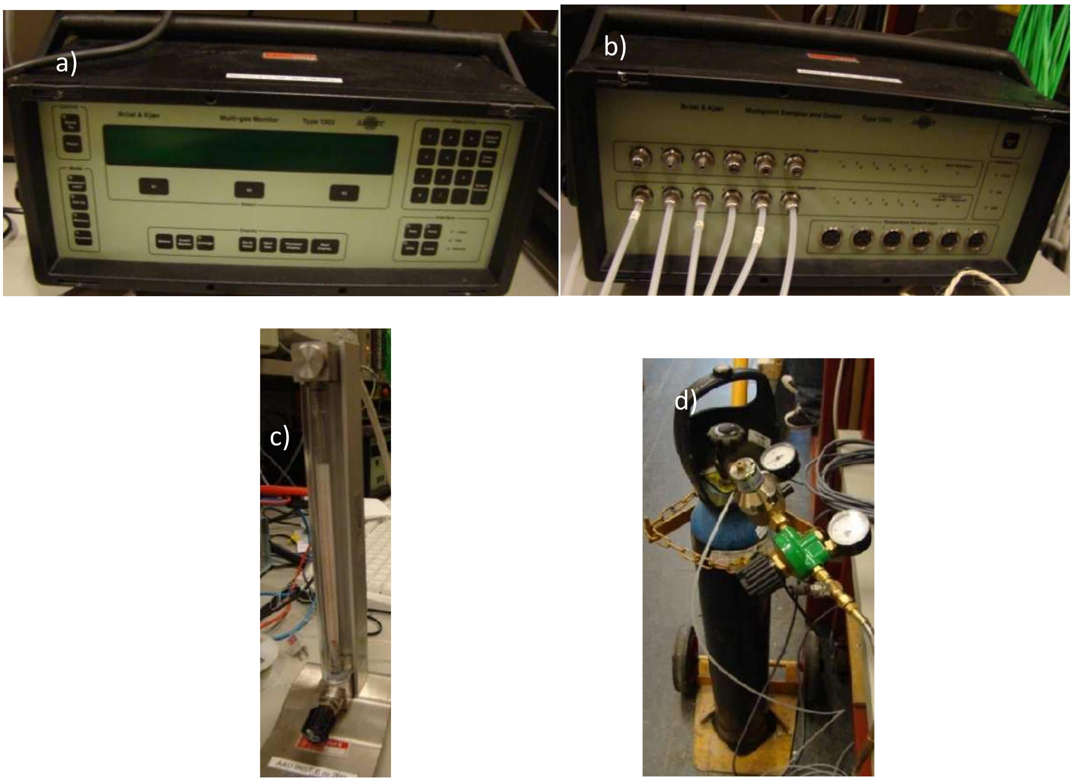

Figure A.5.1: a) Multi Gas Monitor Brüel and Kjær Type 1302; b)Multi Sampler and Doser Brüel and Kjær Type 1303; c) flow meter; d) bottle with traces gas $N_2O$

The tracer gas is supplied to exhalation through flow meter to supply always the same amount of the gas. Multi Sampler and Doser take a air sample and transport the correct amount to the Multi Gas Monitor where sample is tested.

# Appendix B – CFD simulations

## B.1 Governing equations

Fundamental basis of every CFD problem are the Navier-Stokes equations, which define any single-phase fluid flow. They were found by two scientists – a French engineer and physicist Claude-Louis Navier and an Irish mathematician and physicist George Gabriel Stokes. Navier – Stokes equation contains conservation laws as conservation of mass, momentum and energy. It describes state of fluid: temperature, density, pressure and velocity. A fluid particle is considered as a smallest possible element of fluid, and its macroscopic properties are not influenced by other molecules.

Navier – Stokes Equation:

$$\frac{\partial}{\partial t}(\rho u_i) + \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(\mu \frac{\partial u_i}{\partial x_j})$$

Figure C.1.1: Navier – Stokes equation

### B.1.1 Mass conservation in three dimensions

The mass balance for the fluid element:

$$\frac{\partial}{\partial t}(\rho \delta x \delta y \delta z) = \frac{\partial \rho}{\partial t}(\delta x \delta y \delta z)$$

Figure C.1.2: Mass conservation equation

The right hand side of the equation represents a rate of increase of mass in fluid element. It equals to net rate of flow of mass in fluid element.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + div(\rho u) = 0$$

Figure C.1.3: Continuity equation

It means that sum of mass per unit volume and convective term equals to 0. This equation applies to the unsteady, three dimension mass conservation.

### B.1.2 Momentum equation in three dimensions

According to Newton's second law, the rate of change of momentum of a fluid particle equals the sum of the forces on the particle..

