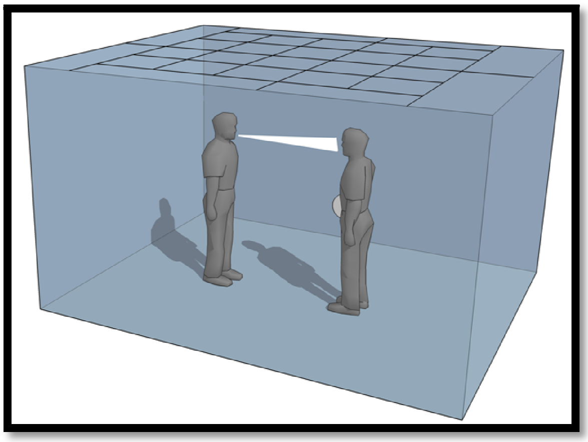
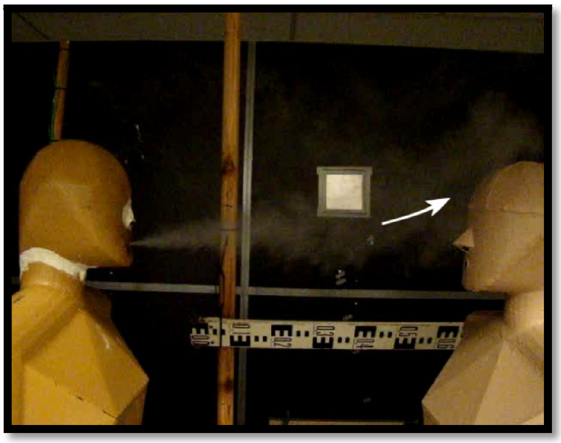
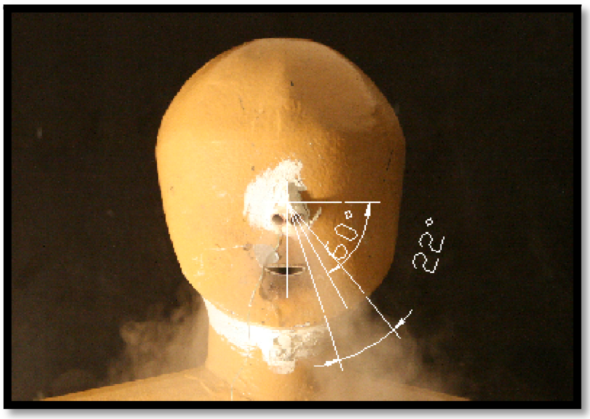
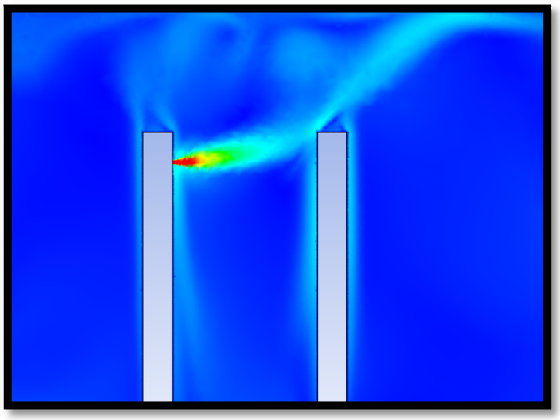
MICROENVIRONMENT AROUND PEOPLE









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Synopsis:

The key case of this report is to characterize the exhalation flow and cross infection in a room with mixing ventilation distribution system. This subject is investigated through several experiments and CFD simulations.

All experiments are conducted in a test room with air distributed by diffuse ceiling inlet, what creates fully mixed conditions inside.

Breathing thermal manikins are used in all of the measurements.

First part of experiments concerns just one manikin and focuses on the exhalation flow. Velocity measurements are done. Moreover, tracer gas is applied to the exhaled air what allows to conduct measurements of concentration.

Second part covers experiments with two manikins. It is investigated how one exhaling manikin affects another one in terms of cross infection.

Moreover, CFD simulations are done to supplement the data.

PREFACE

This report is the documentation of the master thesis "Microenvironment around people" which was done on the final semester of Indoor Environmental Engineering Master Program at the Department of Building Technology and Structural Engineering, Aalborg University from February till June 2010 with Peter V. Nielsen and Rasmus Lund Jensen as supervisors.

We would like to express our gratitude to our supervisor Peter V. Nielsen for his constant support, providing useful information and his engagement in our project.

Also, we would like to thank Rasmus Lund Jensen for introducing us to the laboratory, explaining how to use all the equipment and all his useful tips on the project.

Also we thank Bente Jul Kjargaard for helping as with all paperwork and important information about studying that she provided us with.

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1. INTRODUCTION

Nowadays, a lot of attention is drawn to the subject of airborne diseases. Various measures can be taken in order to prevent the cross infection between people in closed spaces. One of them can be choosing an air distribution system that could work as a way to remove contaminants exhaled by one person before they can affect other people in the room. Most common distribution systems are: mixing and displacement ventilation.

This report focuses on characterizing the cross infection in a room with air distributed by diffuse ceiling inlet what creates fully mixed conditions in the room. Several experiments are carried out to evaluate how this ventilation system works in regards of cross infection.

First part of measurements covers experiments with one thermal manikin. The exhalation jet is examined in order to provide a thorough description of its behavior and to create a mathematical description of velocity and concentration distribution in it.

Second part covers measurements with use of two manikins. It is checked how one exhaling manikin can influence another one in terms of personal exposure.

CFD simulation are also carried out as a way to supplement the results and serve as a comparison for experiments.

By all these measures the subject of cross infection in a mixing ventilated room can be fully described. Moreover, results are compared with previous research that focused on another air distribution system: displacement ventilation. This comparison can lead to conclusions on which system should be used in spaces where there is a need to diminish the effect of cross infection.

2. BACKGROUND

This chapter describes theoretical background that is needed for better understanding of the topic. First two sub-chapter cover the issues concerning breathing functions and heat release from the human body. These information are crucial for this research, because of the use of thermal manikins in the experiments, which can simulate some of the functions of human body.

Next sub-chapter elaborates on coughing. Coughing was meant to be simulated in the experiments, however it turned out to be impossible due to lack of proper equipment.

Last part describes type of air distribution system used during the experiments, which is mixing ventilation, with use of diffuse ceiling inlet.

2.1 Breathing functions

2.1.1 Introduction

‘’Breathing is a complex biological process. Respiration in a man involves three well-defined stages. The first stage is breathing. It comprises inspiration, taking oxygenated air into the lungs, and expiration, discharging air that is rich in carbon dioxide. The second stage involves the transport of oxygen to the cells of the body using the heart and the vascular system. The third stage is called cellular respiration in this stage, oxygen is used in the process of generating energy for physiological activities. ‘’ – Ramya Murthy, Ioannis Pavlidis,[1]. Breathing is an important body function and needs to be very well defined in the process of investigating microenvironment around a human body. This chapter contains literature study about respiration and also comparison between respiration at humans and manikins that are used in further research.

2.1.2 Breathing volume and frequency

There are three basic values connected with breathing that will be discussed further in this chapter. These values are:

- minute volume (MV), which is a total amount of air inhaled and exhaled by a person during one minute [l/min]
- tidal volume (TV), which is amount of air inhaled and exhaled during single breath [l]
- respiration frequency (RF), which is a number of breath in one minute [1/min]

These three values can vary vastly depending on many factors. Most important of them are: metabolic rate, gender and body surface area.

In paper made by Qingyan Chen et al. [2], a very thorough study is made on respiration at subjects at sitting position. The amount of exhaled air and breathing frequency are defined by separate formulas for men and women.

Minute volume is a function of body surface area and is described by formulas below:

$$MV_{male} = 5{,}225 \cdot A_d \left[\frac{l}{min}\right]$$

$$MV_{female} = 4{,}634 \cdot A_d \left[\frac{l}{min}\right],$$

where:

A_d – body surface area [m^2], which can be obtained according to subjects weight and height. According to DuBois and DuBois [3] it equals:

$$A_d = 0{,}202 \cdot W^{0{,}425} \cdot H^{0{,}725}$$

where:

W – mass of a person [kg]
H – height of a person [m]

Respiration frequency is mostly dependent on height of a subject. For men also some correlation with weight is found:

RF for males:

$$RF_{in} = 55{,}55 - 32{,}86 \cdot H + 0{,}2602 \cdot W$$

$$RF_{out} = 77{,}03 - 45{,}42 \cdot H + 0{,}2373 \cdot W$$

For females:

$$RF_{in} = 46{,}43 - 18{,}85 \cdot H$$

$$RF_{out} = 54{,}47 - 25{,}48 \cdot H$$

RF_{in} stands for inhalations and RF_{out} for exhalations. Also, an average flow while reading is described. It can be used in experiments to simulate a talking person.

$$\text{Avg. flow rate} = (9{,}7 \pm 0{,}7) \cdot 10^{-2} \cdot A_d\ [l/min]$$

$$\text{Avg. flow rate} = (8{,}9 \pm 0{,}1) \cdot 10^{-2} \cdot A_d\ [l/min]$$

An average European male has a body surface area of 1,8 m^2, while average European female 1,6 m^2[4]. For these subjects, minute volume and respiration frequency would equal:

For men:	A_d=1,8 m^2	For woman:	A_d =1,6 m^2
	MV=9,41 l/min		MV=7,41 l/min
	RF_{in}=16,92 min^{-1}		RF_{in}=16,3 min^{-1}
	RF_{out}=15,06 min^{-1}		RF_{out}=13,7 min^{-1}
	talking flow=10,476 l/min		talking flow = 8,544 l/min

This study is very thorough, however it deals only with a case of a sitting person. It is also important to investigate what happens under higher metabolic rate, i.e. when person is walking or performing some light work. A study on this was made by William C. Adams [5], who measured MV and RF in several daily activities. Table below presents summary of this research:

men				woman			
activity	Met.	MV	RF	activity	Met.	MV	RF
[-]	[met]	[l/m]	[br/m]	[-]	[met]	[l/m]	[br/m]
lying	nd.	7,12	14,4	lying	nd.	8,93	13,2
sitting	1	7,72	15,2	sitting	1	9,3	13,8
standing	1,2	8,36	15	standing	1,2	10,65	14,3
walking 4 km/h	2,5	19,23	21,7	walking 4 km/h	2,5	22,79	17,7
walking 4,8 km/h	nd.	23,81	25,9	walking 5,3 km/h	nd.	26,78	19,4
running 6,4km/h	nd.	50,44	145	walking 6,4km/h	3,8	35,56	21,9
running 7,2km/h	nd.	48,89	156	driving a car	1,0-2,0	10,79	16,8
driving a car	1,0-2,0	8,95	17,4	woodworking	1,8	24,42	22
housework	2,0-3,4	17,47	21,9	car maintenance	nd.	23,21	23
yard work	nd.	19,4	22,4	mowing	nd.	36,55	24
				yard work	nd.	26,07	21,1

Figure 2.1.1: Minute volume and respiration frequency for men and women performing different activities.

Both the minute ventilation and respiration frequency rise significantly with higher activity levels. These values can equal even up to 50,44 l/min and 156 breathes per minute at very high activity level. Also, we can see that in sitting position results are similar to those discussed before. Based on these values, a relationship can be found out, between metabolic rate and breathing functions:

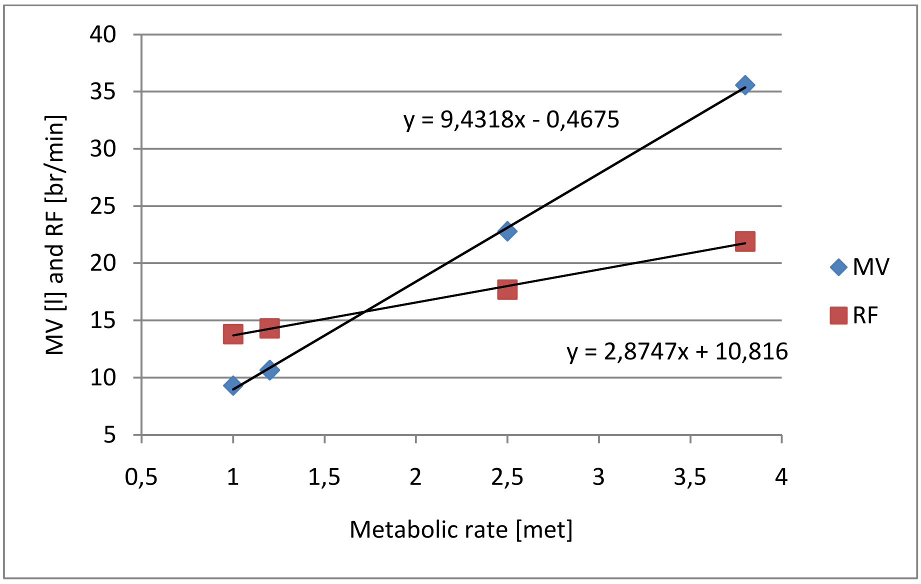


Figure 2.1.2: Minute volume and respiration frequency for men

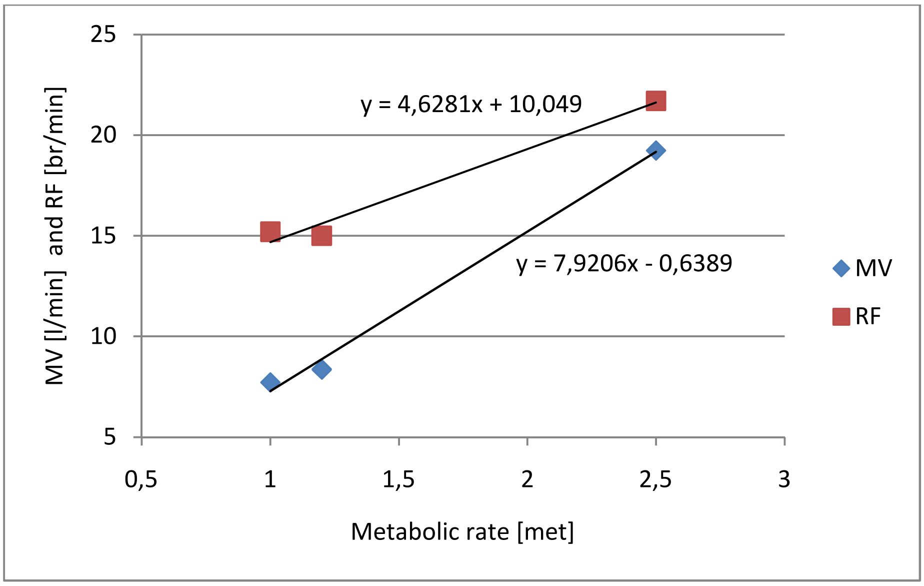


Figure 2.1.3: Minute volume and respiration frequency for woman

Equations presented on the graphs can be further used for artificial lungs connected to the manikin and in CFD simulations. Thus, it will be able to simulate a person under varying activity level.

Also, a formula has been developed by Ole Fanger [3] to estimate pulmonary rate:

$$\dot{m}_{res} = K_{res} \cdot M \cdot A_d$$

where:
m_{res} – pulmonary ventilation rate [kg/s]
K_{res} – proportionality constant, equals $1{,}43 \cdot 10^{-6}$ [kg/J]
M – metabolic rate [W/m^2]

When discussing frequency of breathing, also the ratio between respiration stages has to be considered. The process of breathing can be divided into three phases: inspiration, expiration and pause. Ratio between those stages is 1:1:0,5 (Inspiration : Expiration : Pause) respectably, what can be seen on figure 2.1.4.

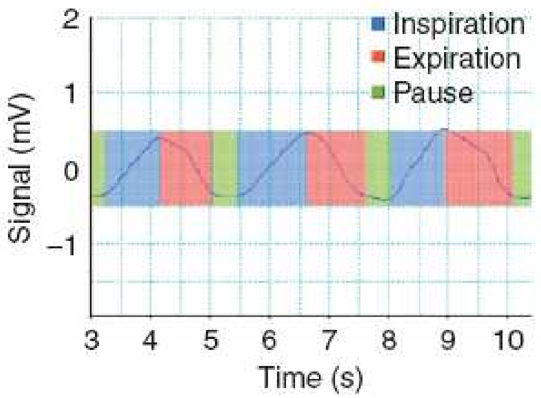


Figure 2.1.4: Output showing three breathing phases during quiet breathing [1]

The x axis shows output from a measuring device, showing the three breathing phases during quiet breathing.

2.1.3 Geometry of exhalation

Geometry of respiration can be defined by describing angles of exhalation jet and also area of mouth and nose when breathing.

Humans can breathe in two ways: either through the nose or the mouth. Usually humans breathe through the nose which is a biological air conditioner and also it helps to purify air from contaminants like large dust particles. [5] Breathing through the nose results in a downward airflow profile. However breathing through the mouth is different and the airflow profile is horizontal. Visualization of breathing and also all interesting angles are shown on figures below:

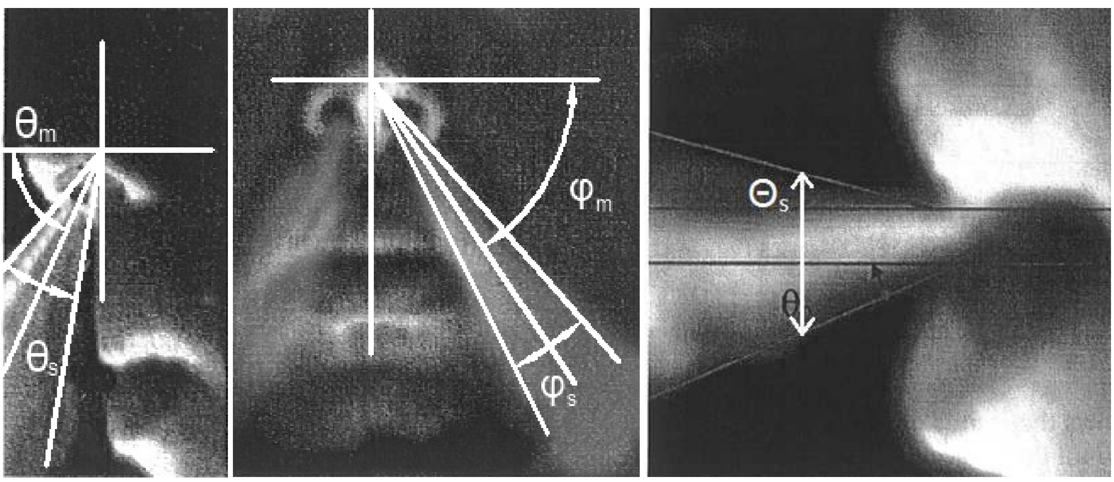


Figure 2.1.5: Breathing through the nose and mouth at human subjects

All of the angles shown above are described in [2]. Some of these angles in thermal manikin are standardized by AAU and DTU – it is stated that jet should be inclined at 45˚ when exhaling trough nose and that angle between jets should equal 30˚. To check additional angles and compare them with those found in literature, smoke simulations have been made. Results of smoke simulations can be seen on figure below:

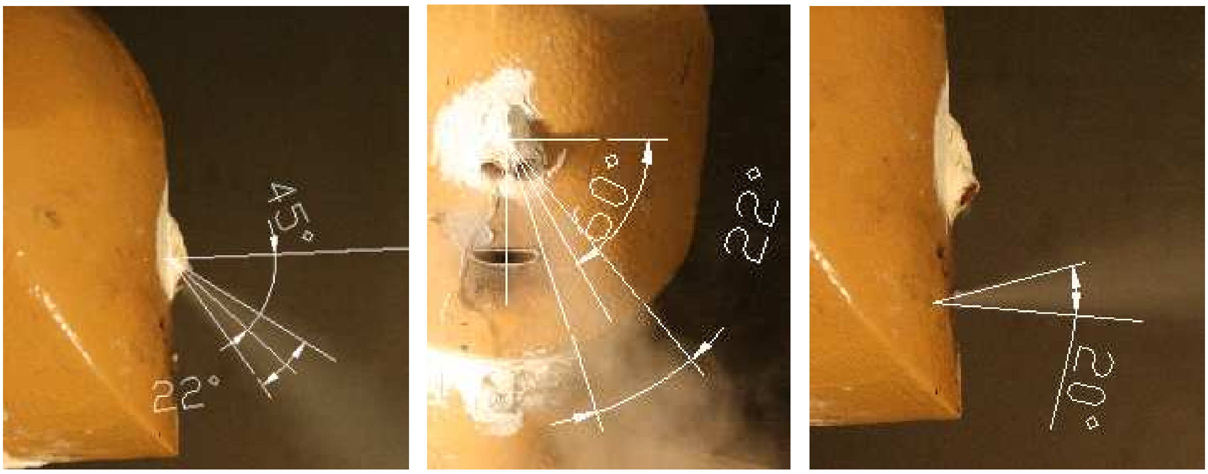


Figure 2.1.6: Exhalation through the nose and mouth for manikin

All angles have been compared. Table below presents the results:

angle	description	human	manikin
θ_m	mean side angle	60±6˚	45˚
φ_m	mean front angle	69±8˚	60˚
θ_s	front spreading angle	23±14˚	22˚
φ_s	side spreading angle	21±10˚	21˚
θ_s^m	front spreading angle (mouth)	30˚	20˚

Figure 2.1.7: comparison between exhalation jet angles at human subjects and manikin

The manikin provides quite satisfactory exhalation jet, however there are some major differences. Mean side angle for respiration through the nose is significantly smaller than at human subjects. This causes the jet to be more horizontal, and human boundary layer may have a smaller effect on its flow.

Mean front angle is not extremely far from reality though and both spreading angles are almost identical as in real exhalation. Exhalation through the mouth shows quite large difference in shape of the jet as well.

This experiment shows that exhalation jet created by the manikin resembles the actual one, but it should be noted that there are some differences that should be considered in experiments.

The area of the mouth and nose is also an important factor. Table below presents values according to [2] and also area of those openings in thermal manikin – measured and according to standards.

	male	female	manikin (measured)	manikin (standards)
mouth [cm^2]	1,20 ± 0,52	1,16 ± 0,67	0,94	1,00
nostril [cm^2]	0,731 ± 0,23	0,56 ± 0,10	0,50	0,50

Figure 2.1.8: Area of mouth and nostril at human subjects and manikin

Area of the mouth and nose of the manikin shows some differences as well and are slightly smaller than those measured at human subjects. However they can be considered correct, since measurements on human subjects show fairly large uncertainty.

While talking, area of mouth equals 1,8 ± 0,03 cm^2 for men and woman. In this case, manikins mouth is not a good representation of reality.

2.1.4 Temperature and composition of exhaled air

The air that one inspires and expires is a mixture of gases as it is shown in table 2.1.9. The most important of these are nitrogen, oxygen, carbon dioxide and water vapor.

Gas	Inspired air (%)	Expired air (%)
Nitrogen	78	78
Oxygen	21	16
Carbon dioxide	0.03	5
Water vapor	Varies	Saturated

Table 2.1.9: Contents of the air of inhalation and exhalation

The temperature of exhaled air may vary in function of ambient air temperature, as shown on figure 2.1.10. It also changes, depending on the way of breathing. Exhalation through mouth provides more stable temperature. [6]

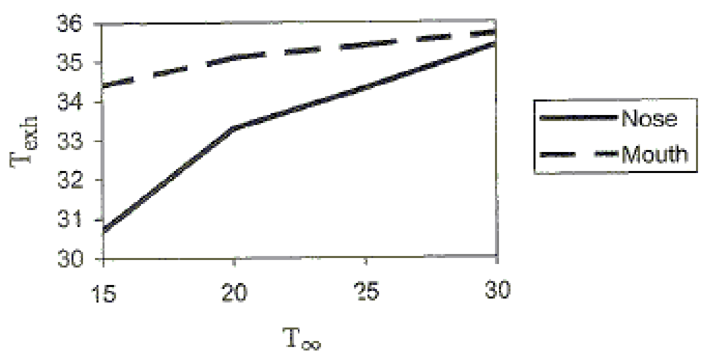


Figure 2.1.10: Temperature of expired air as function of ambient temperature [6]

Since the air used in experiments is normal atmospheric air taken from laboratory and is not saturated, it will have different density than actual exhaled air. This changes its density and thus affects buoyancy. Tracer gas is used in some experiments, what also has some effect on density. Because of this, corrections need to be made while setting the exhaled air's temperature. Figure below presents how temperature should be corrected.

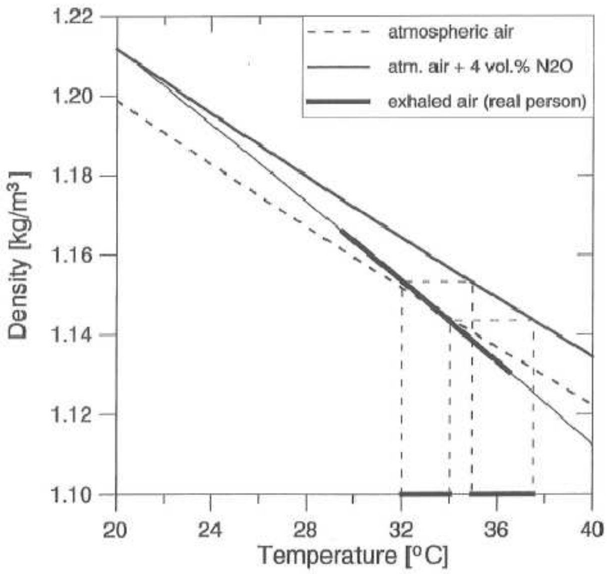


Figure 2.1.11: Influence of water vapour on density of exhaled air [7]

For example, if one wishes to simulate exhaled air at 32 ˚C using dry atmospheric air containing tracer gas N_2O , exhaled air temperature in experiments should be 35˚C.

2.2 Heat flux and breathing functions

Heat generated by a human body is also an essential part of microenvironment around people. This chapter discusses heat flux from a person under varying activity levels. This data will be further used for controlling a thermal manikin so that it imitates a human body and also for CFD simulations.

Heat created inside the human body has to be dissipated to the environment so the body maintains proper temperature. Heat losses occur through skin (by radiation and convection), respiration and evaporation (sweat). The amount of heat generated by a person depends mostly on activity level. A unit that describes metabolic level is 1 met, which stands for a metabolic rate for a sedentary person. 1 met equals 58,1 W/m^2 of body surface area. Table below presents typical metabolic heat flux for various activities. Also, data about breathing functions is put into this table, so it contains of full information about human body functions under varying activity levels.

			men		woman	
Activity	Metabolic rate	Metabolic rate	Minute Volume	Breathing Frequency	Minute Volume	Breathing Frequency
[-]	[W/m2]	[met]	[l/min]	[1/min]	[l/min]	[1/min]
RESTING						
Sleeping	40	0,7	6,1	12,8	4,9	13,3
Seated	60	1	9,0	13,7	7,3	14,7
Standing	70	1,2	10,9	14,3	8,8	15,6
WALKING						
3,2 km/h	115	2	18,4	16,6	15,2	19,3
4,3 km/h	140	2,5	23,1	18,0	19,1	21,6
6,4 km/h	220	3,8	35,4	21,7	29,4	27,6
OFFICE ACTIVITIES						
Reading, seated	55	1	9,0	13,7	7,3	14,7
Writing	60	1	9,0	13,7	7,3	14,7
Typing	65	1,1	9,9	14,0	8,1	15,1
Walking about	100	1,7	15,6	15,7	12,8	17,9
Lifting/packing	120	2,1	19,3	16,9	16,0	19,8
MISCELLANEOUS ACTIVITIES						
Cooking	95-115	1,6-2,0	14,6-18,4	15,4-16,6	12,0-15,2	17,4-19,3
Housework	115-200	2,0-3,4	18,4-31,6	16,6-3,4	15,2-26,2	19,3-25,8
Sawing (table saw)	105	1,8	16,5	16,0	13,6	18,4
Driving a car	60-115	1,0-2,0	9,0-18,4	13,7-16,6	7,3-15,2	14,7-19,3
Handling 50 kg bags	235	4	37,3	22,3	31,0	28,6

Figure 2.2.1: Body functions for various activities

The purpose of the thermoregulation system in the human body is to maintain constant temperature inside. Over a long time it can be assumed that heat production inside the body equals dissipation. For this assumption, a heat balance is shown [8]:

$$H - D - S_w - R_w - R_d = K = R + C$$

where:
H – internal heat production in the human body
D – heat loss by water vapor diffusion through the skin
S_w – heat loss by evaporation of sweat from the skin
R_w, R_d – latent and dry respiration loss
K – heat transfer from the skin to the outer surface of the clothed body
R, C – heat loss by radiation and convection from the outer surface of the clothed body

Metabolic rate, M is in some cases partly converted into external work - W, but mostly it is completely converted into internal body heat, H:

$$M = H + W$$

Mechanical efficiency describes dependency between H and W:

$$\eta = \frac{W}{M}$$

Therefore:

$$M(1 - \eta) - D - S_w - R_w - R_d = K = R + C$$

When considering the heat load used in experiments, for manikin or CFD model, only heat loss by radiation and convection need to be taken into account. Heat loss by evaporation does not result in heat flux, but in phase transition of water into vapor. Respiration loss is also not included, since it is simulated by breathing functions of the manikin.

To find proper heat load for use in simulations, either R and C need to be found or evaporative and respiration heat loss deducted from metabolic rate found in the table.

Heat loss by radiation and convection can be calculated from equations developed by Fanger, however it is this solution is difficult due to complexity of these calculations (radiation especially). However, some values can be found in literature [9]:

Metabolic rate	Convection	Radiation	Evaporation
Low activity (60 W/m2)	35%	35%	30%
Moderate activity (115 W/m2)	30%	30%	40%
High activity (175 W/m2)	30%	15%	55%

Figure 2.2.2: Heat release from the human body by means of convection, radiation and evaporation

Table above presents data for a person with clothes representing 1,0 clo in thermal comfort. When activity level is low, total heat loss is almost equally distributed among the three ways of heat exchange. Heat dissipation by evaporation increases significantly with metabolic rate. Convection does not change drastically, however the part of heat lost by radiation is very small at high metabolic rates.

Heat transfer from the body is only the sum of convection and radiation. In case of low activity level it equals 70%, moderate activity - 60% and high activity – 45% of metabolic level.

2.3 Conclusions on heat flux and breathing functions.

For the experiments in laboratory and simulations in CFD some decisions need to be made upon the manikins sex, metabolic rates and breathing functions.

- Since the manikin in its size (1,7m high) and figure resembles rather a female, than a male, it is decided that it will have body functions of a woman.
- Body surface area will thus equal 1,6 m^2 (average value for a female).
- Temperature of exhalation should equal 38˚C
- Two metabolic rates are chosen: standing and walking 3,2 km/h (manikin will not be actually walking, it will represent a person that was walking and just stopped).
- Manikin will exhale through the mouth, and in some experiments through the nose, but for expiration through the nose, angles will be corrected

Table below presents body functions for two activity levels chosen for research:

	Standing (low activity)	Walking (high activity)
Metabolic rate [met]	1,2	2
Metabolic rate [W/m^2]	70	115
Body surface area [m^2]	1,6	
Metabolic rate [W]	112	184
Part of heat transferred through conv. and rad. [%]	70	60
Heat transfer through conv. and rad. [W]	78,4	110,4
Minute volume [l/min]	8,8	15,2
Respiration frequency [br/min]	16	19

Figure 2.3.1: Body functions

In the rest of the project standing and walking setup will be called low activity and high activity respectively.

2.4 Coughing

2.4.1 Introduction

"Cough is an airway defensive reflex consisting of an inspiratory phase followed by a forced expiratory effort initially against a closed glottis("the combination of the vocal folds and the space in between the folds" [12]) followed by active glottal opening and rapid expiratory flow. The expiration reflex (ER) differentiates from cough for the lack of a preparatory inspiration. The reflexes serves different functions: cough will clear the lower airways from debris and mucus, while the expiration reflex will prevent aspiration. Clinically, a cough is a sequence of motor acts resulting from a combination of true coughs and ERs that need to be accurately identified and measured for adequate quantitative description." - Before We Get Started: What Is a Cough?, Giovanni A. Fontana

Human being is a source of airborne pollutants such as viruses and bacteria. They could be transported by breathing, speaking and sneezing, but mostly coughing which is symptomatic for most of the diseases. Although more droplets are released during sneezing (about 2,000,000) than coughing (fewer than 100,000), coughing is more dangerous, because droplets are more infectious due to their deeper origin from the lungs. [13]

It is very difficult to define unequivocally parameters of a human coughing, because all coughing parameters like volume, range and velocity depend on human age, health, condition, gender, etc. [14]

2.4.2 Volume, range and velocity of coughed air

Different studies show some differences in measurements concerning coughing. Research [15] indicate that the initial velocity of coughed air can vary from 6 to 12 m/s with an average of 11.2 m/s. Results of their measurements are shown on figure 2.4.1.

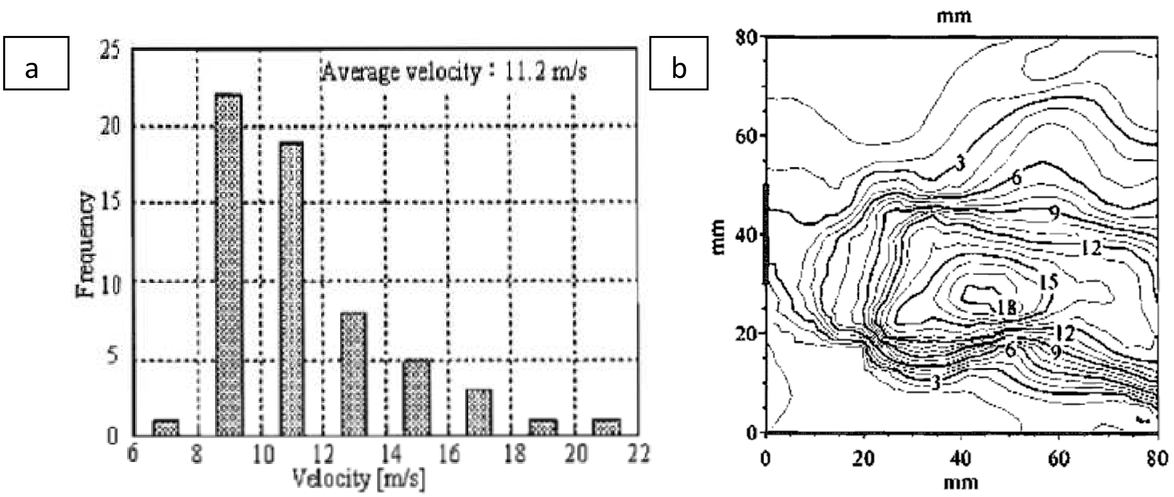


Fig. 2.4.1. a) Velocity frequency distribution; b) velocity distribution in the coughed jet

Velocity distribution at 2.3 ms after coughing can be seen on figure 2.4.1 b). Velocities greater than 18 m/s occur only in a small area, and there is a considerable velocity gradient from the center of coughed air.

Other experiments conducted with flour as a tracer gas have shown that coughed air can travel within range of more than 2m, what can be seen on figure 2.4.2. [15]

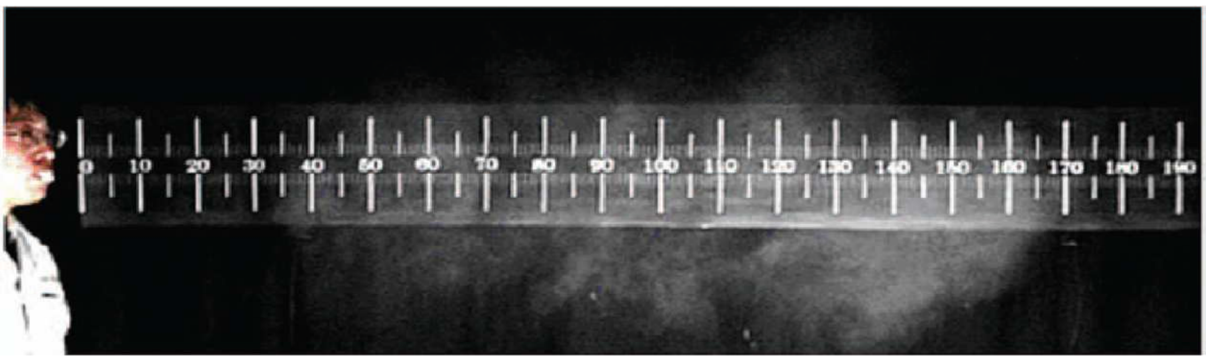


Figure 2.4.2. Visualization of coughed airflow

The coughing image analysis [16] on healthy people, shows how the cough airflow may spread to the indoor environment (figure 2.4.3. A) and what is the velocity map for the coughing (figure 2.4.3. B).

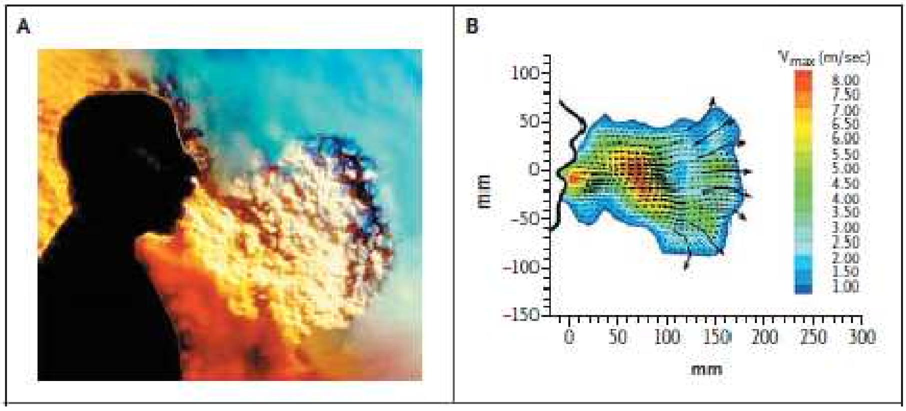


Figure 2.4.3. A) Schlieren photograph of coughed air b) Velocity map of coughing

Gupta at al. [10] carried out another experiment on 25 male and female subjects. In the Experiment Gupta conducted volume measurements of cough flow rates where characteristic values could be determined:

- cough flow peak flow rate (CPFR)
- cough expired volume (CEV)
- peak velocity time (PVT).

This three characteristics are shown on Figure 2.4.4.

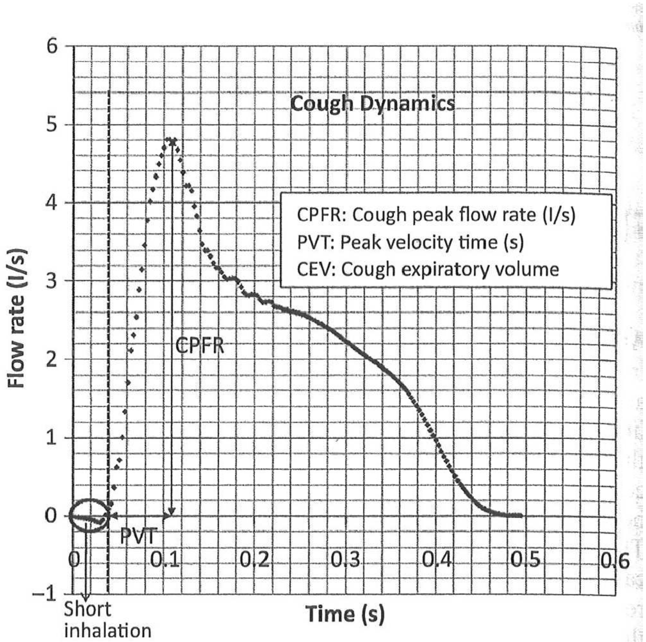


Figure 2.4.4. Cough flow rate variation with time with marked characteristics values [10]

Results of cough flow rates of this experiment are shown below.

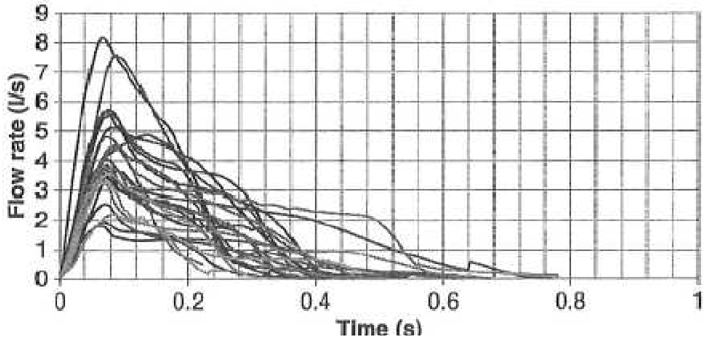


Figure 2.4.5. Cough flow rates for the 25 subjects [10]

By comparing all subjects it can be noticed that CPFR varies from about 1.6 l/s to 8.5 l/s. The variation of other flow characteristics also accrued which can be seen in Table 2.4.6.

	Male	Female
CPFR	3-8,5 l/s	1,6-6 l/s
CEV	400-1600 ml	250-1250 ml
PVT	57-96 ms	57-110 ms

Table 2.4.6. Variation observed in cough flow characteristics [10]

Due to the those considerable fluctuations it can be stated that standard cough does not exist. Because of this fact the dimensionless cough flow rate was calculated:

$$\bar{M} = \frac{Flowrate}{CPFR} \qquad (1)$$

$$\tau = \frac{Time}{PVT} \qquad (2)$$

Where:

$\bar{M}$ – dimensionless flow rate
τ – dimensionless time

Results of dimensionless cough are shown on figure 2.4.7.

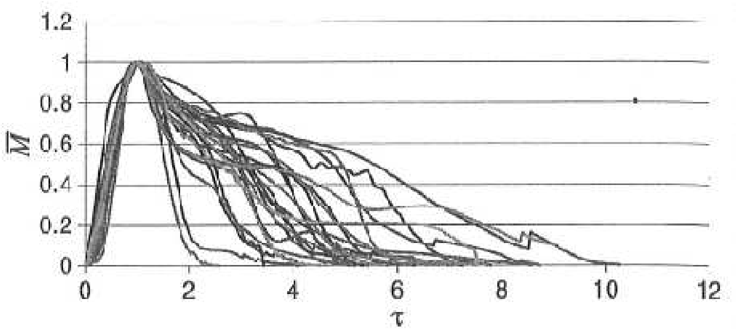


Figure 2.4.7. Dimensionless cough flow rates from the 25 subjects [10]

For dimensionless cough flow rates results Gupta found function which can describe it with the use of different cough flow characteristic values.

$$\overline{M} = \frac{a_1 \tau^{b_1 - 1} \cdot \exp\left(\frac{-\tau}{c_1}\right)}{\Gamma(b_1) \cdot c_1^{b_1}} \qquad for\ \tau < 1.2 \qquad (3)$$

And

$$\overline{M} = \frac{a_1 \tau^{b_1 - 1} \cdot \exp\left(\frac{-\tau}{c_1}\right)}{\Gamma(b_1) \cdot c_1^{b_1}} + \frac{a_2 (\tau - 1.2) \cdot \exp\left(\frac{-(\tau - 1.2)}{c_2}\right)}{\Gamma(b_2) \cdot c_2^{b_2}} \qquad for\ \tau \geq 1.2 \qquad (4)$$

Where:

$$a_1 = 1.680$$
$$b_1 = 3.338$$
$$c_1 = 0.428$$

$$a_2 = \frac{CEV}{PVT \cdot CPFR} - a_1$$
$$b_2 = \frac{-2.158 \cdot CEV}{PVT \cdot CPFR} + 10.457$$
$$c_2 = \frac{1.8}{b_2 - 1}$$

Calculating dimensionless cough flow rate by using equation 3 and 4 leads to relatively good results. Comparison of calculated and measured dimensionless flow rate with the same flow rate characteristic values is shown on figure 2.4.8.

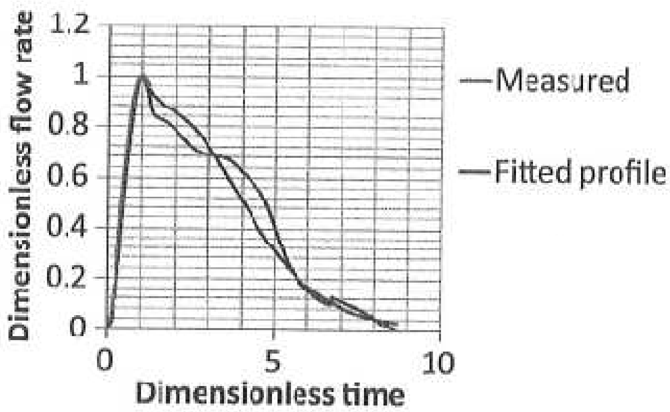


Figure. 2.4.8. Comparasion of the flow rate calculated by Equations 3 and 4 for a single cough for a subject with the measured data [10]

This comparison allows to deduct that it is possible, with quite good accuracy, to calculate a flow rate for single cough. However the calculations depend on previously measured flow rate characteristics i.e. CPFR, PVT and CEV. Gupta noticed that CPFR is related to height and weight of the subjects. Equations to calculate CPFR were developed [10]:

$CPFR = -8.8980 + 6.3952\, h + 0.0346\, w$ [l/s] for male (5)

And

$CPFR = -3.9702 + 4.265\,h$ [l/s] for female (6)

Where,

h - hight of subject [m]

w – weight of subject [kg]

This research also determines the rest of values i.e. PVT and CEV:

$CEV = 0.138\,CPFR + 0.2983$ [l] for male (7)

$CEV = 0.0204\,CPFR - 0.043$ [l] for female (8)

$PVT = 1.360\,CPFR + 65.860$ [ms] for male (9)

$PVT = 3.152\,CPFR + 64.631$ [ms] for female (10)

Processing those equations starting with equations number 5 and 6 throw 7,8,9,10 with the use of know values of hight (h) and weight (w) of subject gives possibility to use equation 3, 4, 2, 1 which in the end gives dimensional flow rate of single cough for appropriate subject. This value can be used as a boundary condition in CFD simulations.

2.4.3 Flow direction of cough and mouth opening area.

Gupta at al. in their research [10] made description of flow direction of cough. Values of angels and angels of flow direction are show below:

$\theta_1 = 15° \pm 5°$ (11)

$\theta_2 = 40° \pm 4°$ (12)

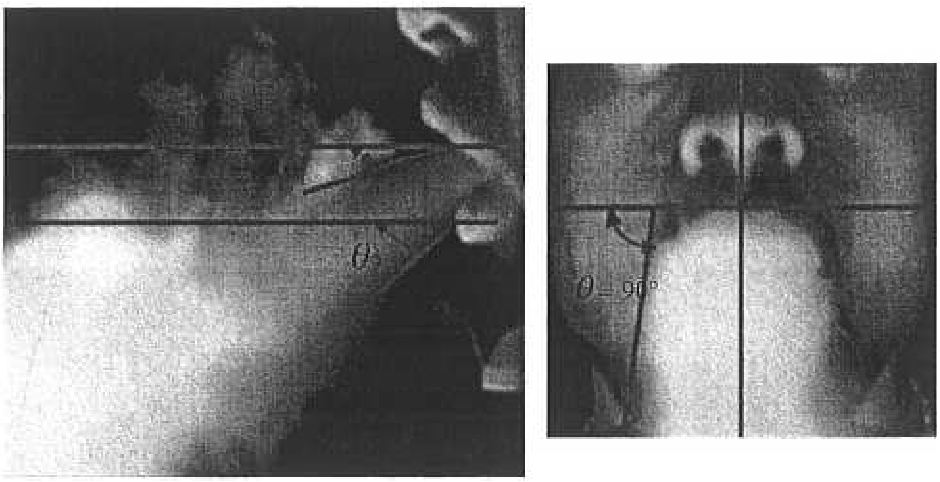


Figure 2.4.9. The cough jet direction from the side and front views

During this research [10] mouth area was also studied and certain values of area where described:

$Mouth\ opening\ area = 4.00\ \pm 0.95$ [cm2] for male

$Mouth\ opening\ area = 3.37\ \pm 1.4$ [cm2] for female

Those values can be used to describe mouth opening during coughing in CFD simulations or to design device which can generate single cough.

2.4.4 Conclusions

Contaminant distribution is among the most significant factors (as an air velocity, flow pattern, air temperature) very important for a indoor air quality.

Knowing how the coughed air with infectious aerosols may spread into the surrounding air could help to understand contamination distribution in spaces, which are strongly influenced by air distribution indoors i.e. ventilation systems.

It is very important not only for hospitals to control airborne transmission of infections, but also for offices, shops, etc. where people spend time during the day, because it could have an influence on health, well-being and productivity of these people.

With the use of previously described equations it is possible to calculate cough flow rate and use it in CFD simulations as a boundary conditions. Mouth area is also described.

2.5 Ventilation

2.5.1 Mixing ventilation

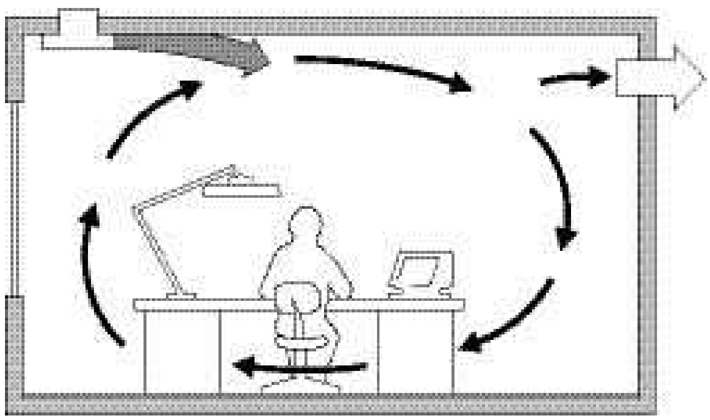


Figure 2.5.1. Mixing Ventilation

Mixing ventilation is a type of mechanic ventilation, which provides clean air to the room, by means of mixing fresh air and air in the room, by keeping constant in time temperature in the room. It is based on an idea, that contaminated air in a room should be fast diluted and then removed. Air supplied to the room with high velocity, causes movement of air in the whole room. This ventilation system enables heating and cooling of the rooms as well. This system provides uniform conditions in regard of temperature and contaminant distribution in the room. Air is usually drifted from the level of a ceiling or windows. Ventilation efficiency is ensured by effective air diffusion throughout the occupied zone and avoiding undesired stagnant zones and flow of the supply air into the exhaust. [3]

2.5.2 Diffuse ceiling inlet

In the experiments, air is distributed to the room by diffuse ceiling inlet. It is constructed of stone wool panels, hanging on suspended ceiling. This kind of inlet creates downward flow in the room. Inlet area is fairly high, since the air enters the room through the cracks in between ceiling panels, what results in small velocities.

The design chart below illustrates the performance of diffuse ceiling inlet in comparison to other air distribution systems. Lines on the chart represent the limits for each ventilation system - maximum flow (q_0) and temperature difference between inlet air and exhaust air (ΔT_0) without causing a draught. It can be seen that diffuse ceiling inlet is superior to all other systems. It is able to handle highest heat loads without creating uncomfortable conditions in the room.

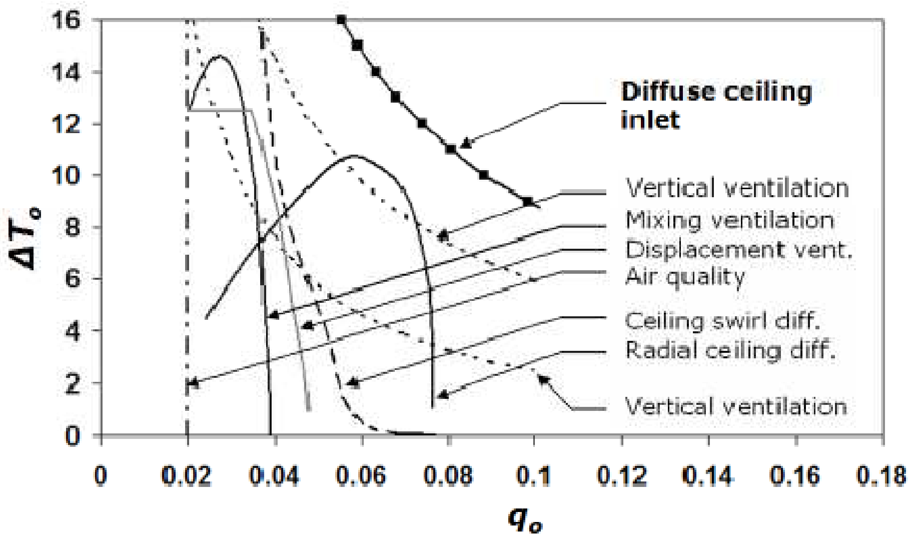


Figure 2.5.2: Design chart [11]

3. LABORATORY SETUP

Major part of this project are experiments, performed in a test room at Aalborg University. This test room has been previously used to carry out experiments concerning indoor climatic conditions.

The following chapters provide thorough description of the test room, equipment used in experiments, location of instruments and methodology of measurements. Also, problems encountered during measurements are discussed and possible solutions for future work are suggested.