There are two different types of forces on fluid particles:

- Surface forces (pressure, viscous forces)
- Body forces (gravity, centrifugal, Coriolis, electromagnetic force)

The x-component of the momentum equation consists of the rate of change of x-momentum of fluid particle. This equals to the total force in x-direction on the element (due to surface stresses) and the rate of increase of x-momentum (due to sources).

$$\rho \frac{Du}{Dt} = \frac{\partial(-p + \tau_{xx})}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + S_{Mx}$$

$$\rho \frac{Dv}{Dt} = \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial(-p + \tau_{yy})}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + S_{My}$$

$$\rho \frac{Dw}{Dt} = \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial(-p + \tau_{zz})}{\partial z} + S_{Mz}$$

Figure C.1.4 Components of momentum equation. A) x – b) y – c) z - component

The source term $S_{Mx}$, $S_{My}$, $S_{Mz}$ contain contributions due to body forces only. To set an example: thanks to gravity body forces would be represented by $S_{Mx} = 0$, $S_{My} = 0$, $S_{Mz} = -\rho g$.

### B.1.3 Energy equations in three dimensions

According to the first law of thermodynamics the rate of change of energy of a fluid particle is equal to the sum of rate of heat addition of a fluid particle and the rate of work done on the particlc. The difference between the rate of heat input across one face and the rate of heat loss across opposite face results in the net rate of heat transferred to the fluid particle (because of heat flow in x-, y-, z-direction). The rate of work done on the fluid particle in the element by a surface force is equal to the product of the force and velocity component in the direction of forcc.

To the energy equation the rate of increase of energy (due to sources) must be added.

$$\rho \frac{DE}{Dt} = -div(pu) + [\frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y} + \frac{\partial(u\tau_{zx})}{\partial z} + \frac{\partial(u\tau_{xy})}{\partial x} + \frac{\partial(u\tau_{yy})}{\partial y} + \frac{\partial(u\tau_{zy})}{\partial z} +$$

$$+\frac{\partial(u\tau_{xz})}{\partial x}+\frac{\partial\left(u\tau_{yz}\right)}{\partial y}+\frac{\partial(u\tau_{zz})}{\partial z}]+div(kgradT)+S_E$$

$$E=i+\frac{1}{2}(u^2+v^2+w^2)$$

Figure C.1.5: The energy equation

**B.1.4 Navier Stokes Equations**

A motion of viscous fluid substances such as liquids and gases is described by these equations. These equations describe that changes in momentum in infinitesimal volumes of fluid are the sum of dissipative viscous forces (similar to friction), changes in pressure, gravity and other forces acting inside the fluid.

$$\rho\frac{Du}{Dt}=-\frac{\partial p}{\partial x}+div(\mu gradu)+S_{Mx}$$

$$\rho\frac{Dv}{Dt}=-\frac{\partial p}{\partial y}+div(\mu gradv)+S_{My}$$

$$\rho\frac{Dw}{Dt}=-\frac{\partial p}{\partial z}+div(\mu gradw)+S_{Mz}$$

Figure C.1.6 Navier – Stokes equation

By means of Newtonian model for viscous stresses in the internal energy equation such version can be developed:

$$\rho\frac{Di}{Dt}=-pdivu+div(kgradT)+\varphi+S_i$$

## B.2. The Turbulence Model Specification

A computational procedure to close the system of mean flow equations is a turbulence model. Because of that different variety of flow may be calculated. CFD deals with different types of turbulence models: algebraic (zero – equation) models, k – ε, RNG k – ε, k – omega, shear stress transport.

**B.2.1 Algebraic (zero equation) model**

This Model does not require the solution of any additional equations and is calculated directly from flow variables. The disadvantage of this model is that for general situations it may be too simplc. On the other hand for simpler flow geometries or in start-up situations it can be quite useful.

**B.2.2 k - ε model**

The K-epsilon model is one of most popular turbulence model. It is a two equation model, that means, it contain two additional extra transport equations to represent the turbulence properties of the flow.

The first transported variable is turbulence kinetic energy. The second one transported variable is the turbulent dissipation ε.

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}[(\mu+\frac{\mu_t}{\sigma_k})\frac{\partial}{\partial x_j}]+P_k+P_b-\rho\varepsilon-Y_M+S_k$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}[(\mu+\frac{\mu_t}{\sigma_\varepsilon})\frac{\partial}{\partial x_j}]+C_{1\varepsilon}\frac{\varepsilon}{k}(P_k+C_{3\varepsilon}P_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon$$

The $K-\varepsilon$ model should be selected for all final calculations for the built environment unless the model is very cluttered with geometry with little open space or is known that the flow is laminar.