3.1 The test room

All measurements are carried out in a special chamber located in "F" Laboratory in Aalborg University. The chamber is a wooden cuboid with two glass walls. Dimensions of the room are 410 cm (L), 320 cm (W), 270 cm (H). 30 centimeters below the ceiling, a suspended ceiling is installed, which serves as an inlet. This is explained in more details in the next subchapter. Figure below presents a sketch of the room:

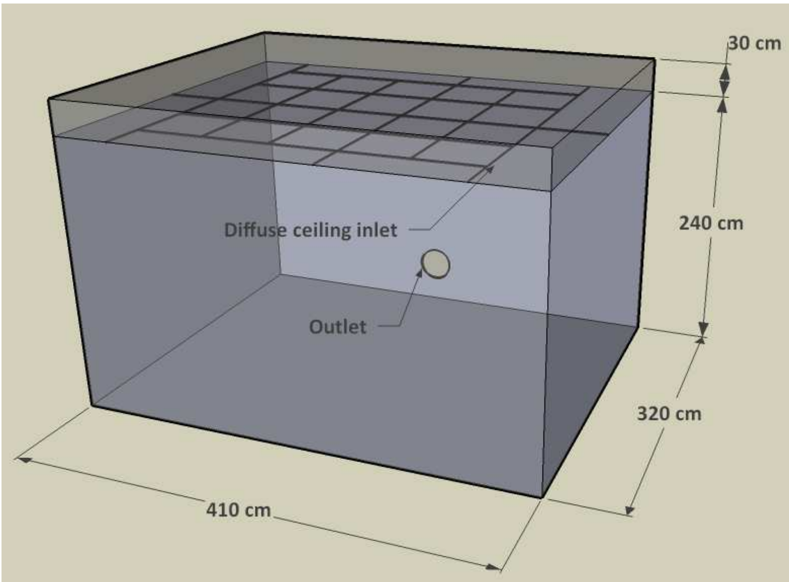


Figure 3.1.1.: The test room

3.2 Ventilation

In the experiments air is supplied to the room by diffuse ceiling inlet. It is constructed of stone wool panels, hanging on suspended ceiling, 30 cm below the room's ceiling. Figure below presents plan view of the ceiling.

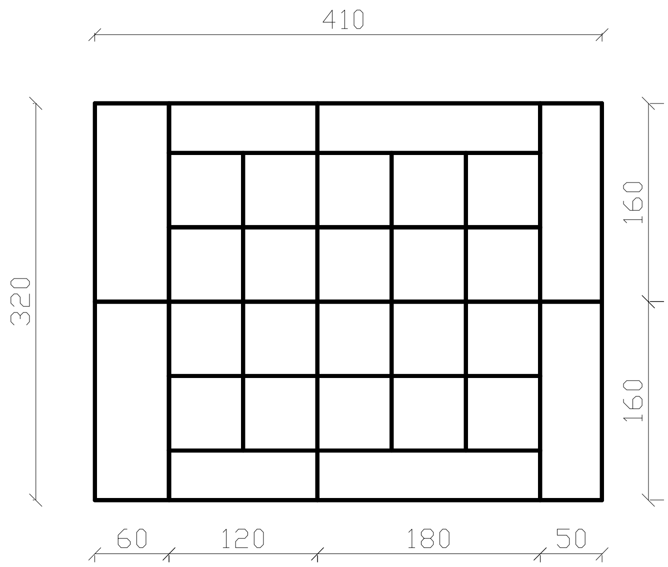


Figure 3.2.1: Plan view of the diffuse ceiling (dimensions in cm)

Fresh air is supplied from the diffuser to the ceiling plenum. From there it is blown to the room through the ceiling. Experiments [11], show that most of the air flows through the slots between ceiling panels and from the connections between the ceiling and the walls. Exhaust is located on one of the chamber's walls, close to the floor and its diameter is 160 mm. This kind of air distribution system provides fully mixed conditions in the room.

This type of ventilation is selected for the experiment since it does not affect airflow in the room to a large extent. Because of that more focus can be put on investigating the manikins and the airflow around them.

3.3 Manikins

Essential part of equipment used during experiments conducted in laboratory is the thermal manikin and breathing devices connected to it. One to two manikins are used in this research.

3.3.1 Construction of the manikin

The manikin is a model that represents a simplified version of a human body. Its photograph and dimensions are presented on the figure below:

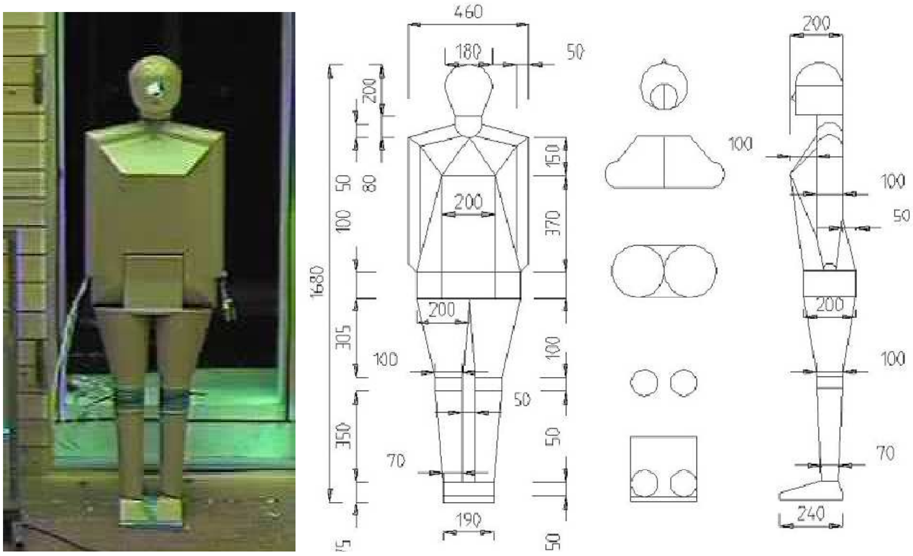


Figure 3.3.1 The manikin and dimensions

Manikin is a model of a 168 cm tall person. In its height and shape it resembles a female. Therefore, it is adjusted to simulate body functions of a woman. It is constructed of aluminum. It has bendable knees and waist, so it can be set to various positions (sitting, standing, etc.).

3.3.2 Breathing equipment

Artificial lungs are connected to the manikin to simulate breathing functions. Air is pumped by a piston. Volume of exhaled air can be regulated by changing travel of the piston. Engine moves the piston at certain frequency, that can be controlled as well.

Before entering the manikin, exhalation air is heated. This is done with the use of simple electric heater. Power can be regulated on a transformer.

3.3.3 Heat sources in the manikin.

The manikin can simulate some of the human body functions. One of them is heat flux from a person. There are three heat sources in the manikin:

- A built inside heater – it can be regulated by a transformer and the heat load can be set up to 145 W.
- Two fans – their primary function is to distribute air around the manikin, thus creating an uniform distribution of temperature on manikin’s surface. However, the fans also create heat load, which in this case equals 30 W.
- Heat loss from exhaled air – exhalation air is heated before entering the manikin. After that, it runs through a copper pipe until it reaches either manikin’s mouth or nose. Copper tube has a high conductivity factor and air inside it flows at high velocities, therefore the heat loss is significant. To measure it, two thermocouples

are used – one in the tube behind the heater and one in manikin's mouth. Heat loss can be calculated from the formula:

$$Q = c_p \cdot \Delta t \cdot \dot{m}\ [W]$$

where:
c_p – specific heat capacity of air [J/kg·K]
Δt – temperature difference [K]
$\dot{m}$ - mass flow [kg/s]

Combination of these three sources is used to achieve desired heat load. Table below presents what each of these values equals in two activity levels of the manikin used in experiments.

	Low activity	High activity
Total heat flux [W]	78,4	110,4
Heater [W]	38,7	76,1
Fan [W]	30	30
Pipe [W]	9,7	4,3

Figure 3.3.2: Amount of heat released by heater fan and tube in the manikin.

In case of higher activity the tube inside the manikin releases less heat. That is because manikin is heated more, what results in lower temperature difference between air in the tube and in manikin.

3.4 Measurements of conditions in the chamber

Main focus of experiments is put on the manikins – their exhalation jet and the way they interact. However, conditions in the chamber also need to be measured and discussed in order to have an understanding how much do they affect measurements connected with the manikins. Therefore, velocity and temperature measurements in the room are conducted.

3.4.1 Temperature measurements

Temperature measurements are carried out with the use of 45 thermocouples. Air temperature and surface temperatures are measured.

- To investigate temperature distribution in the room, vertical gradient is measured with 13 thermocouples located on a stand in a corner of the room. Thermocouples are placed at heights: 0,1 m; 0,3 m; 0,5 m; 0,7m; 0,9m; 1,1m; 1,3m; 1,5m; 1,7m; 1,9m; 2,1m; 2,3m. This stand is presented as stand D on figure 3.4.1 and 3.4.2 below.

- Surface temperatures are measured so they can be used as boundary conditions in CFD. One thermocouple is placed on each wall and floor. On the ceiling, 4 thermocouples are used and placed on different panels.

- Temperature of surface of manikin is also measured to investigate how it can change with varying heat load. Those measurements are conducted in four points. One thermocouple on the leg, one on the abdomen, one on the torso and the last one on the forehead.

- Temperature of inlet air is measured by two thermocouples to ensure that inlet air temperature stays at constant level throughout all measurements

3.4.2 Velocity measurements

Velocity measurements are conducted with the use of hot sphere anemometers. Velocity distribution in the room is checked by measuring vertical gradient. In two corners of the room, there are stands (stand A and B, see figure below) with anemometers placed on 3 different heights: 0,1m; 1,1m; 1,8m.

Also, to check more closely the air movement at the area surrounding the manikin's head, some additional anemometers are placed on a stand (stand C) close to manikin at the heights of 136 cm to 164 cm, every 4 cm.

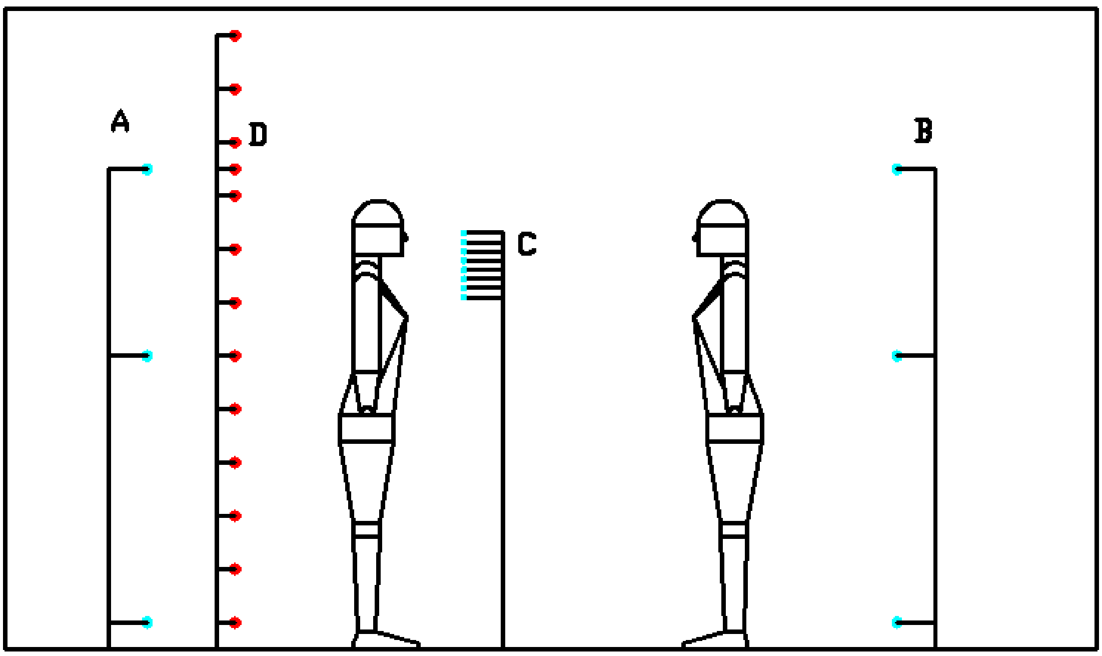


Figure 3.4.1: Location of measurement instruments in the room. Red dots represent thermocouples, blue dots – anemometers.

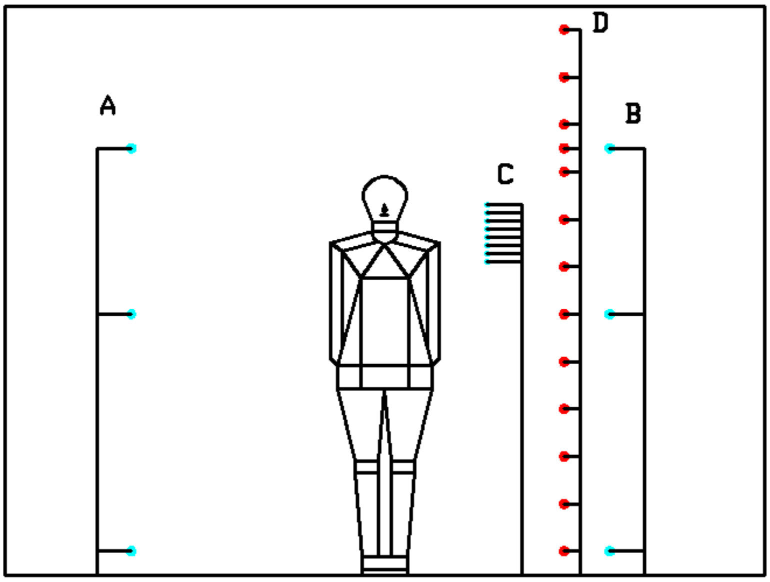


Figure 3.4.2: Location of measurement instruments in the room

3.5 Measurements conducted with one manikin

For this part of the experiments only one manikin is placed inside the chamber. Measurements conducted with one manikin are focused on the exhalation jet. Velocity distribution in the jet is measured. For concentration measurements, tracer gas (N_2O) is supplied to the air exhaled by manikin. Thus, concentration distribution in the jet can be also checked.

3.5.1 Velocity measurements in exhalation jet

Velocity of exhalation is measured with a single anemometer. It is installed on a stand, shown on figure 3.5.2. The arm of the stand is moveable in vertical direction and can be operated by a remote control from outside of the room. Experiments are conducted for expiration only through the mouth. The idea of how the velocity is measured is shown on figure 3.5.1. Anemometer is firstly placed at a certain horizontal distance from the mouth and then moved vertically to obtain a complete view of velocity distribution.

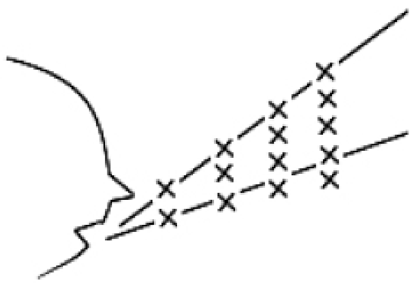


Figure 3.5.1: Measurements of velocity distribution in the jet

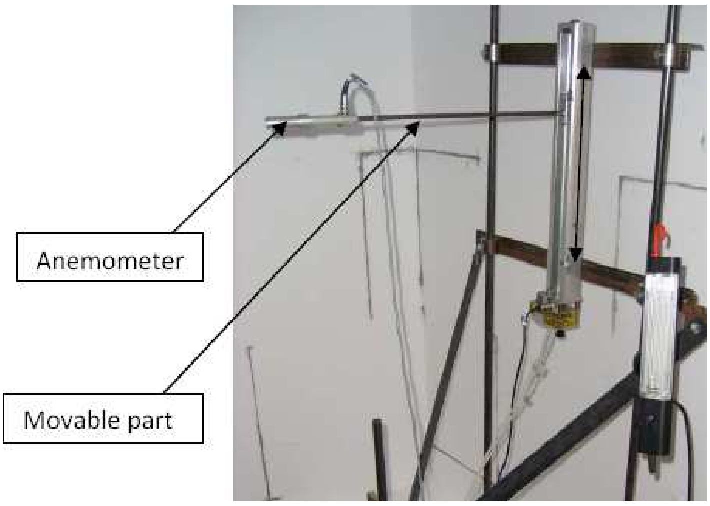


Figure 3.5.2 Mechanical stand with hot sphere anemometer.

Exhalation is a pulsating flow. Figure below shows output from an anemometer measuring velocity in exhalation jet. Each of the “peaks” on the graph represents one expiration. In each measuring point, velocity is measured for 10-15 expirations. Then only peak velocities are taken into consideration. An average value is made of those peaks and it is used for further analysis.

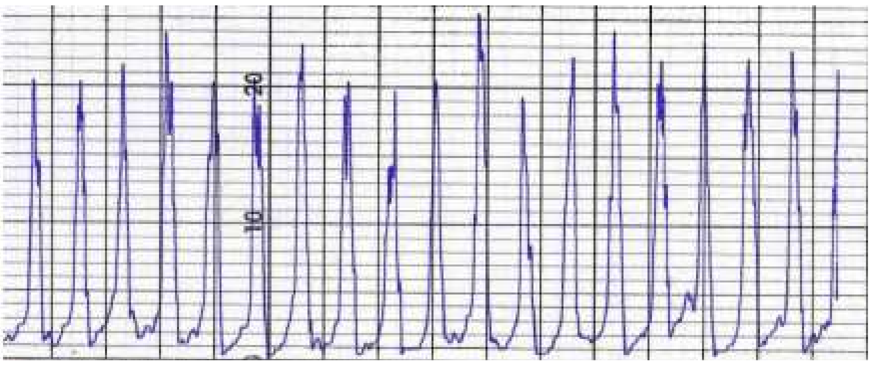


Figure 3.5.3: Output from anemometer.

3.5.2 Concentration

Concentration measurement points are placed as shown on figure 3.5.4. Four tubes for taking samples of the air are placed on the stand close to the manikin. One is located near the tracer gas bottle and one more in the outlet of ventilation system inside the chamber.

Concentration measurements in the jet are conducted in a similar fashion to velocity measurements. Stand is being placed at different horizontal distances from the manikin. Four measurement points are placed on the stand at different heights to obtain distribution of concentration in a vertical plane.

Concentration in outlet is always being checked. Reason for that is to obtain dimensionless values of concentration $\frac{C_x}{C_R}$ where C_x is the value at certain distance and C_R is the value in the outlet.

Moreover, value of concentration near the bottle with tracer gas is checked because of safety causes (tracer gas can be lethal at high doses).

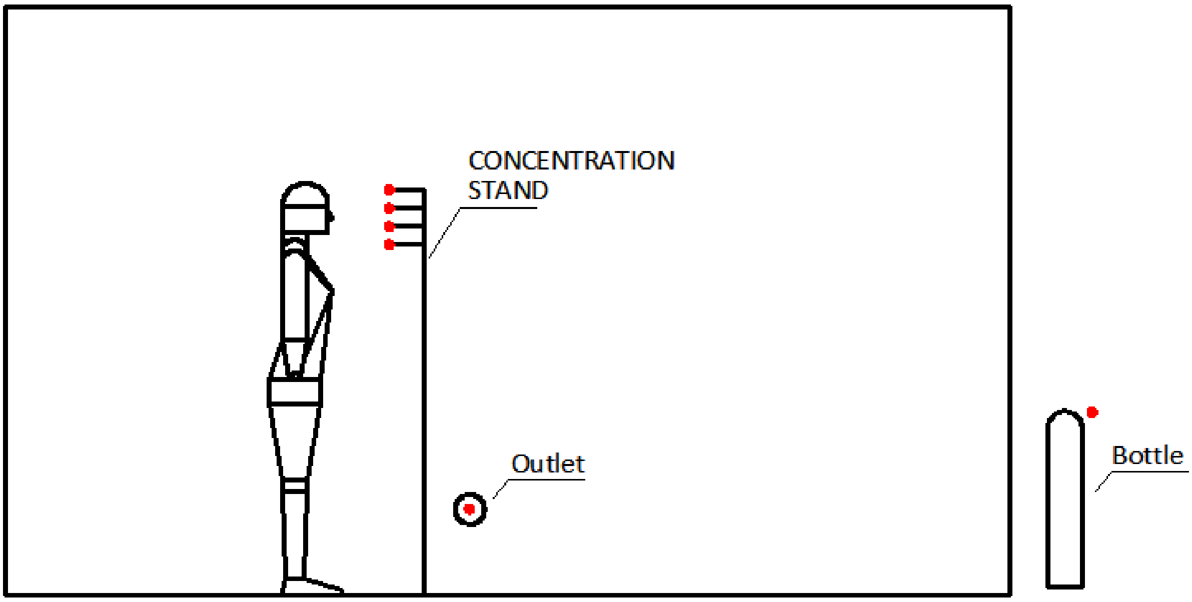


Figure 3.5.4. Situating of concentration measurement points (represented as red dots).

Equipment used for concentration measurements, records the data with much longer intervals. It is therefore very difficult to find peak values. It is decided to measure over a long period and take average of all measured values. One of the exemplary measurements is shown below.

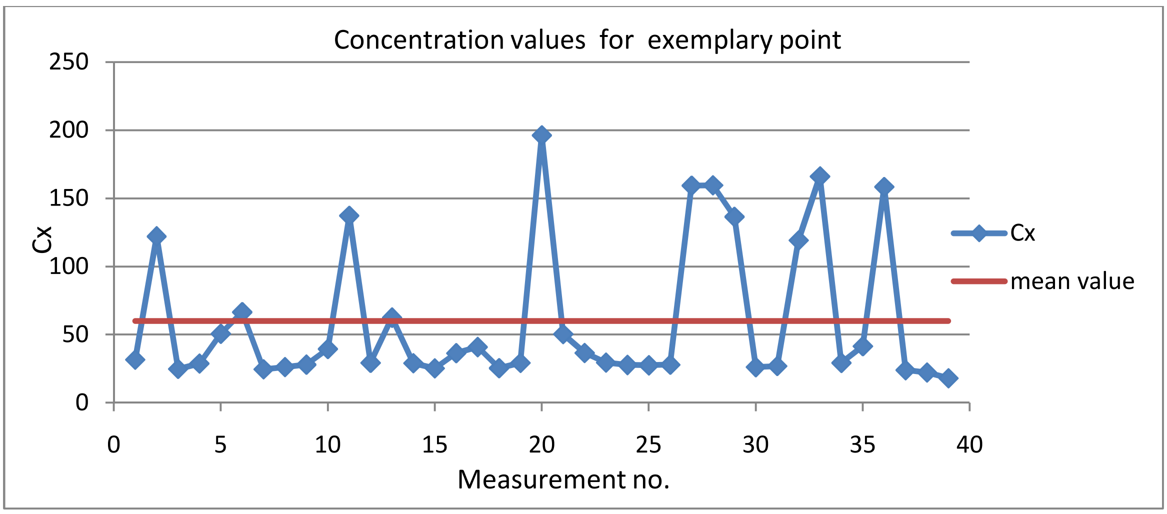


Figure 3.5.5 Mean concentration result for one of measurements

3.5.3 List of measurements with one manikin

The manikin is set to two different activity levels. For both of them air is exhaled only through the mouth.

For situation with low activity, concentration and velocity are measured at horizontal distances from the mouth of: 10, 20, 30, 40 and 50 cm. Placing of measuring points in vertical direction is chosen in a way to cover the whole jet in a certain plane.

For the case with higher activity, the same measurements are made, but up to 60 cm distance.

3.6 Measurements with two manikins

This part of experiments focuses on how one exhaling person can affect another one in regard of cross infection. Thus, two manikins are placed inside the chamber, facing each other. One of them is exhaling air – this one is referred to as source manikin. Another one only inhale and is further called target manikin.

3.6.1 Concentration measurements

Figure below presents location of measurement points near second manikin. Apart from those places, concentration is also checked in the outlet and near the bottle as previously.

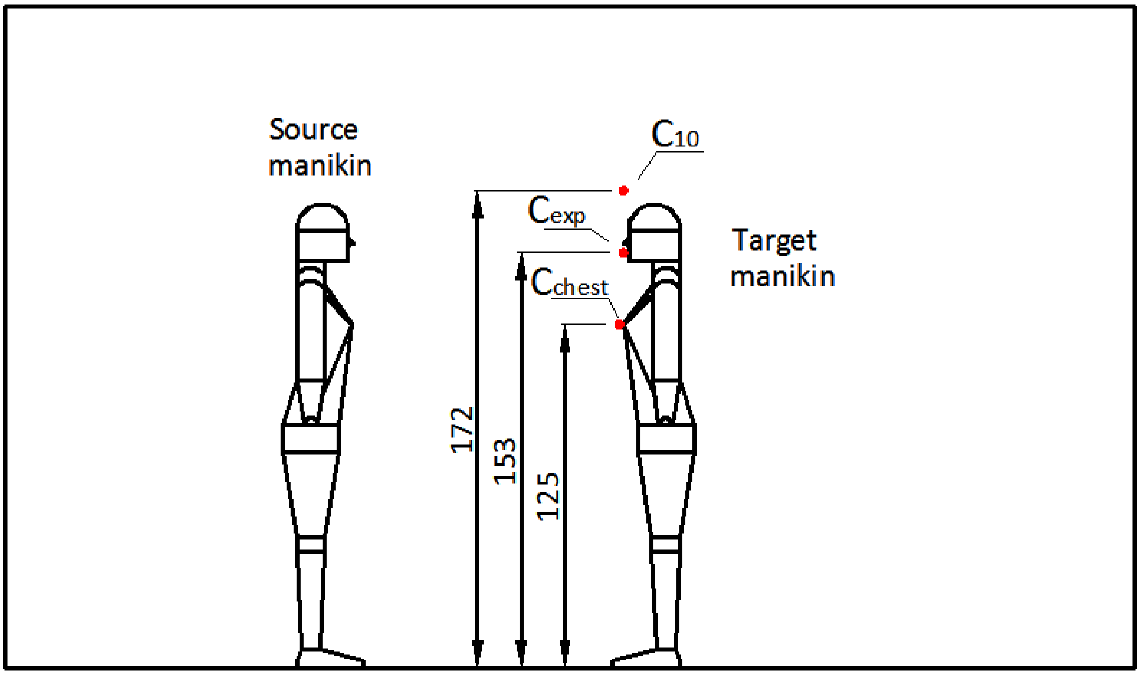


Figure 3.6.1. Location of measurement points

Point C_{chest} is located at the chest of target manikin. It is checked because it shows the level of concentration in the place from where a person inhales the biggest amount of air.

Point C_{exp} represents personal exposure of target manikin. It is located close to the mouth, in the area where air is inhaled. Concentration measurements in this point will give an idea of how much a person is exposed to contaminants exhaled by another one.

Point C_{10} is located 4 cm above the top of manikin's head. It is suspected that it most cases exhalation jet will go above the manikin and this point is chosen to check if that is true.

3.6.2 List of measurements

Table below shows the measurements conducted in this part of the research:

No	Activity level	Exhalation through	Distance between manikins	Description
1	Low	Mouth	35, 50, 80, 110 cm	-
2	High	Mouth	35, 50, 80, 110 cm	-
3	Low	Mouth	50 cm	Target manikin placed on different heights above ground – 0; 8; 16cm
4	Low	Nose	35, 50, 80, 110 cm	Corrected exhalation angle
5	Low	Nose	50 cm	Old exhalation angle

Figure 3.6.2: List of measurements with two manikins

Case no 1 is an investigation of one manikin exhaling on another one, both with the same activity level at various distances between them (35-110 cm). Case no 2 is the same, but with higher activity level of source manikin.

In case no 3, both manikins are again set to low activity. The target manikin is placed on different heights to simulate interaction with a taller person.

Last two experiments are conducted with exhalation through the nose and low activity. For case no 4, the exhalation angle is corrected and for case no 5 left as before (more explanation on that in chapter 4.3.5).

3.7 Smoke visualizations

Smoke visualizations are also conducted in order to have a better understanding on how the exhalation jet behaves and to what extent it can affect other manikin. A camera is placed on a tripod, inside the chamber to record the simulations. Smoke is supplied to the exhalation. For more description of the used equipment see appendix A.

3.8 Problems occurring during measurements

3.8.1 Problems encountered with the manikin and equipment

Manikin used in experiments is capable of simulating a breathing person, however it is not perfect. Problems that were encountered during experiments:

- Heat loss of air between the heater and mouth of manikin is very large. Due to this problem, it is impossible with available equipment to obtain proper exhalation temperature of 38˚C. Temperature of 33˚C is used instead.
- Angles of exhalation are not perfect, especially when exhaling through the nose (see chapter 2.1.3).

Manikins constructed in the future can be easily modified to be more realistic and easier to use. Problem with the heater could be solved by installing the heater inside the manikin or changing the copper pipe to different one, of smaller conductivity coefficient. It could be also insulated with mineral wool or other material.

Construction of the nose can also be modified to obtain appropriate exhalation angles.

3.8.2 Problems encountered with the velocity equipment

Anemometer is constructed of 2 hot spheres and the distance between them is too large to measure velocity at very close distance (approximately 1 cm) to the mouth. Flow stream near the mouth is too small to be measured by hot sphere anemometer.

When placing the measurement points in space, it is very difficult to obtain desired location. It is suggested to use self leveling laser or constructing laser for checking if the points are in the same plane.

Another problem is, that anemometers used in the experiments are most suitable for measuring steady flow. It can be difficult to measure actual instantaneous velocity. It is also necessary to use a data registering device with very small measuring interval, so it can capture peak instantaneous velocity.

Available data loggers had shortest interval of 1 seconds so, which is not good enough for finding peak velocities. Pen writer gives much better and instantaneous results and is used in experiments.

3.8.3 Problems encountered with the concentration equipment

Placing of concentration points is very hard and thus not precise enough, the same situation as with the velocity points . It is suggested to use self leveling laser or constructing laser for checking if the points are in the same plane. Measurements of concentration in single point in exhalation jet sometimes show drastically varying results which causes that measurements of concentration in a point in a small jet are very time-consuming. In our case each point was checked 40 times and value taken to consideration was the mean value of 40 measurements.

4. RESULTS

This chapter covers results of measurements conducted in the test room. Firstly, conditions in the chamber are described in order to provide a description of what is happening inside, in terms of velocity and temperature distribution.

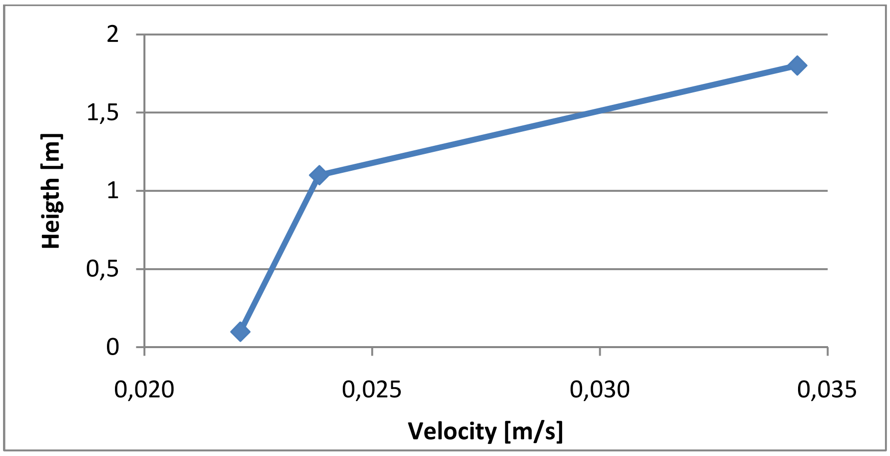
Next chapters elaborate on experiments carried out with the use of one and two manikins

4.1 Conditions in the chamber

For better understanding of processes happening in the chamber where experiments are conducted, precise conditions inside need to be known and analyzed. Most important parameters that might influence the experiments are air temperature and velocity distribution. This chapter contains analysis of these values in different cases.

4.1.1 Velocity distribution

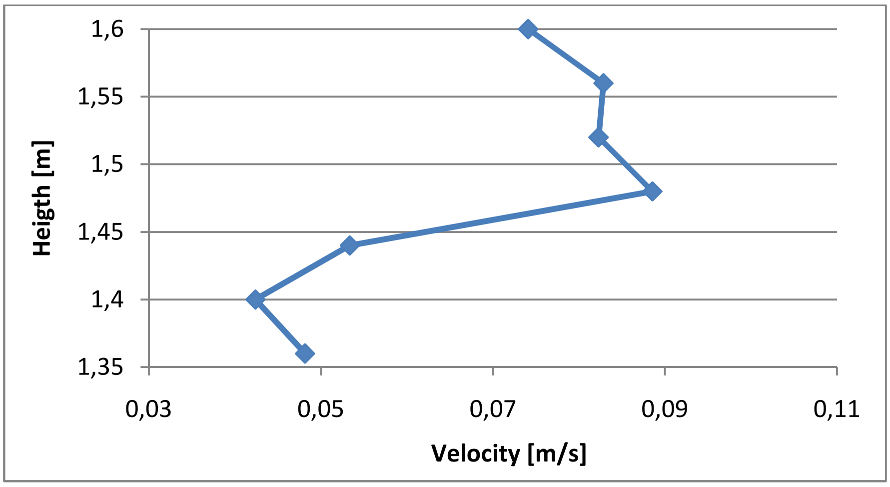
Air movement caused by the ventilation system in the room creates a certain velocity field. Figure below shows vertical velocity distribution in three heights above the floor.



Height [m]	Velocity [m/s]
0,1	0,0221
1,1	0,0238
1,8	0,0343

Figure 4.1.1: Velocity distribution in the room

Anemometers located in the highest position record largest velocity, as they are closer to the diffuse ceiling. However, it seems that even there velocity is extremely small and should not have any impact on experiments.



Height [m]	Velocity [m/s]
1,36	0,048
1,4	0,042
1,44	0,053
1,48	0,089
1,52	0,082
1,56	0,083
1,6	0,074

Figure 4.1.2: Velocity distribution near the manikin

Another vertical gradient of velocity has been made in close proximity to the manikin, in order to have a better view of conditions in that area.

It can be seen that velocities here are also fairly small, but there is a large increase at the height of around 1,5 m above the ground. This is also the same level where manikin's mouth is located. It leads to conclusion that exhalation jet from the manikin is affecting these measurements and the stand with anemometers has been placed too close to it. However, even in this situation velocities do not exceed 0,1 m/s, what is a very small value.

4.1.2 Temperature distribution

Temperature distribution in the room should vary to some extent, since in different cases, various heat loads are supplied to the room. Inlet temperature however is maintained on the same level throughout all the experiments and equals approximately 19,4 ˚C.

Four different heat loads (HL) are supplied to the room in different experiments:

- HL 1: one manikin with lower activity. Heat load equals 78,4 W
- HL 2: one manikin with higher activity level. Heat load equals 110,4 W
- HL 3: two manikins, both with lower activity level. Heat load equals 156,8 W
- HL 4: two manikins, one with low, one with high activity level. Heat load is 189 W

Temperature gradients in the room under different conditions are shown on the figure below:

height [m]	HL 1 [˚C]	HL 2 [˚C]	HL 3 [˚C]	HL 4 [˚C]
0,1	20,63	21,02	21,04	21,40
0,3	20,65	21,05	21,07	21,46
0,5	20,68	21,07	21,11	21,50
0,7	20,63	21,03	21,06	21,45
0,9	20,67	21,07	21,12	21,51
1,1	20,66	21,05	21,10	21,49
1,3	20,66	21,07	21,10	21,48
1,5	20,64	21,09	21,07	21,45
1,7	20,66	21,09	21,09	21,47
1,8	20,66	21,09	21,10	21,47
1,9	20,64	21,06	21,07	21,45
2,1	20,63	21,05	21,01	21,39
2,3	20,69	21,12	21,09	21,54
mean:	20,65	21,07	21,08	21,47

Figure 4.1.3: Temperature gradients in the room. Level of manikin's mouth is shaded.

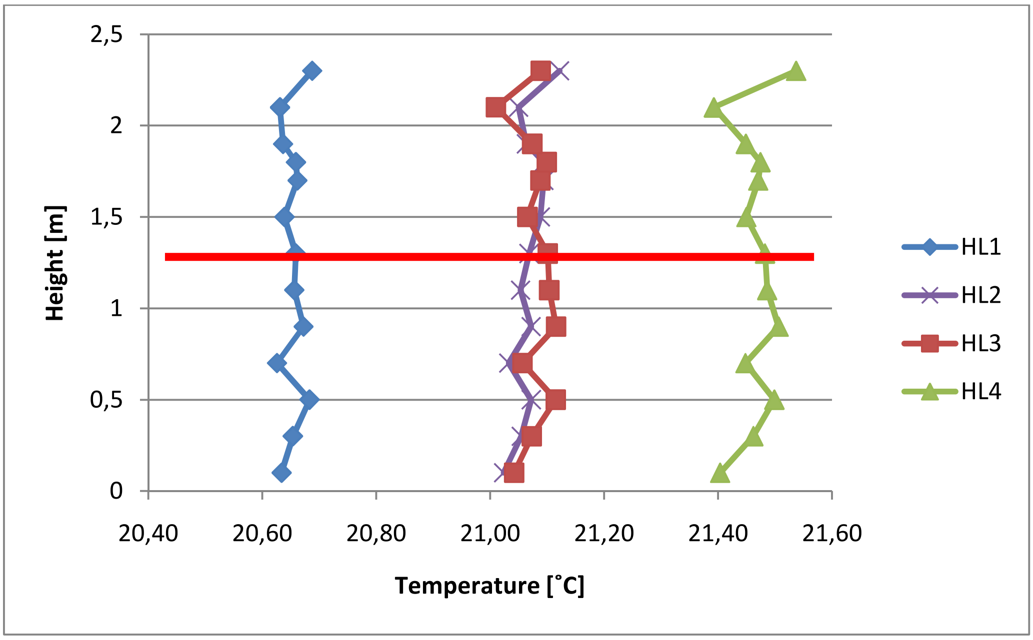


Figure 4.1.4: Temperature gradients. Red line represents level of the mouth of manikin

It can be seen that conditions in the room in regard of temperature are uniform. There is very little change in temperature with height above the floor. Conditions are also to some extent dependent on the heat load. A small rise of temperature can be seen with higher heat loads supplied to the room.

Since exhalation of the manikin is a key case in this thesis, temperature on the level of manikin's mouth is the most important information and is marked on figures above.

Surface temperature in the room are also important, since they are to be used as boundary conditions in CFD simulations. Figure below presents these values:

surface [-]	HL 1 [˚C]	HL 2 [˚C]	HL 3 [˚C]	HL 4 [˚C]
walls	20,77	21,30	21,29	21,66
ceiling	20,43	20,80	20,90	21,13
floor	20,55	21,02	20,63	21,45

Figure 4.1.5: Surface temperatures in the chamber

There is no significant difference in temperature of different surfaces. Ceiling is in this case acting as an inlet, therefore in most cases it has lower temperature than the walls and ceiling. Again, a small temperature rise can be seen with increasing heat load.

4.1.3 Surface temperature of the manikin

Some thermocouples are also placed on different parts of the manikin to check its temperature under different activity levels. Figure below presents results for manikin with higher and lower activity levels.

activity [-]	legs [˚C]	stomach [˚C]	chest [˚C]	head [˚C]	mean [˚C]
low	27,97	28,13	27,99	25,80	27,47
high	31,21	31,25	31,01	28,82	30,57

Figure 4.1.6: Temperature of manikin's body

With the exception of the head, temperature distribution over the body of the manikin is rather uniform. A rise in temperature of about 3K can be seen when manikin's activity level is switched to a higher one.

Surface temperature obtained in experiments can be compared with skin temperature of people. Mean temperature of the human skin is described by the equation [8]:

$$t_s = 35{,}7 - 0{,}032\frac{M}{A_d}\ [°\mathrm{C}]$$

What would equal to skin temperature of 34,4 ˚C and 33,7 ˚C for lower and higher activity respectively. Temperature slightly decreases with higher activity levels due to larger sweat secretion what cools the skin down. The manikin cannot simulate the sweating process, therefore the temperature rises with higher heat load.

These temperatures differ from those obtained with the manikin. A way to find some correlations with reality would be to describe the manikin as a clothed person. Mean temperature on the surface of clothes equals [8]:

$$t_{cl} = 35{,}7 - 0{,}032\frac{M}{A_d} - 0{,}18 \cdot I_{cl}[\frac{M}{A_d} - 0{,}35\left(43 - 0{,}061\frac{M}{A_d} - p_a\right) - 0{,}42\left(\frac{M}{A_d} - 50\right) - 0{,}0023\frac{M}{A_d}(44 - p_a) - 0{,}0014\frac{M}{A_d}(34 - t_a]\ [°C]$$

where:

I_{cl} – dimensionless expression for total heat transfer resistance from the skin to the outer surface of the clothed body [clo]
p_a – partial pressure of water vapor in inspired air [mm Hg]
t_a – ambient temperature [˚C]

This temperature depends mostly on the I_{cl} factor. When it is the same for both activity levels, there is a large difference in temperature. For example when I_{cl} factor equals 1, temperature on the clothing equals 29,01 and 26,32 ˚C for lower and higher activity respectively. It seems that increasing activity level in experiments with manikin and in reality actually have an opposite effect on the surface temperature.

It can be however assumed that the manikin represented a person with different kind of clothing. Temperatures recorded in experiments and calculated are matching when I_{cl} equals 1,3 for low activity case and 0,4 for high activity case.

4.2 Results of measurements with one manikin

4.2.1 Manikin set to low activity

This chapter describes results of the measurements conducted with one manikin set for lower activity level. Concentration and velocity distribution in the jet are discussed, in order to provide thorough description of how the jet behaves.

Velocity measurements:

Measurements of velocity distribution in the exhalation jet are presented in the table below. Each of the tables depicts vertical velocity profile at a certain horizontal distance from the manikin's mouth. Zero in the row "vertical distance" represents the middle of the jet, i.e. the place where highest velocity was recorded.

Horizontal distance: 10 cm												
Vertical distance:	[cm]	-3	-2,5	-2	-1,5	-1	-0,5	0	0,5	1	1,5	2	2,5
Velocity	[m/s]	0,23	0,38	0,38	0,60	0,74	1,09	1,21	1,16	0,97	0,92	0,71	0,27

Horizontal distance: 20 cm								
Vertical distance:	[cm]	-3	-2	-1	0	1	2	3
Velocity	[m/s]	0,39	0,57	0,82	1,02	0,98	0,62	0,24

Horizontal distance: 30 cm								
Vertical distance:	[cm]	-4,5	-3	-1,5	0	1,5	3	4,5
Velocity	[m/s]	0,24	0,30	0,47	0,61	0,53	0,56	0,22

Horizontal distance: 40 cm								
Vertical distance:	[cm]	-4,5	-3	-1,5	0	1,5	3	4,5
Velocity	[m/s]	0,30	0,34	0,35	0,53	0,47	0,54	0,38

Horizontal distance: 50 cm								
Vertical distance:	[cm]	-9	-6	-3	0	3	6	9
Velocity	[m/s]	0,10	0,19	0,19	0,24	0,19	0,18	0,10

Figure 4.2.1: Velocity distribution of exhalation jet

To have an understanding of velocity decay in the jet, the initial velocity at manikin's mouth should be known. It is calculated from the formula:

$$v = \frac{\dot{V}}{A} \ \left[\frac{m}{s}\right],$$

where V is the volume flow and A is mouth's area. Initial velocity in this case equals 3,12 m/s. It can be seen that in the first 10 centimeters there is a significant drop in velocity. In the further distances, decay is less rapid. Measurements are stopped at the distance of 50 cm where velocity equals 0,24 m/s. Further, the jet is moving with very low speed and it is difficult to find peak velocities.

The data presented above can be also put in a form of a graph:

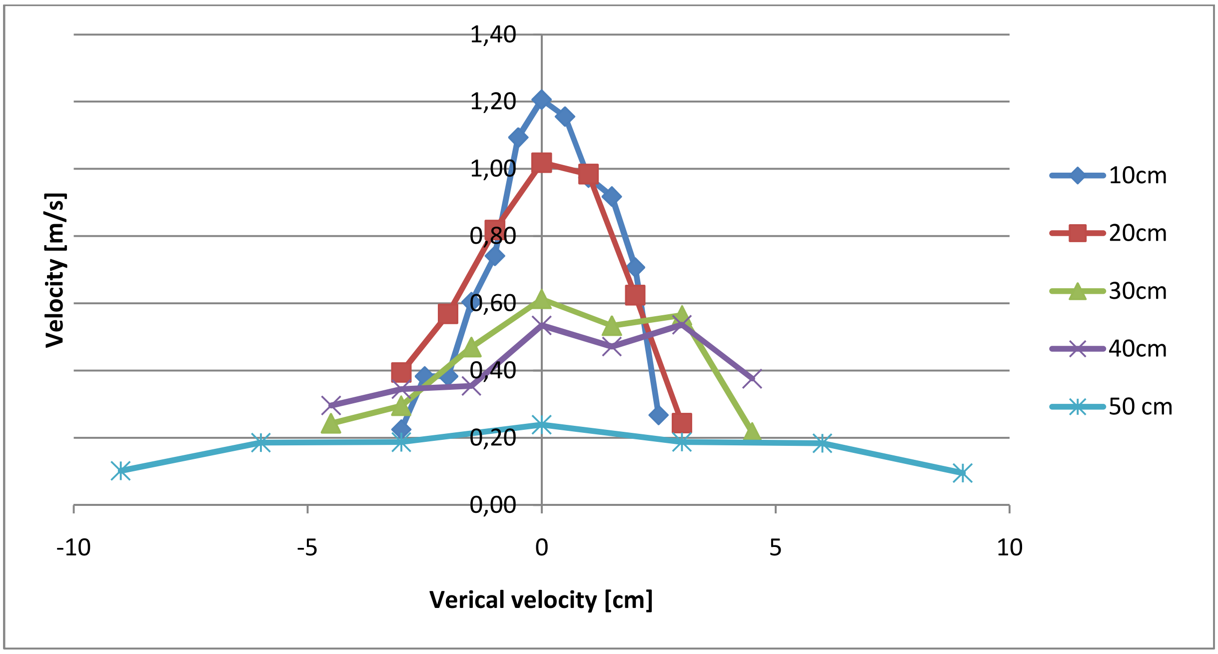
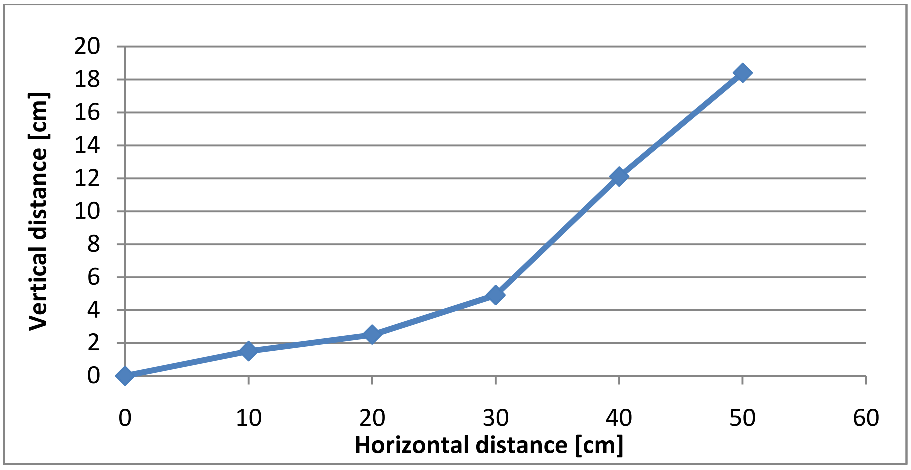


Figure 4.2.2: Velocity distribution in the exhalation jet.

On this graph it can be seen that with greater distance from the mouth, the jet becomes wider, but has lower velocities. This happens because more and more air is entrained into the jet as it travels, thus losing its velocity. At 50 centimeters from the mouth the jet is approximately 20 cm wide.

Figure below presents the flow path of exhalation jet. Points on the graph represent positions where highest velocities in each vertical plane where found. Vertical distance is in relation to manikin's mouth.



horizontal distance [cm]	vertical distance [cm]
0	0
10	1,5
20	2,5
30	4,9
40	12,1
50	18,4

Figure 4.2.3: Flow path

It was suspected that the jet would have an upward direction. There is a temperature difference of 12,4 K between expired air and ambient air, what creates certain density difference. This creates buoyancy force that can change direction of the flow.

For the first 20 centimeters the rise of the exhalation flow is rather slow. At larger distance however, it seems that the jet becomes more and more influenced by buoyancy, as the velocity decreases and the rise of the jet becomes faster. It has been seen in previous research [17] the jet eventually stops progressing forward and only moves upwards as a result of temperature difference.

Concentration measurements:

Concentration distribution is shown in the table below. Data is presented in the same way as with velocity measurements.

Horizontal dist:	[cm]		0		10		
Vertical distance:	[cm]		0		-2	0	2
Concentration	[-]		58,55		9,17	25,09	5,46

Horizontal dist:	[cm]		20					30			
Vertical distance:	[cm]		-3,7	-0,8	0	3,7		-3,7	-1	0	3,7
Concentration	[-]		7,41	10,50	20,64	9,37		10,94	7,51	12,77	10,67

Horizontal dist:	[cm]		40					50			
Vertical distance:	[cm]		-7	-3,5	0	3		-8	-4	0	3
Concentration	[-]		7,83	7,10	10,83	8,57		6,13	5,08	6,78	4,26

Table 4.2.4: Concentration distribution

Similarly to velocity measurements, these show a rapid decay in concentration of tracer gas in close distance to the mouth. Further, it tends to decrease more slowly. At the distance of 50 cm the concentration is almost 10 times lower than at the source. Figure below presents the same data, depicted on a graph:

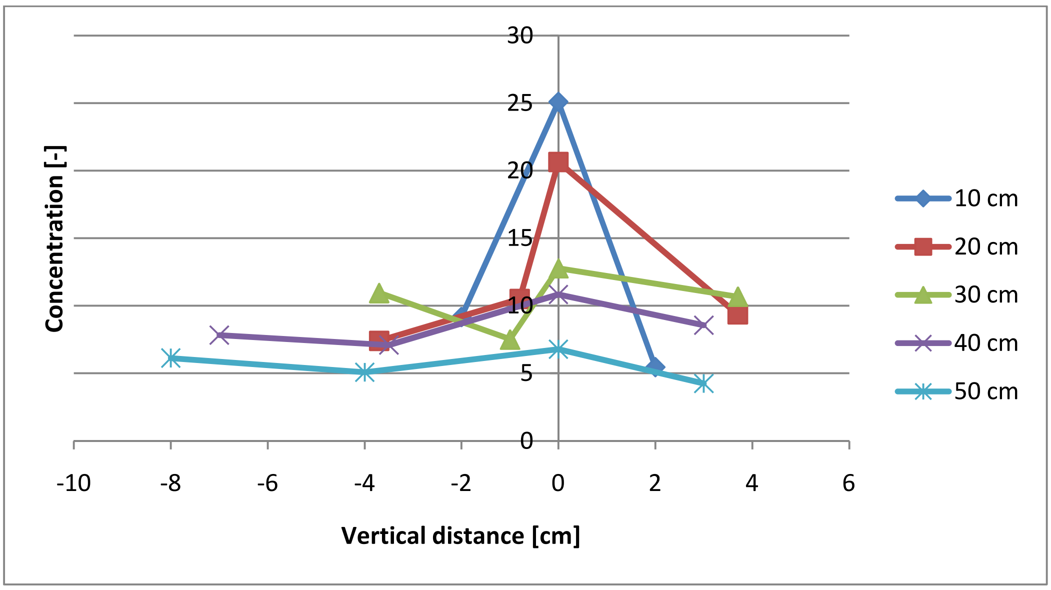
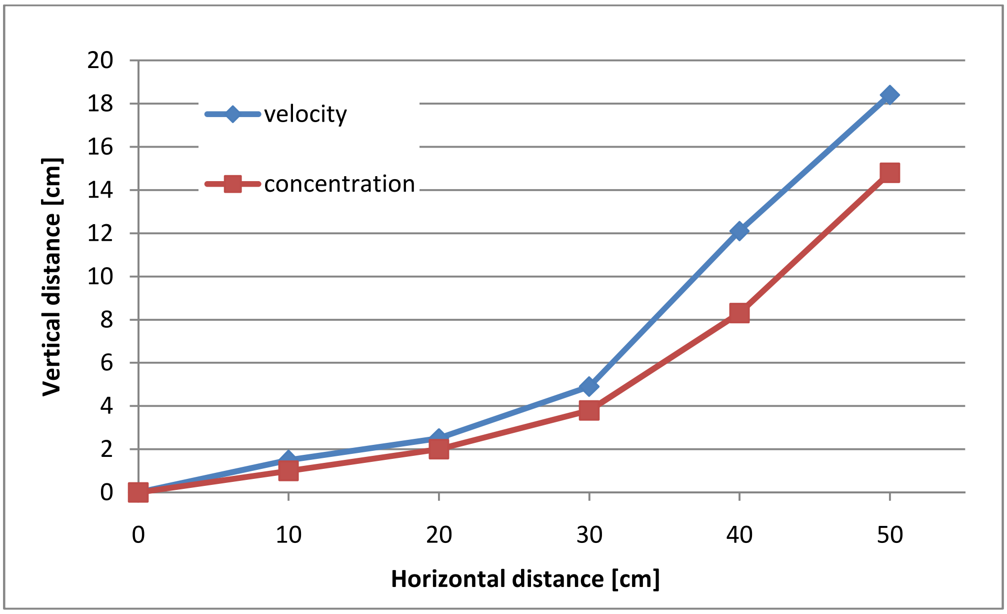


Figure 4.2.5: Concentration distribution

While in first few measurements, a clear peak value can be seen, further the distribution of concentration is more uniform across the whole plane. Air in the room is fully mixed, so concentration in most places should equal approximately 1. In distance of 50 cm from the mouth of exhaling person, concentration equals approximately 6, what means that another person standing there would be exposed to 6 times more contaminants. However only in a case where the mouth of another person would be exactly in the center of the exhalation jet.



horizontal distance [cm]	vertical distance [cm]
0	0
10	1
20	2
30	3,8
40	8,3
50	14,8

Figure 4.2.6: Flow path for velocity and concentration

Figure above shows flow path for concentration measurements. For comparison, results of velocity are also shown. Concentration behaves similarly to velocity, with little rise in short distance and a much higher further, when the jet loses most of its velocity. Trajectories of both lines behave almost the same up to the distance of 30 centimeters from the mouth. Further, it seems that peak concentration values are slightly below the places where highest velocities are found.

Figure below shows how possibly the interaction between two people would look when one was exhaling in direction of another, standing in 50 cm distance.