### B.2.3 RNG k - ε model

The RNG model was developed using Re-Normalisation Group (RNG) methods by Yakhot et al to renormalise the Navier-Stokes equations, to account for the effects of smaller scales of motion. In the standard k-epsilon model the eddy viscosity is determined from a single turbulence length scale, so the calculated turbulent diffusion is that which occurs only at the specified scale, whereas in reality all scales of motion will contribute to the turbulent diffusion. The RNG approach, which is a mathematical technique that can be used to derive a turbulence model similar to the k-epsilon, results in a modified form of the epsilon equation which attempts to account for the different scales of motion through changes to the production term.

Transport equations

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+P_k-\rho\varepsilon$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial k}{\partial x_j}\right]+C_{1\varepsilon}^*\frac{\varepsilon}{k}P_k-C_{2\varepsilon}^*\rho\frac{\varepsilon^2}{k}$$

where $C_{1\varepsilon}^*=C_{1\varepsilon}-\frac{C_\mu\eta^3(1-\eta/\eta_0)}{1+\beta\eta^3}$

and $\eta = Sk/\varepsilon$ and $S = (2S_{ij}S_{ij})^{1/2}$

### B.2.4 k - omega model

It is one of the most common turbulence models. This model is a two equation model. It includes two extra transport equations to represent the turbulent properties of the flow.

The first transported variable is turbulent kinetic energy, k. The second transported variable in this case is the specific dissipation, ω. It is the variable that determines the scale of the turbulence, whereas k determines the energy in the turbulence.

Kinematic Eddy Viscosity

$$\nu_T = \frac{k}{\omega}$$

Turbulence Kinetic Energy

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \tau_{ij} \frac{\partial U_i}{\partial x_j} - \beta \cdot k\omega + \frac{\partial}{\partial x_j}[(\nu + \sigma \cdot \nu_T)\frac{\partial k}{\partial x_j}]$$

Specific Dissipation Rate

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha \frac{\omega}{k} \tau_{ij} \frac{\partial U_i}{\partial x_j} - \beta \omega^2 + \frac{\partial}{\partial x_j}[(\nu + \sigma \nu_T)\frac{\partial \omega}{\partial x_j}]$$

### B.2.5 SST k-omega model

The SST k-ω turbulence model [Menter 1993] is a two-equation eddy-viscosity. The SST formulation combines the best of two worlds. The use of a k-ω formulation in the inner parts of the boundary layer makes the model directly usable all the way down to the wall through the viscous sub-layer, hence the SST k-ω model can be used as a Low-Re turbulence model without any extra damping functions. The SST formulation also switches to a k-ε behavior in the free-stream and thereby avoids the common k-ω problem that the model is too sensitive to the inlet free-stream turbulence properties.

Kinematic Eddy Viscosity:

$$\upsilon_T = \frac{a_1 k}{\max(a_1 \omega, SF_2)}$$

Turbulence Kinetic Energy:

$$\frac{\partial k}{\partial t}+U_j\frac{\partial k}{\partial x_j}=P_K-\beta^{*}k\omega+\frac{\partial}{\partial x_j}\left[(\upsilon+\sigma_K\upsilon_T)\frac{\partial k}{\partial x_j}\right]$$

Specific Dissipation Rate:

$$\frac{\partial \omega}{\partial t}+U_j\frac{\partial \omega}{\partial x_j}=\alpha S^2-\beta\omega^2+\frac{\partial}{\partial x_j}+\left[(\upsilon+\sigma_\omega\upsilon_T)\frac{\partial \omega}{\partial x_j}\right]+2(1-F_1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i}$$

## B.3 Description of CFX software

First part of conducting simulations was creating a 3D model of the test room and the manikin. This was done in Rhino software. Simulations were conducted in program called CFX.

CFX consists of following parts:

1) Ansys Workbench - a tool where the mesh can be generated. This means that the 3D model is divided into small cells in different shapes (tetrahedrons, prisms, pyramids). The more mesh elements there is generated, the more complex the mesh is and more accurate results can be obtained.
2) CFX – Pre – software for inserting parameters. Thanks to them further calculation may be made. There is a possibility of configuring such parameters as: boundary conditions, turbulence model or kind of heat transfer. Moreover it is possible to configure parameters of CFX – Solver such as maximal iterations number, convergence criteria and etc., which has influence on length and accuracy of calculations.
3) CFX – Solver - program that uses numerical methods and algorithms in calculation obtaining purpose.
4) CFX – Post - the final stage of simulation. It gives the user the power to extract any desired quantitive data from the solution. It also provides a comprehensive set of flow visualization options. What is more it enables mesh quality examination.

For all simulations the 3D models were made in Rhino and afterwards CFD simulations were carried out with CFX.