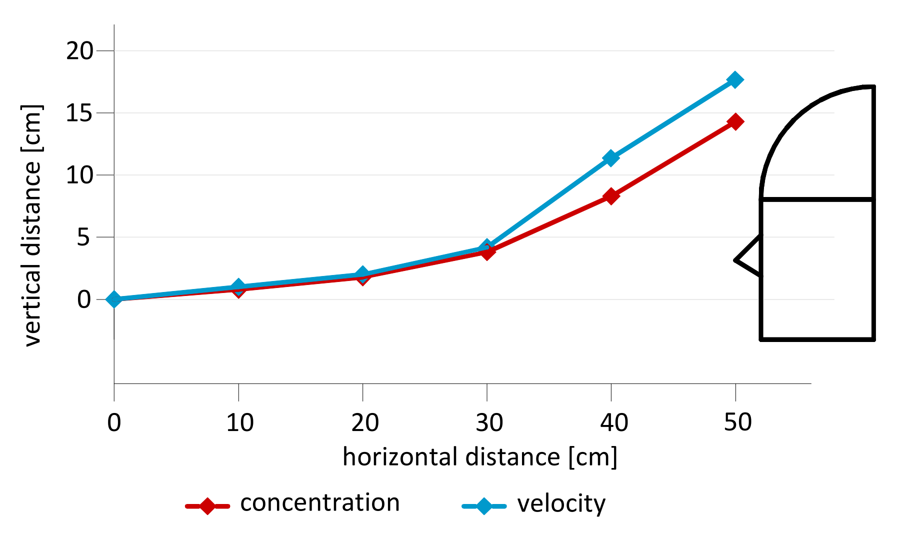


Figure 4.2.7: Flow path in relation to other person

To show how does one exhaling person interact with another one, a head of a manikin is drawn on the graph. It's mouth is located on the same level and distance between the heads equals 50 cm, which is a reasonable distance between people when they interact.

At 50 centimeters, the jet is above another person's head. Even considering that the jet is very wide in this distance, it should not have any influence on the area from where the person is inhaling air. A conclusion can be drawn from this, that mixing ventilation might be very satisfying in regard of preventing cross infection. This is further verified in chapter describing concentration results with two manikins.

It should be stressed that this figure is only a depiction used to have an understanding of how does the jet move in space, compared to another person. If another manikin was used in this experiment and placed as on the figure, the outcome would be different, as its boundary layer would affect the jet.

4.2.2 Manikin set to high activity

Results of experiments conducted with manikin set to low activity show that the exhalation of one person should not have a large influence on the breathing zone of another human. To check if this situation changes with higher activity, another set of measurements is made. Manikin is breathing more heavily (higher volume and frequency), what should result in exhalation jet of higher momentum and range. However, manikin also emits more heat and previous research [17] have shown that boundary layer of the manikin has a big influence on direction of the jet. Therefore it is expected that it might also have an impact here.

Velocity measurements

Results of velocity distribution measurements in the exhalation jet are shown on figures below:

Horizontal distance: 10 cm										
Vertical distance	[cm]	2	1,5	1	0,5	0	-0,5	-1	-1,5	-2
Velocity	[m/s]	0,56	0,91	1,51	2,02	2,55	2,51	2,19	1,44	0,86

Horizontal distance: 20 cm													
Vertical distance	[cm]	3,5	2,5	2	1,5	1	0,5	0	-0,5	-1	-1,5	-2	-3
Velocity	[m/s]	0,40	0,85	0,97	1,11	1,41	1,51	1,59	1,48	1,49	1,15	0,99	0,54

Horizontal distance: 30 cm													
Vertical distance	[cm]	-5,5	-4,5	-3,5	-2,5	-1,5	-0,75	0,75	1,5	2,5	3,5	4,5	5,5
Velocity	[m/s]	0,34	0,39	0,68	0,72	0,95	1,09	1,09	1,05	0,84	0,56	0,41	0,28

Horizontal distance: 40 cm								
Vertical distance	[cm]	4,5	3	1,5	0	-1,5	-3	-4,5
Velocity	[m/s]	0,40	0,42	0,72	0,78	0,70	0,67	0,43

Horizontal distance: 50 cm								
Vertical distance	[cm]	8	6	4	2	0	-2	-4
Velocity	[m/s]	0,41	0,53	0,61	0,63	0,72	0,52	0,40

Horizontal distance: 60 cm									
Vertical distance	[cm]	8	6	4	2	0	-2	-4	-6
Velocity	[m/s]	0,36	0,41	0,44	0,50	0,54	0,51	0,42	0,38

Figure 4.2.8: Velocity distribution in exhalation jet

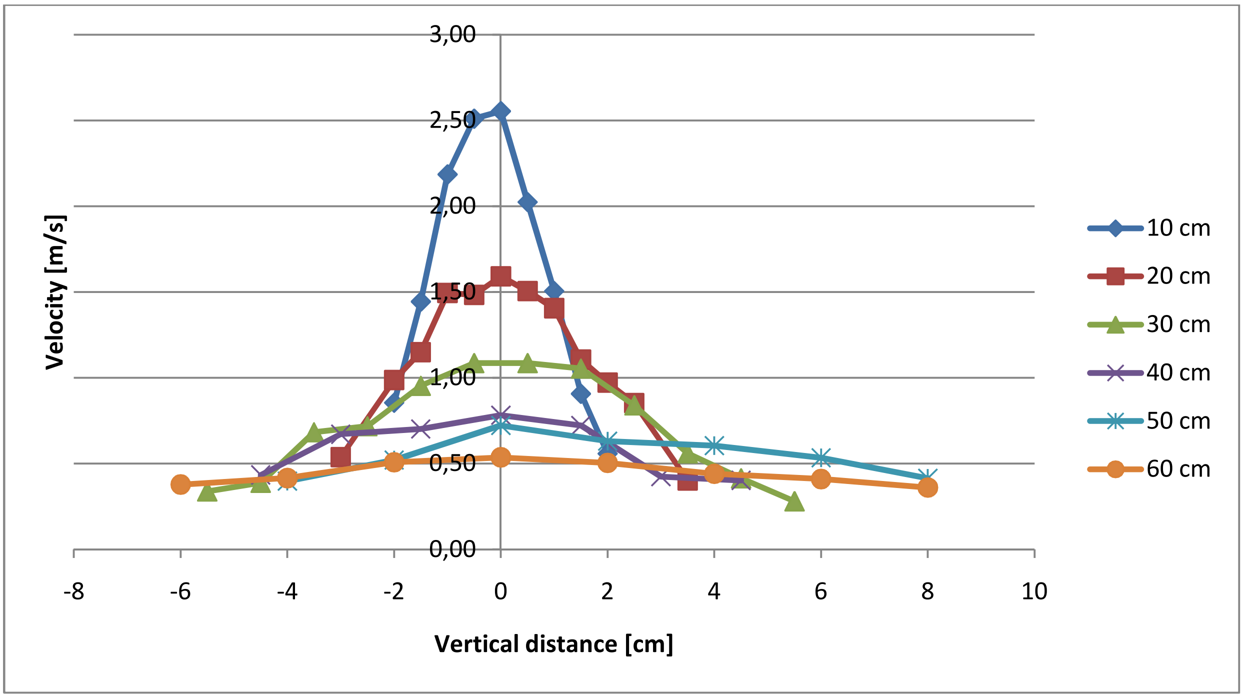
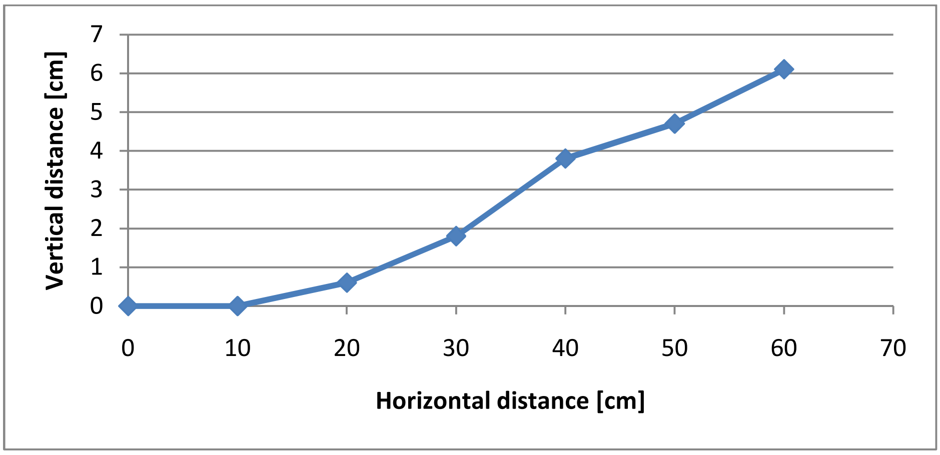


Figure 4.2.9: Velocity distribution in exhalation jet

Initial velocity equals 5,39 m/s. In this case also velocity decay is very large in the first phase of exhalation. The further it goes, the smaller the rate of decay is. In general, the distribution seem fairly similar to that from lower activity case. However, here velocities are much higher. At distance of 10 cm from the mouth it is twice as high. Range of exhalation is also larger. In this case the measurements are stopped at further distance than in previous case - 60 cm from the mouth and still, here the velocity is still fairly high – around 0,5 m/s.

Figure below presents trajectory of the jet:



Horizontal distance [cm]	Vertical distance [cm]
10	0
20	0,6
30	1,8
40	3,8
50	4,7
60	6,1

Figure 4.2.10: Flow path

Compared to case with lower activity, here the rise of the jet is much lower. Since the momentum is higher, the buoyancy is not affecting the jet to such a great extent. At distance of 50 cm the core of the jet is located 13,7 cm lower, what is a considerable difference.

It seems that, even though boundary layer is stronger in this case, momentum of the jet is the prevailing force. The exhalation jet moves faster, is more horizontal and reaches higher distances.

Concentration measurements

Horizontal dist.:	[cm]	10		
Vertical distance	[cm]	-2	0	2
Concentration	[-]	3,08	27,73	13,17

20			
-4	-2	0	2,5
8,11	11,97	14,39	8,29

Horizontal dist.:	[cm]	30			
Vertical dist.	[cm]	-2	0	2,2	4,5
Concentration	[-]	8,4	10,89	8,94	7,25

40			
-2,5	0	2	4
6,72	9,7	8,74	8,47

Horizontal dist.:	[cm]	50			
Vertical dist.	[cm]	-4,5	-2	0	2
Concentration	[-]	6,39	6,6	7,73	7,34

60			
-4	-2	0	2,5
6,05	6,15	6,77	6,3

Figure 4.2.11: Concentration distribution

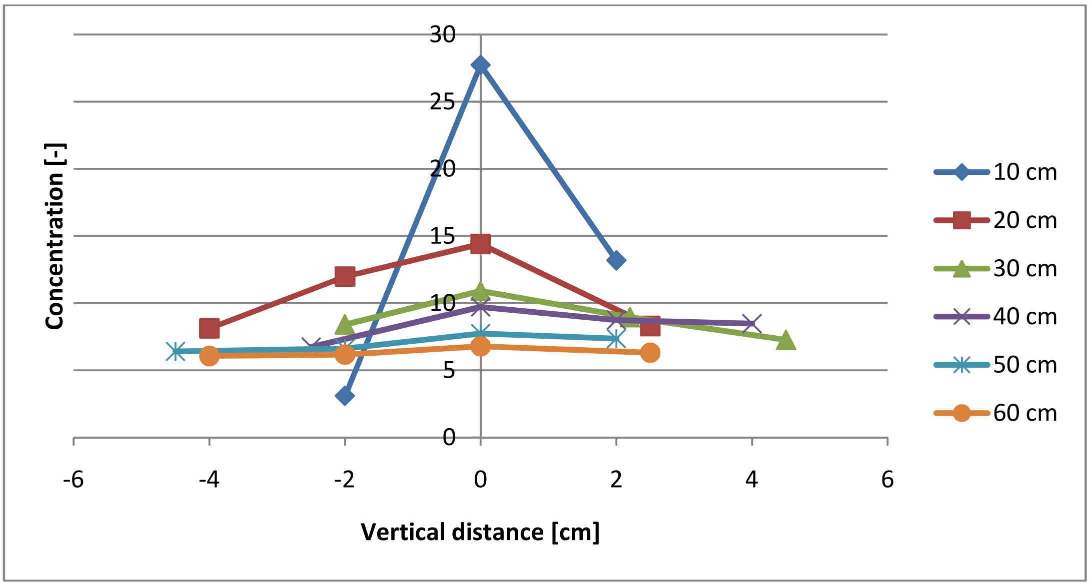
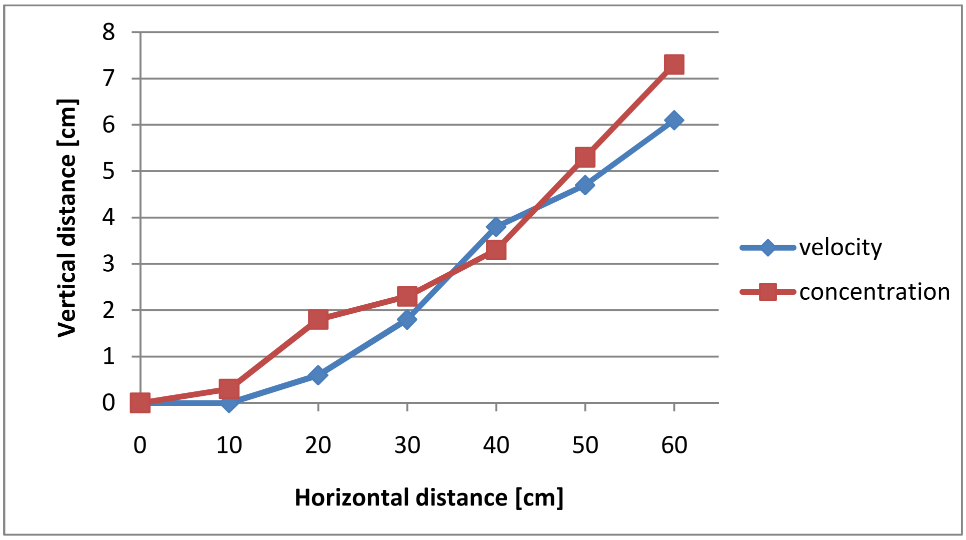


Figure 4.2.12: Concentration distribution

Compared to lower activity case, the values measured here are mostly slightly lower. This may happen because the jet is faster and tracer gas is being spread over a larger distance. However, more importantly, the trajectory of the jet changes to more horizontal, what might result in larger influence on another person. Figure below shows where peak concentrations are measured:



Horizontal distance [cm]	Vertical distance [cm]
10	0,3
20	1,8
30	2,3
40	3,3
50	5,3
60	7,3

Figure 4.2.13: Flow path of velocity and concentration

Both lines are fairly similar. Compared to low activity case, the rise is much lower. At 50 centimeters it is approximately 7 cm above the mouth, compared to 15 in previous situation. This means that contaminants have a higher possibility of reaching other's person breathing zone. Figure below shows more on that issue:

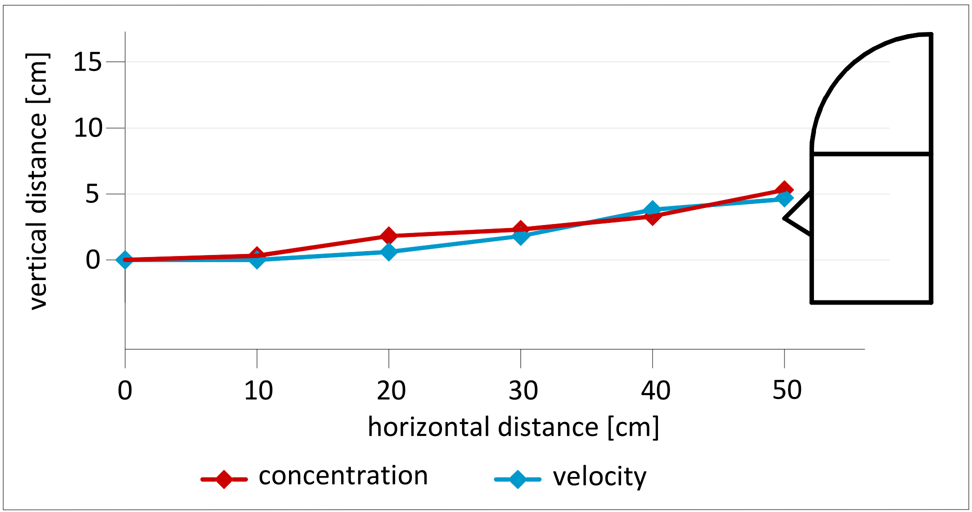


Figure 4.2.14: Concentration and velocity trajectories in relation to other person

In previous case, the jet was going right above the place where head of another person could be. Here the direction is straight into the face. At distance of 50 cm, the jet is only approximately 5 cm above the mouth. Considering that the jet is relatively wide in this plane (around 12 cm), it could have a considerable effect on another's person inhalation zone. This shows that risk of cross infection might be much higher when a person has higher activity level.

It should be noted that there is a certain flaw to experiments conducted with high activity. Normally, a person would open the mouth more widely when exhaling more air. In measurements conducted with thermal manikin it is impossible to change area of the mouth. In reality, the results for exhalation with high activity level would be probably different

4.2.3 Mathematical description of velocity and concentration distribution

The exhalation flow is pulsating and very turbulent what makes it difficult to describe. It can be seen as something between a vortex ring and partly an instantaneous jet. However, it has been studied [23] that it can behave similarly to a jet when using peak velocity values. In this chapter exhalation flow is described as a jet, using known equations.

According to [18], velocity decay in isothermal jets in surroundings with mixing ventilation can be determined by the following equation:

$$\frac{u_x}{u_0} = K_v \left(\frac{x}{\sqrt{a_0}}\right)^{n1} \quad (1)$$

Where: K_v – is the proportionality constant
x – distance from the mouth where peak velocity was found
a_0 – area of the mouth
u_0, u_x – initial velocity at the mouth and peak velocities at distance x

A free jet has n_1 value of -1, what means that in log-log depiction of the equation, the slope would be -1. This case is however different and any value of n_1 can be expected to describe the relationship between velocity and distance from the mouth.

The same way, concentration decay can be depicted:

$$\frac{c_x}{c_0} = K_c \left(\frac{x}{\sqrt{a_0}}\right)^{n2} \qquad (2)$$

Where: K_c – is the proportionality constant

c_0, c_x – initial concentration at the mouth and average concentration values at distance x

c_r - concentration in the outlet

In this case, average values are used instead of peaks, since it is very difficult to capture a peak concentration value of concentration.

Table below presents data for velocity measurements for both activity levels:

x	[m]	0,10	0,20	0,30	0,42	0,53
u_x/u_0	[-]	0,39	0,33	0,20	0,17	0,08
C_x/C_0	[-]	0,43	0,35	0,22	0,18	0,12
$x/a^{1/2}$	[-]	10,43	20,79	31,35	43,10	54,95
Kv	[-]	3,82				
Kc	[-]	2,95				
n_1	[-]	-0,88				
n_2	[-]	-0,76				

Figure 4.2.15: Calculations for low activity

x	[m]	0,10	0,20	0,30	0,40	0,50	0,60
u_x/u_0	[-]	0,48	0,30	0,21	0,15	0,14	0,10
C_x/C_0	[-]	0,47	0,24	0,18	0,16	0,13	0,11
$x/a^{1/2}$	[-]	10,31	20,64	31,00	41,43	51,80	62,20
Kv	[-]	3,31					
Kc	[-]	2,70					
n_1	[-]	-0,82					
n_2	[-]	-0,77					

Figure 4.2.16: Calculations for high activity

Calculations show that proportionality constant for velocity equals 3,82 and 3,31 for low and high activity cases respectively. This value is similar to one obtained by Inez et al. (2010). Exponent n_1 equals -0,88 and -0,82.

For concentration, the constant equals 2,95 for low activity case and 2,70 for high activity. The exponent equals -076 and -0,77.

Graphs below present depiction on a log-log graphs of velocity and concentration decay in relationship to dimensionless velocity.

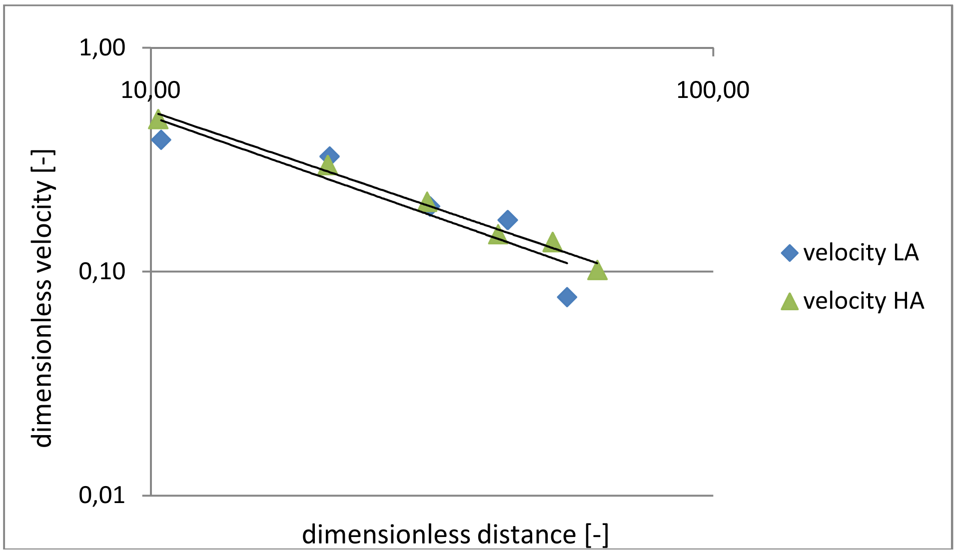


Figure 4.2.17: Dimensionless distance and velocity for both activity levels

Both slopes are similar, with a value approaching -1. This suggests that exhalation flow can be described as a free jet when peak velocities are used.

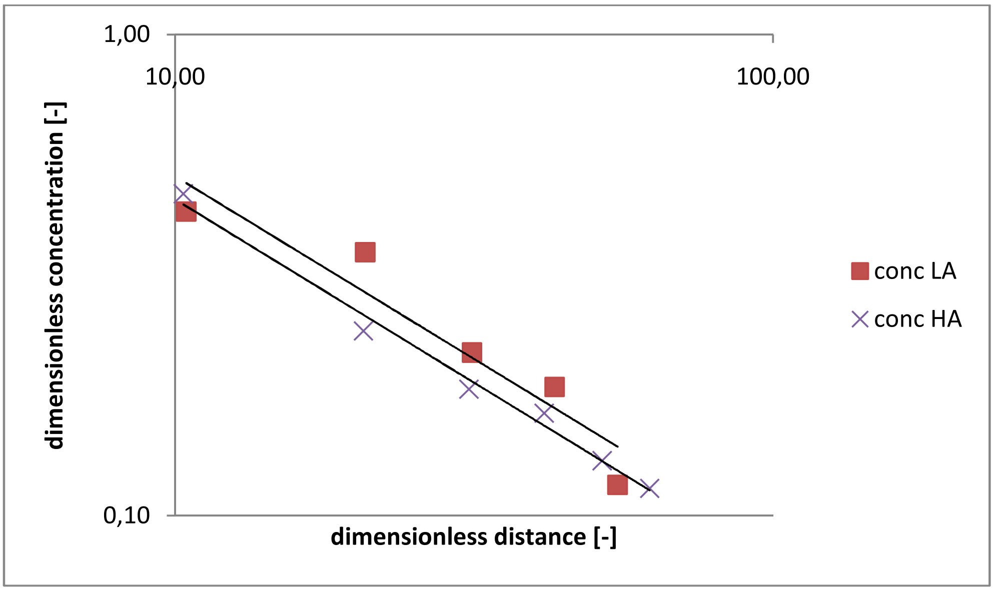


Figure 4.2.18: Dimensionless distance and concentration for both activity levels

Dimensionless concentration shown on a log-log graph in relation to dimensionless distance also follows a slope close to -1. Both slopes are parallel to each other. This means that equations for free jet also can be applied for describing concentration decay, with the use of average values.

4.3 Results for two manikins

This part of the project is done to check correlation between contaminant source manikin (exhaling manikin) and target manikin (inhaling manikin). In the first part of the project the flow path for concentration was described, what shows how the jet can influence the other manikin. It can be noticed that for low activity situation main core of the jet moves above the mouth of inhaling manikin. This part of the project will describe how big is the influence of exhalation on another person in cross infection meaning for airborne diseases. Several cases are investigated: exhalation through the mouth with different activity levels, exhalation through the nose with various angles of expiration. Comparison with previous experiments that investigated similar cases in different air distribution systems is also made.

4.3.1 Reference to measurements with one manikin

First part of investigation is to check the concentration profile for two manikins facing each other. The target manikin is placed at different distances form source manikin (35cm, 50cm, 80cm and 110cm). List of measurements done in this part is shown in table 3.6.2.

Conditions in the room during the experiments are described in chapter no. 4.1.

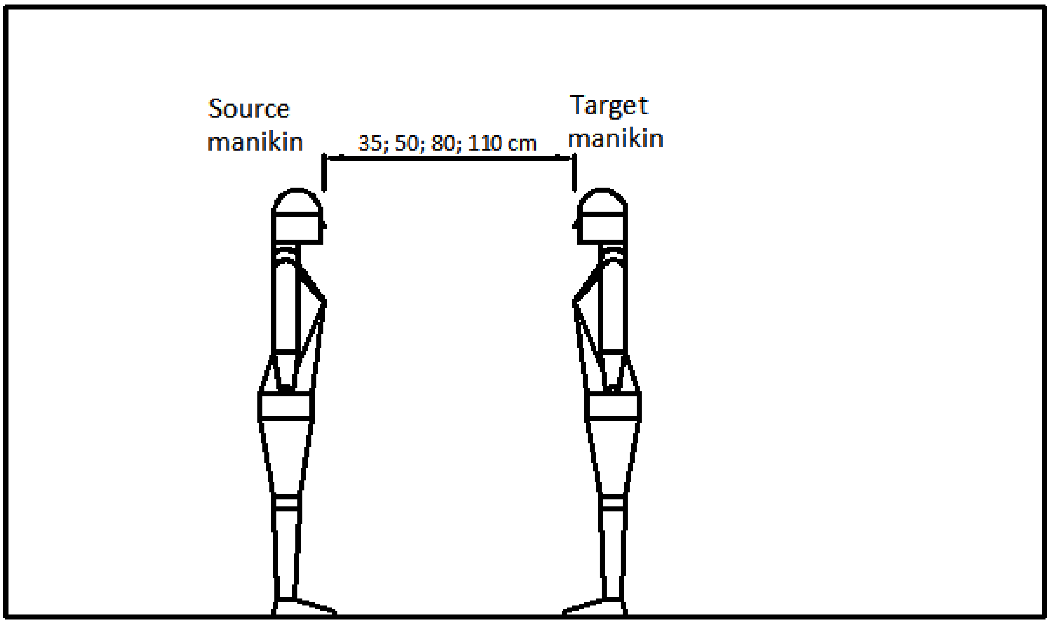


Figure 4.3.1: Placing the manikins in the room during measurements

Situating the inhaling manikin in this four distances was chosen after analyzing the flow path of exhalation based on velocity measurements. Figure below shows flow paths obtained in experiments with one manikin in relation to locations of target manikins in this case. It can give an idea of what to expect in this part of research.

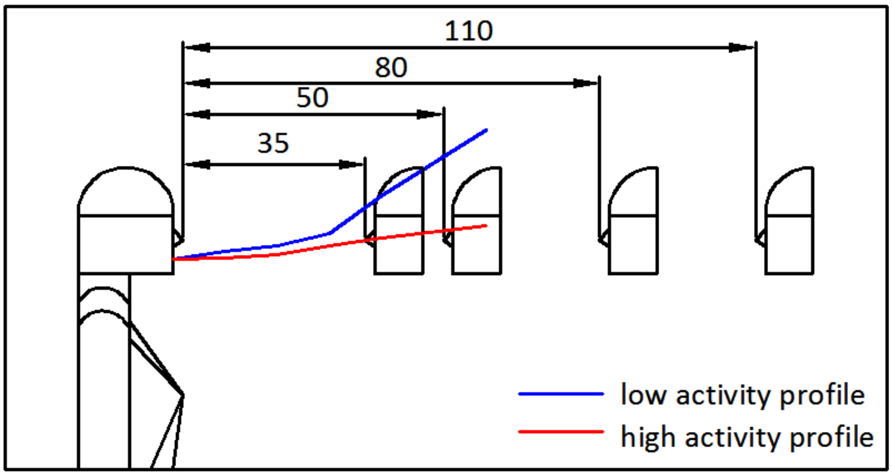


Figure 4.3.2: Situating of the target manikin according with exhalation profile of source manikin

It can be seen very clearly that in 35 cm distance, exhalation with high activity setup should hit the face of target manikin almost with its core. In low activity exhalation in 35 cm distance, the jet does not hit areas where mouth or nose of inhaling manikin is. Also, thermal plume of target manikin should have some influence on these two jets. The flow paths shows that low activity profile should not affect the target manikin in 80 cm and 110 cm distance from source manikin and all three concentration points should give ambient concentration value. For high activity, ambient value should probably occur in 110 cm distance from exhaling manikin.

4.3.2 Exhalation through the mouth, target manikin with low activity

The results for low activity situation are shown below.

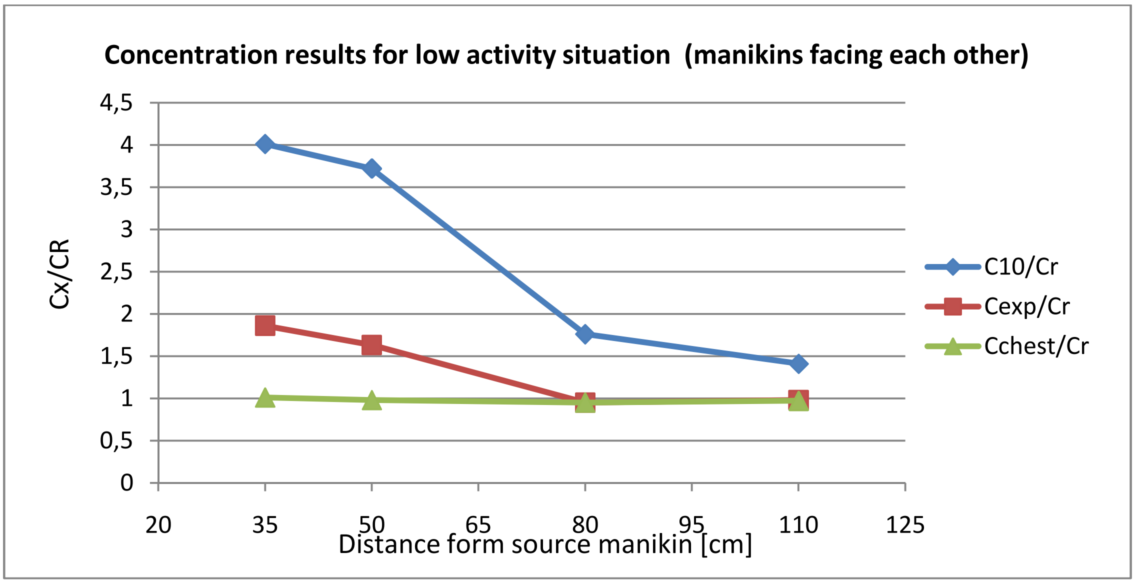


Figure 4.3.3: Concentration results for low activity setup.

Measurement point $C_{10}$is the point on 172cm height from floor, C_{exp} is point near the mouth of target manikin and C_{chest} is the point near the chest of manikin, more detailed description in chapter 3.6.1.

After analyzing results for case with low activity setup for one manikin (table 4.2.4 in chapter 4.2.1) it can be assumed that at 35 cm distance from source manikin at the height of the mouth, the concentration should be around 8. As we can see on figure no 4.3.3, result for exposure at 35 cm distance form source manikin is equal to 1,8, which is more than 75% lower value than it was measured before. It can be assumed that exhalation is affected by target manikin thermal plume, which works as a sort of protective boundary layer.

The part of the jet which is near the mouth is the edge part of the jet which has very low velocity and it can be easily moved by thermal plume.

With increasing distance values of concentration near mouth (C_{exp}) and in C_{10} point decrease what was established before. At the 80 cm distance $\frac{C_{exp}}{C_R}$ is almost equal to 1 which means that concentration near the mouth is equal to concentration in the test room where air in the room is fully mixed. At 80cm distance between manikins there is no direct influence of exhalation on target manikin and all contaminant air inhaled by manikin is ambient air.

Concentrations near the chest equal 1 in all distances, what would suggest that the air in the room is fully mixed.

4.3.3 Exhalation through mouth, source manikin with high activity

In the next measurement manikins are placed at the same distances as previously, but activity level of source manikin is changed to a higher one. As it was seen in experiments with one manikin, the flow path for exhalation with high activity is different. The trajectory is more horizontal, therefore it should have bigger influence on the target manikin.

The results for this are shown below.

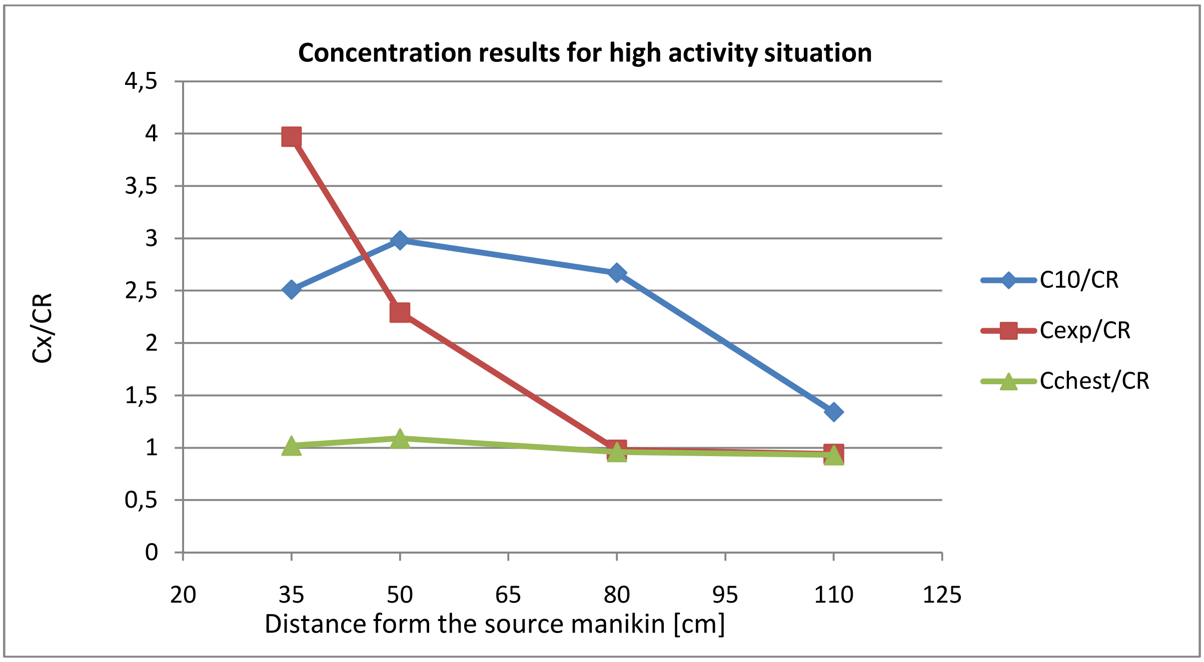


Figure 4.3.4: Concentration results for low activity setup.

Because of much higher momentum of the exhaled air, concentration near the target manikin's mouth at the 35cm distance form source manikin is almost equal to 4, compared to value 1,86 for low activity situation. It shows much higher influence of the high activity jet on target manikin. This means that the risk of cross infection in this case is much higher. At distance of 50cm value near the mouth is equal to 2,3 which is still much higher than value for low activity setup at the same distance. It is the confirmation of the statement that higher results on mouth level are caused by higher momentum of the jet. However, at the distance of 80 cm there is no influence of source manikin's exhalation on the target. This means that regardless of activity level, in this distance there is no risk of cross infection.

Also result for C_{10} point at the distance of 35cm shows that momentum of exhalation drives the jet in more horizontal direction. Value for this point is 2,5 for high activity and it is lower than for previous measurement. The growth of concentration between 35cm and 50 cm distance is caused by direction caused by higher momentum.

Again, concentration level at the height of the chest stays at a constant level of approximately 1.

4.3.4 Exhalation through the mouth, height difference between manikins.

In this case, the target manikin is placed at fixed horizontal distance from source manikin which is equal to 50cm. Measurement is made for three different vertical distance of target manikin i.e. manikin standing on the floor, manikin on 8cm stand and manikin on 16 cm stand. Both manikins (facing each other) were set to low activity parameters during this measurement . Description how inhaling manikin is placed in accordance to the jet shows figure 4.3.5.

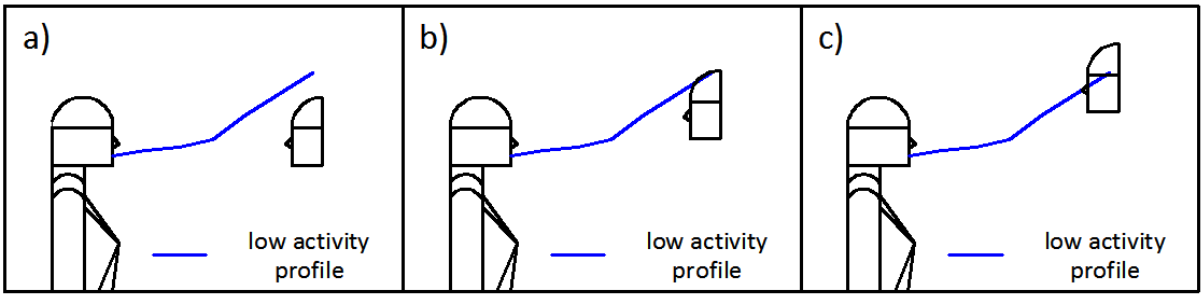


Figure 4.3.5:. Situating of target manikin in accordance to the jet i.e. a) standing on the floor, b) standing on 8cm stand, c) standing on 16cm stand

This measurement is made to check what influence the height of inhaling person has on the cross infection. It is expected that concentration near the mouth of target manikin will increase with increasing height of inhaling manikin. The results for concentration measurements are shown below.

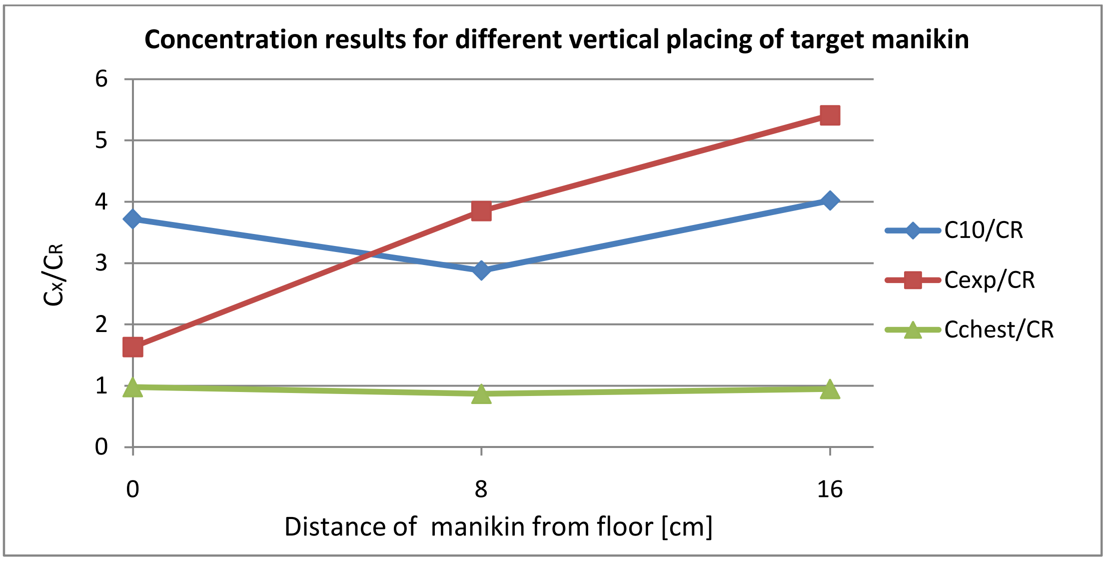


Figure 4.3.5: Concentration results for different vertical placing of target manikin

Measurement point are on the fixed heights referred to the feet of the manikin which means that all measurement points were moved in vertical direction with the same value as manikin. Concentration near the mouth of the manikin increases with vertical distance from the floor as is it was mentioned before.

When the manikin is risen by 8 cm, the exposure rises significantly from 1,63 to 3,85. With another 8 cm rise, it changes to 5,4. In measurements with 1 manikin, at this height the concentration equaled around 5,8. It shows that thermal boundary layer of target manikin removes some tracer gas, before it is inhaled. However, the drop is not significant. This might mean that when the middle of the exhalation jet hits target manikin's mouth it is not removed by thermal plume to a big extent, due to higher velocity.

Concentration at the chest does not change with different heights.

4.3.5 Exhalation through the nose

As described in chapter 2.1.3 the exhalation angles for the nose do not resemble reality. To create more real exhalation conditions, angle is corrected with temporary measures. Two different angles are shown below.

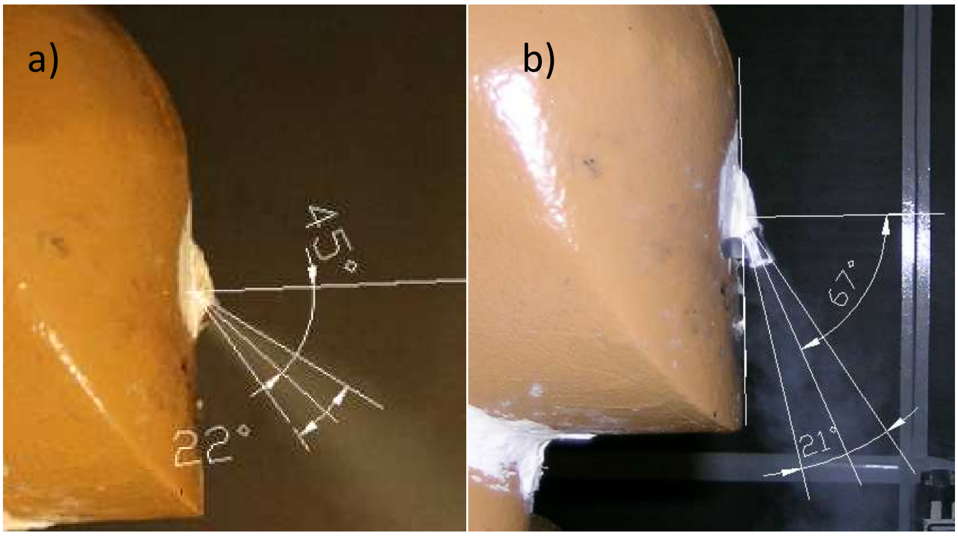


Fig. 4.3.6: a) Manikin before angle change, b) manikin after angle change

Even though the standard θ_m angle for exhalation through nose is 60° +- 6° for human it is decided to carry out measurements with two different angles. First measurement in this case is with the θ_m equal to 45° which is not a standard geometry described by [2](see table 2.1.7 and figure 2.1.5) but might still occur in reality. Second measurement is made for most vertical standard exhalation through nose, the angle is chosen to be 67° to get the highest difference between standard exhalation and default geometry of the manikin. This comparison will show what influence does different θ_m angle have for contaminant distribution near the target manikin.

For these two measurements both manikins are set to low activity parameters.

Measurement for unmodified geometry of manikins nose is made only at 50cm distance between source and target manikin where measurement for modified geometry is made at all four distances (35-110cm between manikins).

Because of geometry of the nose and downwards direction of expiration it is estimated that results in all points will be higher that for the case when manikin is expiring through the mouth. It is also expected that at distance of 50, 80 and 110cm concentration value should be similar in all three check points i.e. near the chest, near the mouth and at above the head, because exhalation has a downward direction and it hits thermal plume of both manikins and afterwards it is probably dissipated by thermal plume of target manikin. In about 50cm from source manikin buoyancy force and thermal plume of target manikin will move the exhaled contaminated air upward. This conjectures can be made after studying Liu et al. [17] where exhalation through nose was investigated.

Results for concentration measurement are shown below.

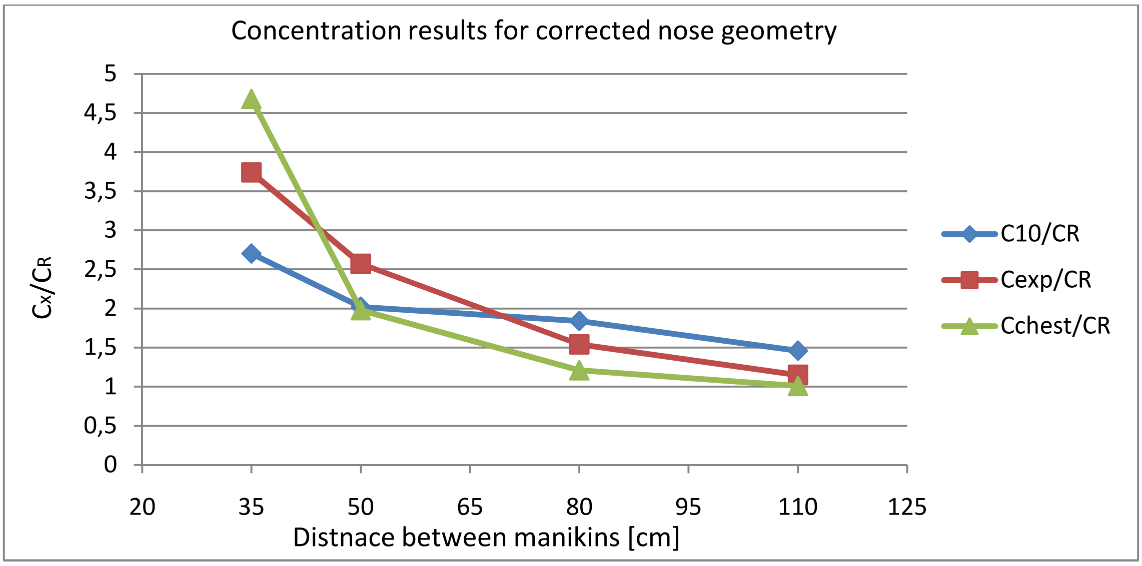


Figure 4.3.7: Concentration results in four distances between source and target manikin for corrected nose geometry of exhaling manikin.

As it was stated, concentration near the chest and the mouth is higher than for exhalation through the mouth. It is caused by geometry of exhalation. Results in these two measuring points (near chest and mouth) are higher in all distances between target and source manikin. At 35 cm distance, the result at the mouth equals 3,8, what makes the exposure here more than twice higher than in exhalation through the mouth. At distance of 80cm the result is 1,6, where in mouth case, target manikin inhales fully mixed ambient air (concentration equal to 1).

Results between all three measuring points in the distances of 50, 80 and 110cm are quite close to each other and they have similar decay of concentration with the distances from manikin (especially near mouth and chest). It can be stated that in more than 50cm form exhaling manikin a pall of contaminant is rising with the thermal plume of target manikin.

To sum up, the geometry of expiration and conditions in the test room cause the exhalation through the nose to be more dangerous for another person i.e. target manikin inhales more contaminant than in exhalation through mouth.

Running and comparing cases of exhalation through nose for high activity settings are unnecessary because person with higher activity usually breaths through the mouth.

Now when concentration results for standard geometry of nose are described the chapter can move to another part i.e. comparing results of exhalation through nose for two different θ_m angles.

It is expected that concentration will be higher near the mouth and above the head of target manikin for default geometry of exhalation of source manikin. Lower concentration is expected to be near the chest at 50 cm distance between manikins for angle θ_m equal to 45°. The difference are caused by different flow path of exhalation. It is supposed that thermal plumes of both manikins will spread the exhalation to the wide area and afterwards contaminant will be moved by thermal plume and buoyancy force.

The comparison of the concentration results are show on the graph below where the concentration measurements point are described.

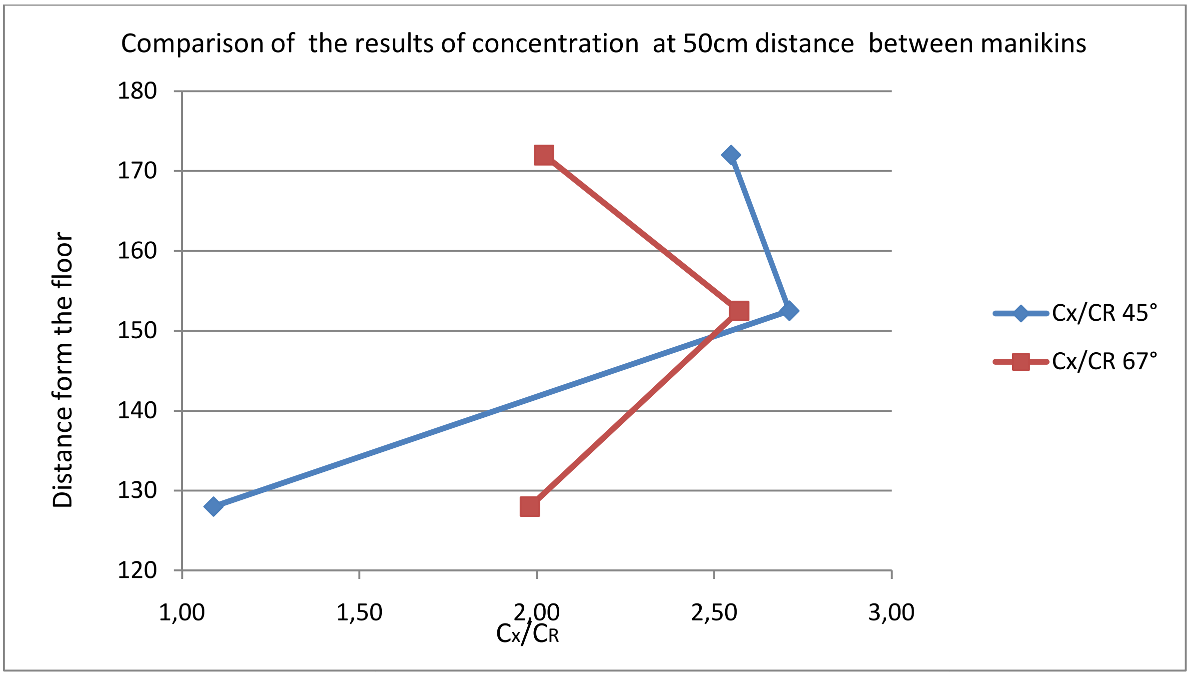


Figure 4.3.8: Comparison of concentration results at 50 cm distance between manikins for two different angles of exhalation

As it was expected results near the chest are much higher for more vertical exhalation however concentration near the mouth is very similar for both angles which was not expected. It can be stated that exhalation in the 50cm distance form source is so wide that it has no significant difference between θ_m angle in expiration, the similar pall of exhaled air is moved by thermal plume and inhaled by another manikin even though the expiration is more horizontal for θ_m equal to 45°.

4.3.6 Comparison with previous research

At Aalborg University similar experiments were performed by Peter V. Nilsen et al., 2008 [20] and Piotr Grzelecki with Ines Olmendo , 2010 [19] with various types of air distribution systems. Parameters used in that researches are shown below:

Parameters	2010	2008	Unit
Air distribution system	Displacement	Mixing	-
Air changes rate	5,7	5	1/h
Temperature in the test room	21,6	23	ºC
Exhaling manikin heat flux	124	73	W
Temperature of exhalation	34	32	ºC
Volume of exhalation	11	6,8	l/min
Frequency of exhalation	15	10	breath/min
Inhaling manikin heat flux	124	73	W
Volume of inhalation	11	6,8	l/min

Table 4.3.9: Parameters set in previous experiments

Comparison to Grzelecki et al.

Placing the manikins and parameters of exhalation and activity are similar which means that results can be compared with these measurements. Most important difference between those two experiments is the ventilation system. System which was used in Grzelecki's et al. experiment was a displacement ventilation system. The basic assumption of displacement ventilation is that stratified conditions in the room should not expose the target manikin to inhale the notable amount of tracer gas particles. However, experiments [17] conducted with the use of displacement ventilation and exhaling thermal manikin show that exhalation in stratified conditions is more horizontal and could have higher influence on target manikin placed face to face with source manikin.

The result for Grzelecki's et al. experiment is show below.

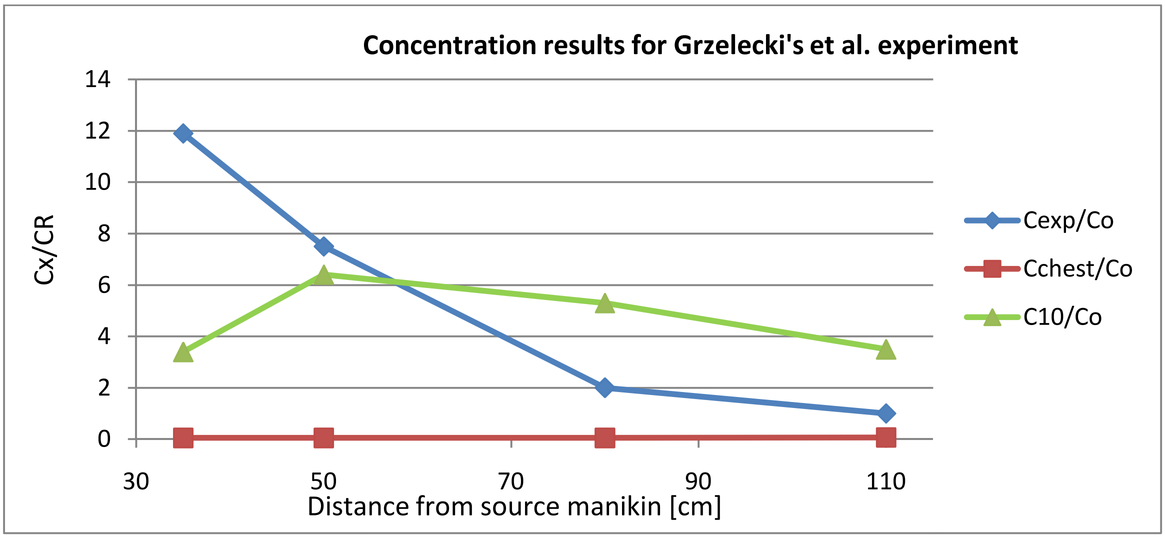


Figure 4.3.10 Concentration measurements for displacement ventilation experiment

Displacement ventilation create stratified conditions in the test room. Jet in this kind of conditions is more horizontal comparing to mixing ventilation. Influence of stratified flow is show on figure 4.3.10 where at distance of 35 cm between manikins value of concentration is almost equal to 12. Comparison of results near the mouth of measurements with mixing and displacement ventilation experiment is shown on figure 4.3.11.

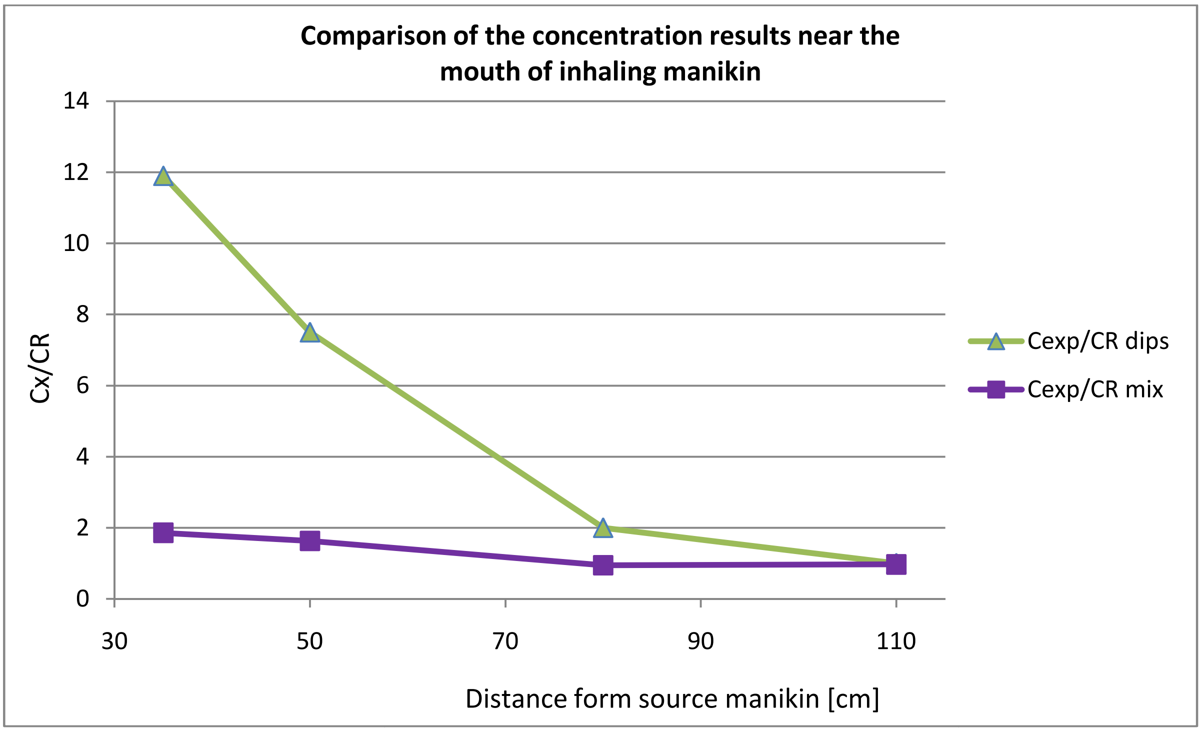


Figure 4.3.11: Comparison of mixing and displacement ventilation results of concentration near the target manikin mouth

As it is pointed out on the figure 4.3.11, concentration near the mouth of target manikin is much higher in all distances from source manikin for displacement ventilation case which is caused by stratified flow. In 35 cm distance, the exposure is almost 6 times higher in displacement ventilation case. In 110 cm, the exhalation has still influence on target manikin because ambient concentration in occupied zone should be close to zero, which is show on figure 4.3.10 by results near the chest.

It has to be mentioned that during experiment, which were carried out by Grzelecki et al., parameters of manikin and conditions in the test room i.e. heat flux, higher volume of exhalation and number of air changes contributed to lower results for concentration.. Which means that if during this experiment parameters were the same us parameters during our measurements, the concentration results for displacement ventilation should be significantly higher.

Comparison to Nielsen et al.

This research included cases with exhalation through the nose and through the mouth in a room with mixing ventilation. This case was however slightly different than our experiments. Different inlet was used – a radial diffuser. Figure below shows concentration level in the occupied zone in those experiments.

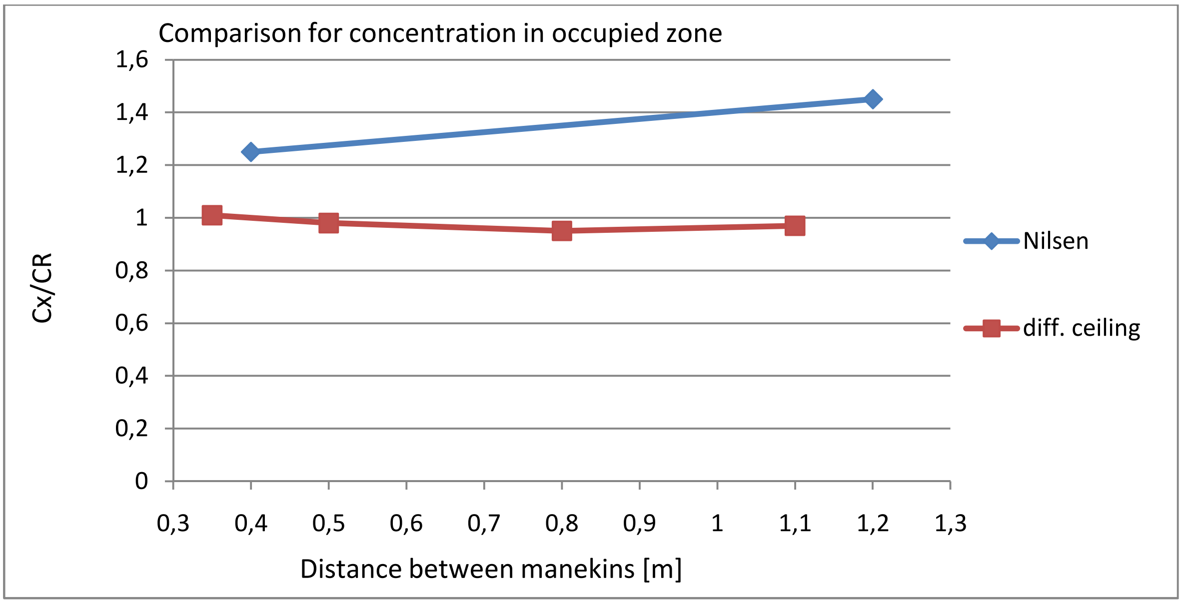


Figure 4.3.12: concentration in occupied zone

It can be seen, that in previous experiments, the concentration in the surroundings is not constant. That means that the air in the room is not fully mixed. This can affect the results of the measurements and should be taken into account when discussing results for cross infection.

In present research, the concentration level shows very little change with distance what means that the air is mixed.

Figure below shows results for exhalation through the mouth.

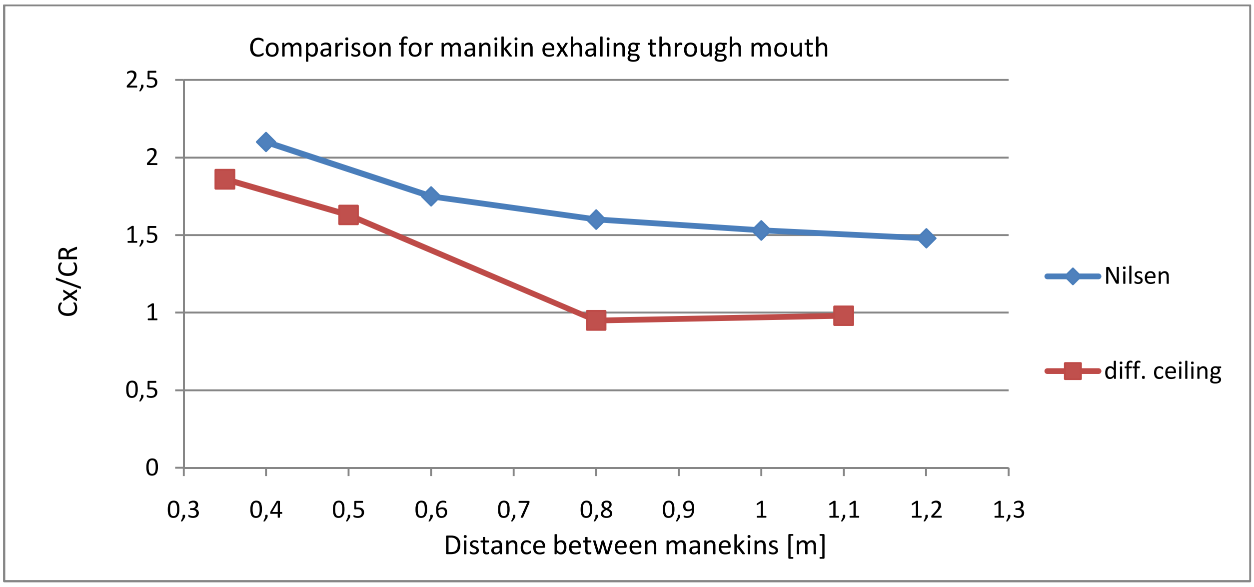


Figure 4.3.13: Comparison for manikin exhaling through mouth

Up to distance of 0,6 m the results are similar, although the concentration obtained in previous research is slightly higher. Further, the results obtained with use of diffuse ceiling equal 1 what means the concentration is the same as in the surroundings. Results from the past show constant but slow fall in the concentration level, but it does not decrease to a value of 1. This probably happens because air is not fully mixed and as figure 4.3.13 shows, the surrounding concentration equals approximately the same as concentration measured near the mouth.

Figure below shows results for exhalation through the nose:

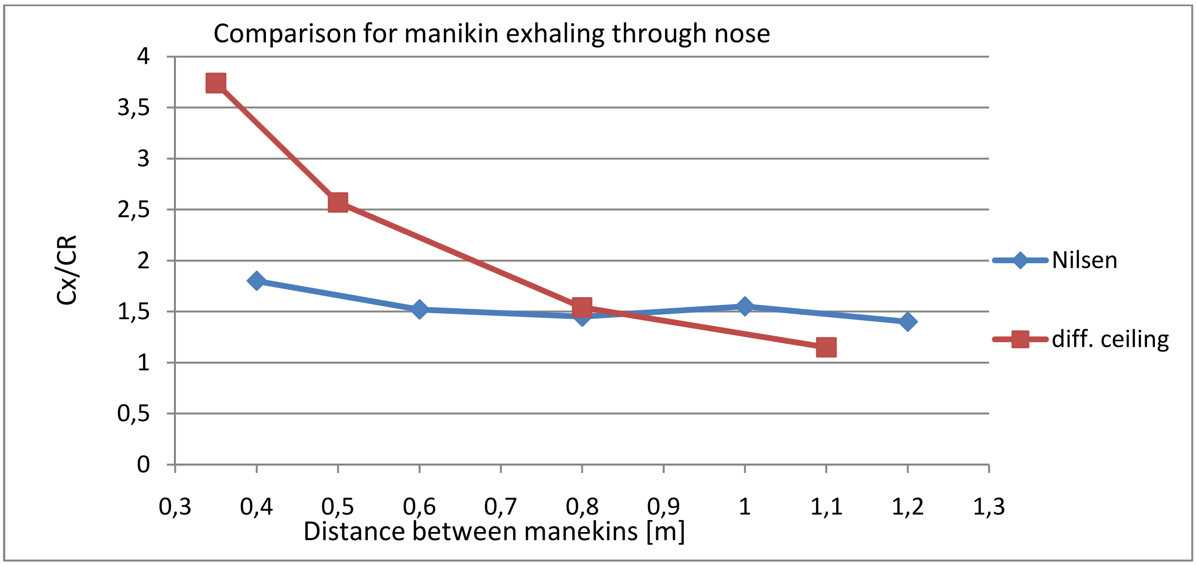


Figure 4.3.14: Comparison of results with exhalation through the nose

There is a significant difference in the results. Experiments conducted with diffuse ceiling show that exhalation through the nose is more dangerous in terms of cross infection with highest personal exposure value of 3,7. Previous research do not confirm that statement. Concentration level is fairly low, with values not higher than 2. The values are very to those in the surrounding air, what would mean that exhalation jet has almost no effect on target manikin.

It is unclear why there is such a difference in results for these two experiments. It can be a result of different temperature difference between expired air and ambient air (3 K lower in previous research) what could lead to smaller buoyancy force. Another explanation might be different air distribution system which could cause the flow to have a different direction.

Results for exhalation through the mouth are however very similar in both cases. It leads to a conclusion that exhalation through the nose is more dependent on a type of diffuser than exhalation through the mouth.

4.4 Smoke simulations

For supplementation of the measurements and visualization of the breathing process, smoke simulations are also made. This chapter presents the results of visualizations.

4.4.1 Exhalation through the mouth, low activity

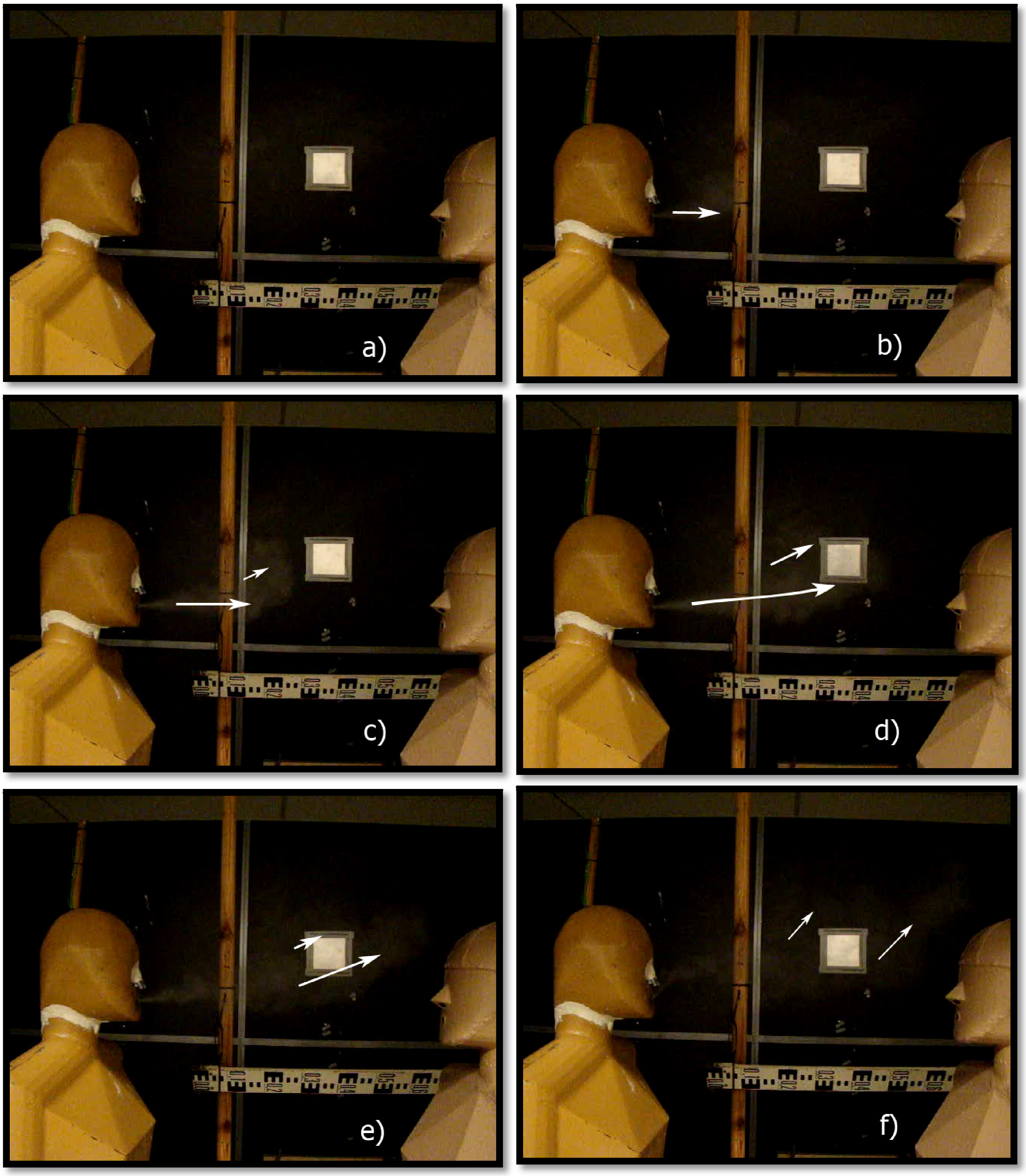


Figure 4.4.1: Single exhalation through mouth for low activity setup in a)0s; b)0,5s; c)1s; d)1,5s; e)2s f)2,5s of expiration

Figure above presents the case with manikin set to low activity and exhalation through the mouth. Manikins are placed in 50 cm distance

In the first moments, the exhalation has a horizontal profile. The more distance it covers, the more upward its direction becomes. It can be seen that the whole jet goes above others manikins head, what confirms previous measurements and statements. It can be clearly seen that the exhalation flow has very little effect on another person.

4.4.2 Exhalation through the mouth, high activity

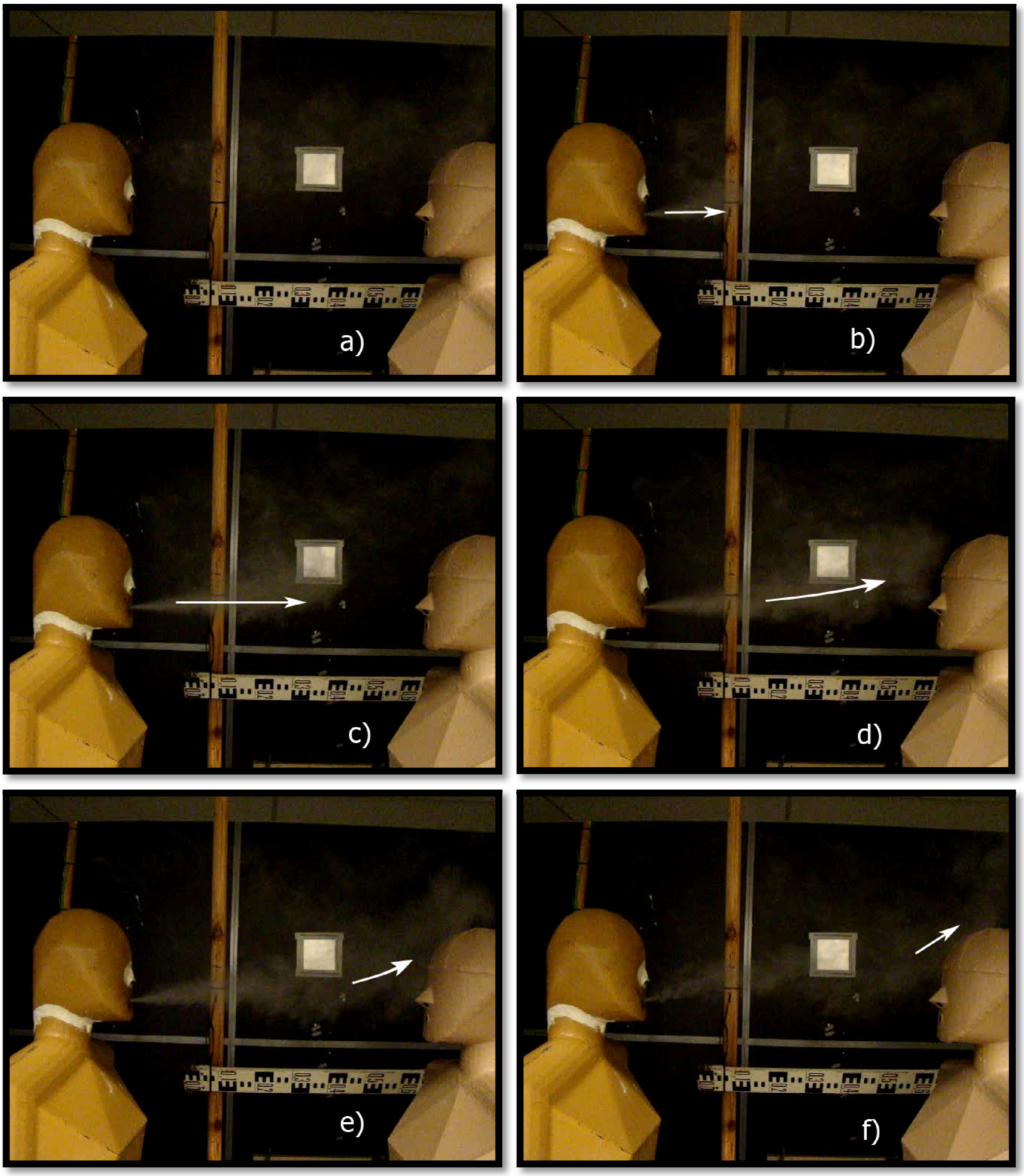


Figure 4.4.2: Single exhalation through mouth for high activity setup in a)0s; b)0,5s; c)1s; d)1,5s; e)2s f)2,5s of expiration

When the manikin is set to high activity, the exhalation flow has a different behavior. Velocity is higher and because of that, buoyancy has a smaller influence on the direction of the flow. Profile of the jet is much more horizontal. It can be seen, that exhalation jet hits the head of target manikin.

This experiment proves that with higher activity level, personal exposure is much higher. Direction of the flow is changed and it has a bigger chance of influencing another person.

4.4.3 Exhalation through the nose, changed angle

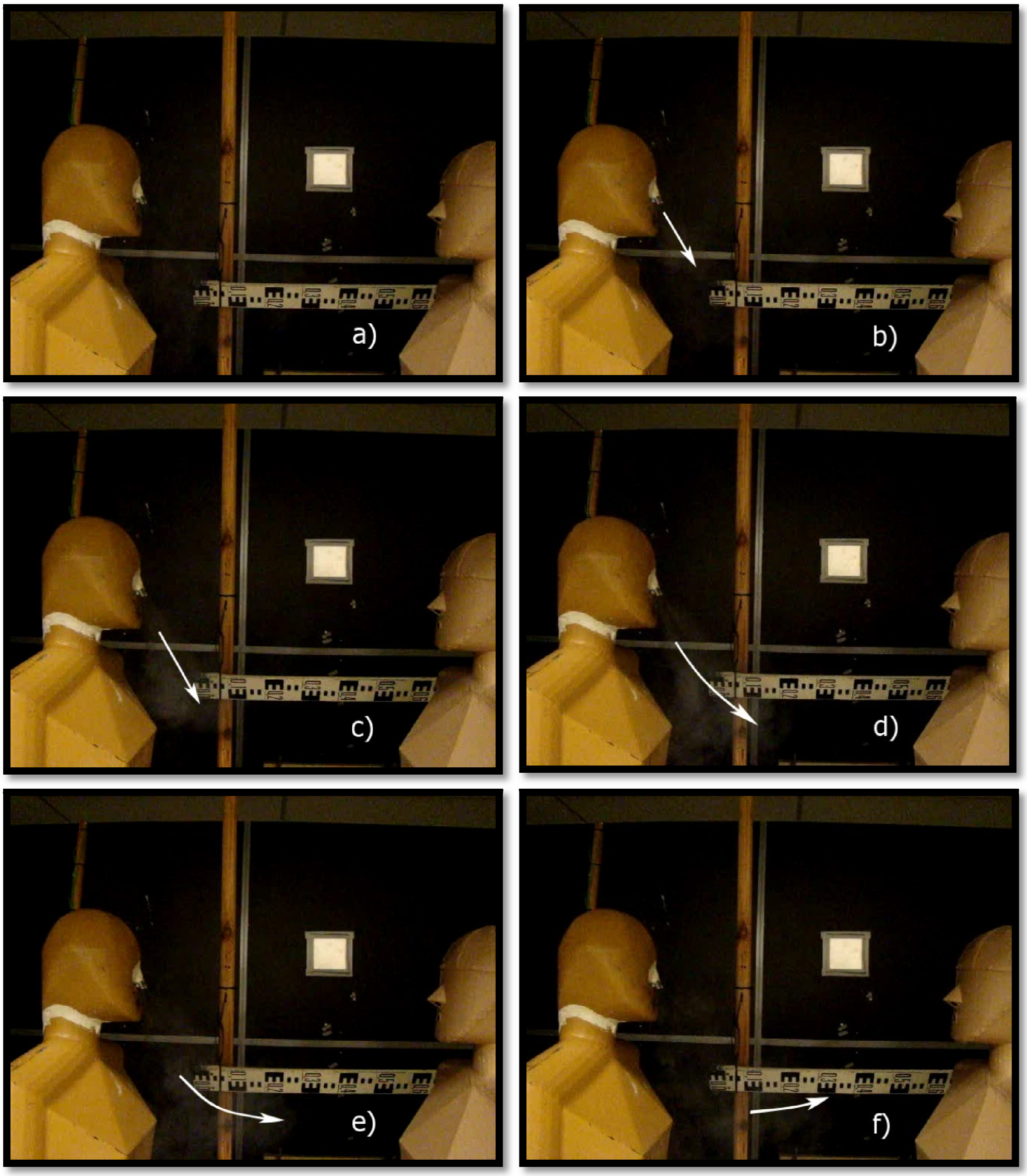


Figure 4.4.3: Single exhalation through nose for θ_m equal to 66° in a)0s; b)0,5s; c)1s; d)1,5s; e)2s f)2,5s of expiration

In the first part the flow has a downward direction because of geometry of the nostrils. In the next stages, when the expired air is at the level of chest it starts to move in horizontal direction. When it reaches the range of another manikin thermal boundary layer and buoyancy effect move exhalation upwards. Movie visualizations prove the statements from chapter 4.3.5 to be true.

4.4.4 Exhalation through the nose, default angle

Next figure shows single expiration through nose for θ_m equal to 45°. The difference between those two angles is easy noticeable. Exhalation is much more horizontal for smaller angle.

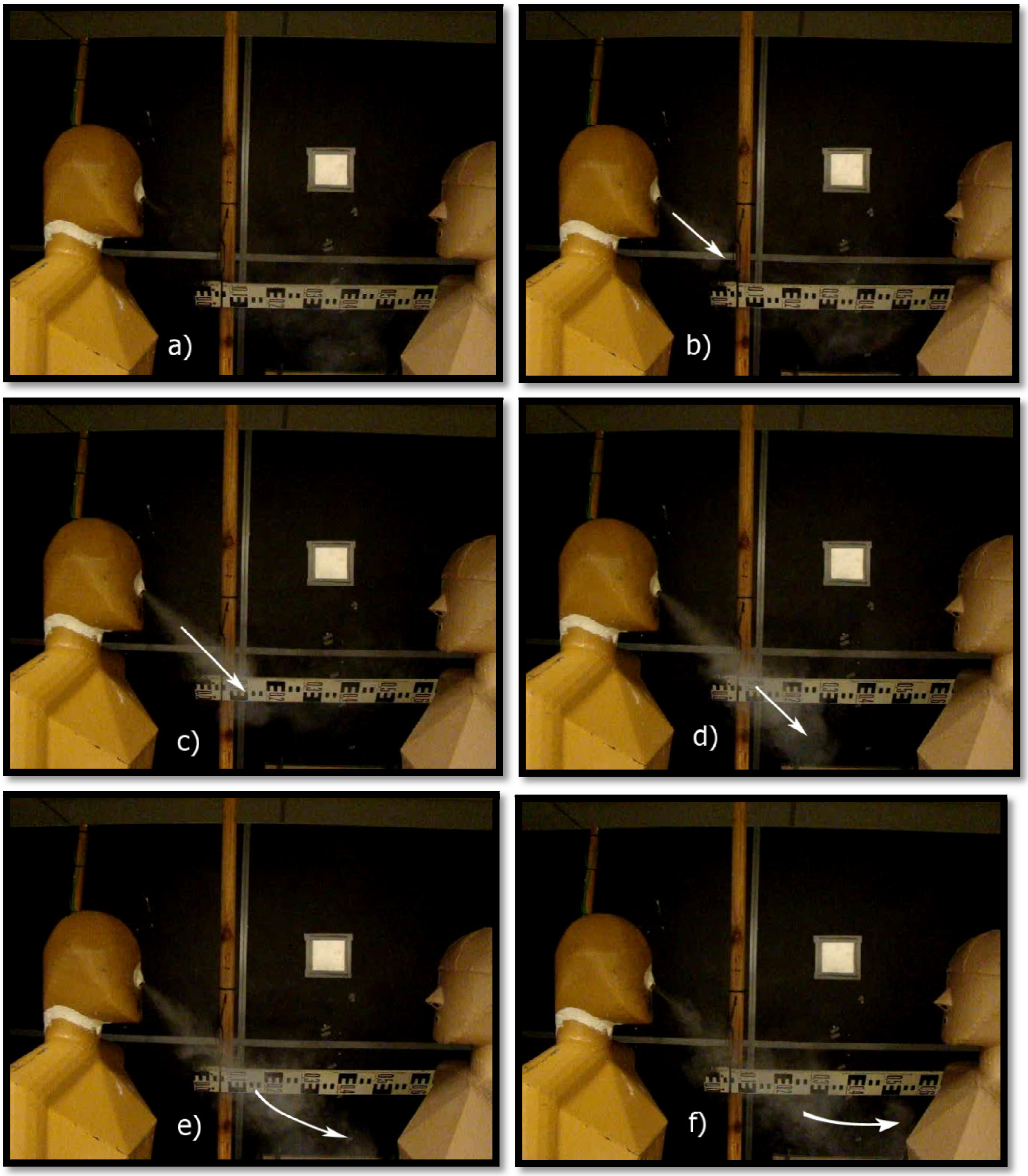


Figure 4.4.4: Single exhalation through nose for θ_m equal to 45° in a)0s; b)0,5s; c)1s; d)1,5s; e)2s f)2,5s of expiration

The expiration with smaller angle is show on the figure 4.4.3. It can be noticed that exhalation is much more horizontal and it is not affected in significant way by thermal boundary layer of source manikin. However after 2,5s expiration is a cloud of smoke rising with thermal plume of target manikin, the same phenomena can be noticed in figure with bigger θ_m angle.

5. COMPUTATIONAL FLUID DYNAMICS

Computational Fluid Dynamics represents one of the branches of Fluid Dynamics. It is capable of solving and analyzing problems that involve fluid flow. It is performed by means of numerical methods and algorithms. All predictions of air movement, temperature, contaminant distributions and others are based on a solution of fundamental flow equations (continuity, three momentum, the energy and the transport equations).

In order to get a simulation, millions of calculations are done. Sometimes even if the model is simplified, simulation is so complicated that eventually the solution is only an approximation.

Software used in the project is Ansys CFX. It simulates fluid flow in a variety of applications. It allows engineers to test system in a virtual environment.

5.1 Description of model

CFD simulations are carried out with a model of the test room with a two manikins inside. Ventilation system is a mixing ventilation diffusing ceiling modified in order to get simplified version of real ceiling from the test room.

5.1.1 Dimensions

Dimensions of the model are shown on figures below:

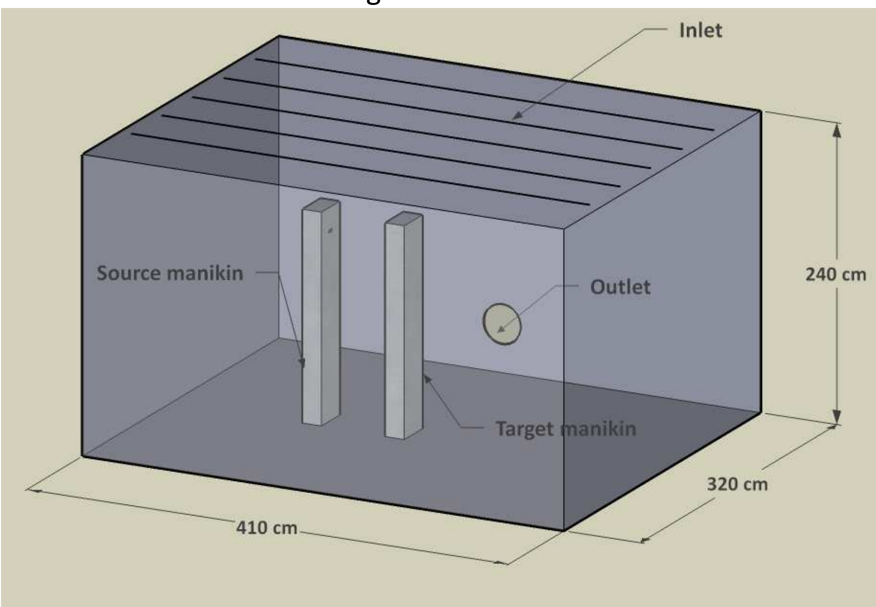


Figure 5.1.1: Test room in a 3D view

Inlet for mixing ventilation is much simplified. In reality there is a diffuse ceiling, where air falls through the slots between ceiling panels and from the connections between the ceiling and the walls. In the model five long thin slits (dimension of one slit is 2 x 390cm) serves as a diffusive ceiling.

Outlet for mixing ventilation is the same as in actual model. Its diameter equals 160 mm.

5.1.2 Description of manikin

A simplified model of the manikin is used for the simulations. The manikin in CFD simulations is a cuboid with the dimensions equal to 170 x 30 x 16,1 cm, as described in [21]. The manikin is shown on table below:

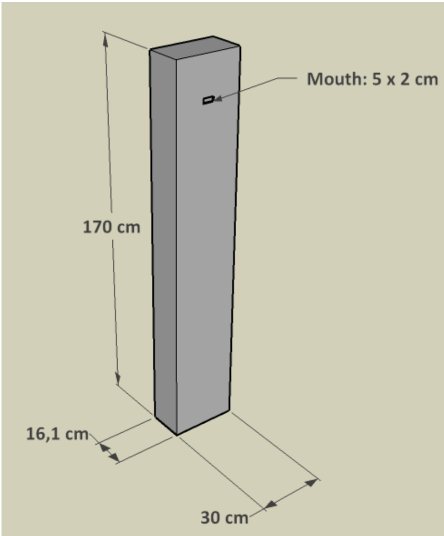


Figure 5.1.2: Manikin in CFD simulations

Mouth of the manikin is also simplified. It is designed as a rectangle with dimensions of 20 x 5 mm. Area of the mouth equals 100 mm2.

5.1.3 Boundary conditions

In the following the boundary conditions of CFD simulations are described.

Heat load

Heat load released from a manikin is 78 W for low activity setup, for high activity a manikin is 110. Because radiation is not taken into consideration, the heat loads are divided by two.

Airflow in the test room

All simulations are performed in steady airflow conditions. Diffuse ceiling ventilation settings are 252 m³/h of inlet air, outlet is set to 0 Pa of average static pressure. Temperature of inlet air was set to be the same as in measurements and is equal to 19,4 C°.

Airflow from the mouth

Breathing is characterized by pulsating flow. CFD is a powerful tool for simulating the airflow, but it has some limitations. It is expensive to work with unsteady state situation. For that reason it is difficult to use CFD for modeling of breathing. One of goals of the measurements was to acquire data that would help create boundary conditions for CFD simulations that would represent the reality. Several simulations were conducted and then compared with results from previous research to find appropriate conditions for describing the flow from the mouth.

At the beginning, the flow is defined as doubled volume of normal exhalation. The reason for that is to achieve the same momentum flow and concentration distribution in some distance as in reality and that is why two volumes of exhaled air are checked. Later it is changed to 75% of that flow (explanation for that in chapter 5.2).

The manikins breathing function consists of 2 phases – exhalation and pause which occur in ratio of 1:1 (2 seconds each). In CFD the flow has to be steady, without pauses. The flow in CFD equals 17,6 l/min for doubled volume and 13,2 l/min for 75% of doubled volume. Temperature of exhalation is set to 38°C.

Temperature of the walls

Temperature of the walls, floor and ceiling were set to be the same as in the measurements, as described in chapter 4.1.2. Table with temperatures are shown below.

surface [-]	temperature [˚C]
walls	21,29
ceiling	20,9
floor	20,63

Figure 5.1.3: Surface temperatures

5.1.4 Turbulence model

First important thing is choosing the right turbulence model. The k – ε model is chosen because it is one of the most common turbulence model where only initial and boundary conditions must be prescribed. Additionally it is well established and most widespread. It obtains good results for industrial flows. In this model transport equations are solved for the turbulent kinetic energy, k, and its dissipation, ε.

Value of kinetic energy of turbulence and dissipation rate of turbulence for flow from mouth of the manikin are calculated according to an equation which were taken from “Specification of a two-dimensional test case” [Peter V. Nielsen, 199]:

Kinetic energy of turbulence $k_0 = (\frac{3}{2}) l_0^2 U_0^2$

where

$l_0 = 0{,}04$

Dissipation rate turbulence $\varepsilon_0 = \frac{k_0^{\frac{3}{2}}}{l_0}$

where

$l_0 = 0{,}1 \cdot h$

For diffusive ceiling turbulence was set to medium intensity.

5.1.5 Grid

Simulations with very similar geometry were carried out in our 9th semester project [23]. Investigation of grid independence, proved that approximately 900 000 cells in the mesh is enough to obtain grid independent results. It is decided not to repeat grid independence simulations. Number of cells used in most simulations equals approximately 1,2-1,3 millions, what should provide satisfactory results.

In order to obtain most accurate geometry of breathing, the mesh was improved manually in areas with high velocity gradients, that is: around the manikins and mostly around the mouth and in the exhalation area.

5.2 Results

This chapter presents and discusses the results obtained in CFD simulations. Only simulations with two manikins are done and only for low activity setup.

Figures below present conditions in the room in a single plane across the room. This plane crosses the center of the mouth of source manikin. This way distribution of concentration an velocity in exhalation jet can be shown.

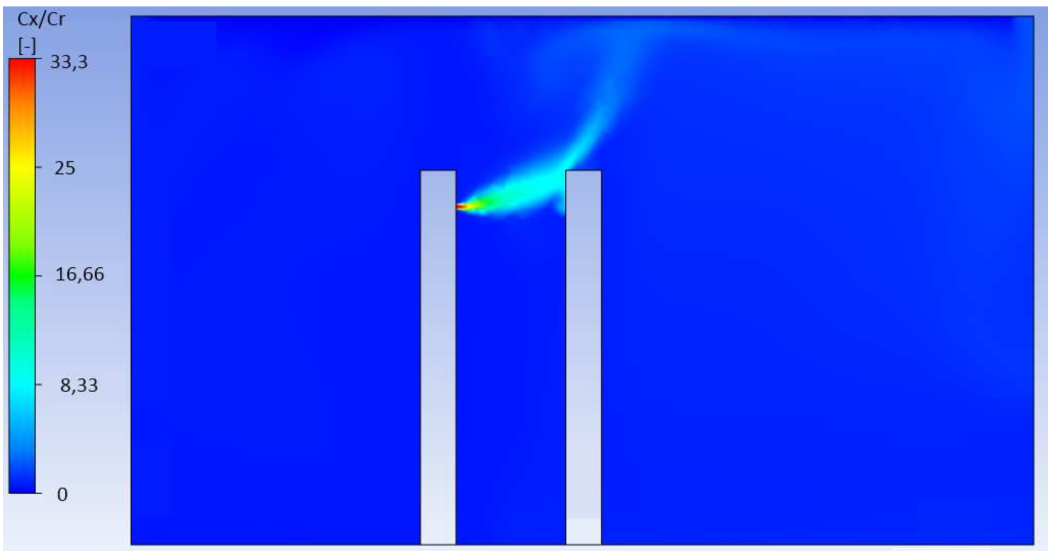


Figure 5.2.1: Concentration distribution, 50 cm distance between manikins

Figure above shows concentration distribution in exhalation jet with two manikins at 50 cm distance. Initial concentration equals 33,3. A fast decay can be observed in short distance, to a value of approximately 9. Further, the decay is much slower.

It can be seen that the jet hits upper corner of the target manikin and it is split into two parts. Some amount of contaminants flows downward towards the mouth and some is lifted above the target manikin. It is noticeable that exhalation flow is not the same as in real life experiments. It was seen, for instance in smoke simulations, that exhalation did not reach target manikin. Here, the jet is wider and its direction is different and some parts of it interact with inhaling manikin.

Simulations for other distances as in experiments (35-110 cm) were also conducted. Figure below presents the results.

These values however, cannot be really compared with those obtained in measurements. Exhalation in CFD is defined as a jet with the same momentum as in experiments. That means the velocity is equal to peak velocity in a single expiration in measurements what would mean that values obtained here correspond to peak values of concentrations. Since it was impossible to obtain peak values in experiments with thermal manikins, no direct comparison can be made.

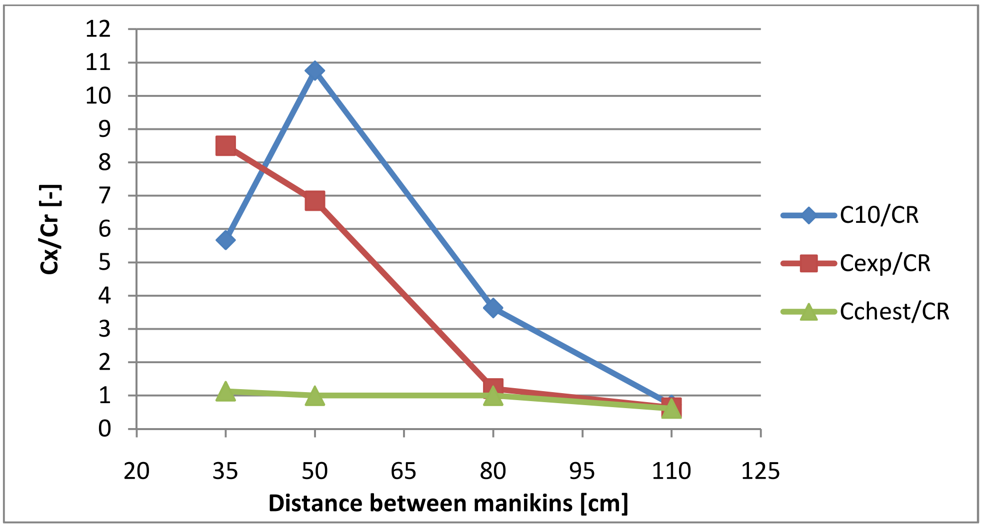


Figure 5.2.2: Concentration levels in CFD simulation

At the distance of 35 cm, there is more tracer gas at the level of the mouth, than above the head, what is in contradiction with the experiments. Level of concentration is decreasing from this point. At the distance of 80 cm, it equals 1. The same value is obtained in experiments.

The curve of concentration above the head resembles rather the one from results of high velocity case in experiments. The value at small distance is lower than measured at the mouth. At 50 cm it reaches its peak, and then decreases in further distances.

At the level of the chest, concentrations is low and equals approximately 1 in most cases.

At 110 cm distance between the manikins, the concentration levels equals approximately 0,6 in all measurement points. It shows that the air in the room in simulations is not fully mixed.

Although the values obtained here cannot be compared to those from measurements, some conclusions can be made, based on shape of the curves. The exhalation jet is more horizontal, therefore its influence on target manikin's inhaling zone is higher. This leads to conclusion that boundary conditions of airflow from the mouth are not chosen correctly.

Figure below presents velocity distribution:

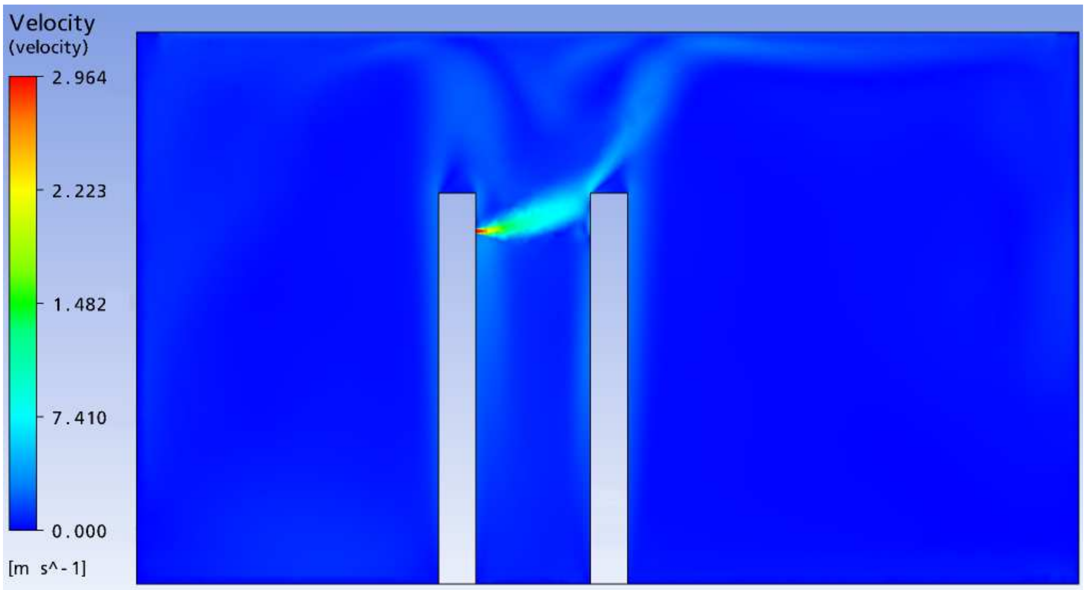


Figure 5.2.3: Velocity distribution in CFD simulation

Velocity distribution is very similar to concentration distribution in the jet. The flow hits the edge of the manikin. It can also be seen that the air is rising along the manikin as it is heated by its surface, creating a boundary layer. At target manikin it removes, to some extent, the exhalation jet.

Changed amount of exhaled airflow

It might be assumed that correct concentration distribution in exhalation jet might be obtained when the airflow from the mouth was smaller. The following simulations are made with amount of expired air reduced by 25%. Due to lack of time, only simulations for 50 and 80 cm distance are made.

Table below presents values of concentration.

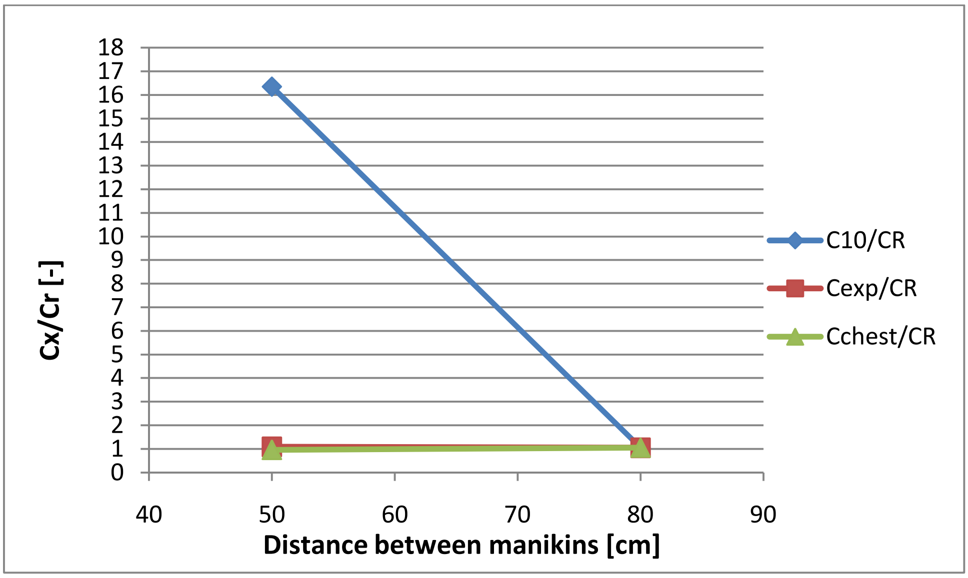


Figure 5.2.4: Results with changed airflow

Concentration at the mouth in 50 cm distance equals 1. This means there is no effect of exhalation on target manikin in this point. Concentration above the head is slightly higher than in previous case.

Figure below shows comparison of flow directions in regard of velocity distribution for 3 different cases.

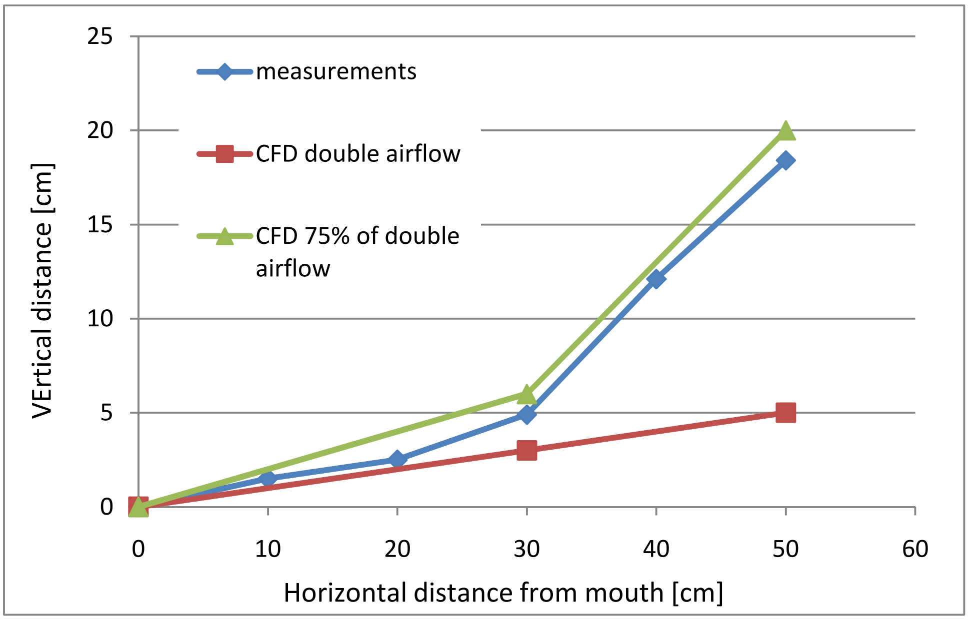


Figure 5.2.5: Comparison between different velocity cases

Doubled airflow in CFD does not give satisfying results. When the amount of air is decreased, direction of the flow is very similar, although it is slightly more upward.

It seems that decreasing the amount of exhaled air shows a change in results in a right direction. The right amount can be probably found somewhere between 75 and 100% of the value set at the beginning.

6. CONCLUSIONS

Several conclusions can be drawn from the research done for this thesis. This chapter will elaborate on the most important of them:

- Experiments conducted with use of one manikin show that there is a significant difference between a manikin with low and high activity level. The latter creates a much higher exhalation flow which has higher velocities and is being spread over a larger distance.
- More importantly, the direction of the flow is different. It has a much more horizontal profile, what makes it more dangerous in regard of cross infection.
- Research carried out with the use of two manikins shows that risk of cross infection in a mixing ventilated room is not high in a case with low activity and exhalation through the mouth. Highest concentration of tracer gas is found above the head of target manikin, where it cannot affect it.
- The situation changes with higher activity level of source manikin. In this case, concentration at the mouth of inhaling manikin is much higher.
- At distances larger than 80 cm between manikins, there is no influence of exhalation jet on target manikin in both cases mentioned above.
- Exhalation through the nose seems to be more dangerous in terms of cross infection. However, comparison with previous research shows that it might be to a large extent dependent on the air distribution system in the room.
- Displacement ventilation proves to be a worse system when looking at cross infection. Due to stratified conditions, exhalation flow can reach inhaling zone of another person more easily.
- Heat released by the manikin creates a certain boundary layer, which can, to some extent, diminish the risk of cross infection.
- CFD results for concentration cannot be compared with measurements due to different type of exhalation (pulsating and steady air flow).
- Doubled airflow in CFD simulations for steady state simulation is not an appropriate volume of exhalation to obtain the same flow path as in measurements. Simulations for smaller volume of exhaled air gave better results.

Apart from those conclusions, this research has also shown certain flaws in experiments with use of manikins, which can be avoided in the future work:

- Exhalation angles of the manikin are not all corrected. For this research, some of them have been temporarily corrected, but proper alterations should be made in future.
- Construction of the heater for exhalation air should be changed, since the present solutions do not provide desired temperature.

- Heat release from the manikin has to be considered as three parts: convection, radiation and sweat evaporation.
- When looking at heat release of the manikin, perhaps a new approach should be taken. Increasing the heat flux makes the manikin higher, while in reality, higher activity levels result in lower temperature of the skin due to sweat secretion. Therefore, heat release in the manikin should be set accordingly to the surface temperature, so that it would match skin temperature of a human body.
- Placing measurement points is not precise enough. It its suggested to use leveling or construction laser to place points in the correct plane.
- It is suggested to examine the correct volume of exhaled air in CFD simulations in order to simulate pulsating flow as a constant jet

BIBLIOGRAPHY

[1] Ramya Murthy, Ioannis Pavlidis, ''Noncontact measurement of breathing function'' ; IEEEEngineering in Medicine and Biology Magazine, May/June 2006

[2] Jitendra K. Gupta, Chao-Hsin Lin, Qingyan Chen, "Characterizing exhaled airflow from breathing and talking", Indoor Air 2010

[3] 2009 Ashrae Handbook – Fundamentals

[4] William C. Adams (1993) , "Measurement of Breathing Rate and Volume in Routinely Performed Daily Activities", California Environmental Protection Agency

[5] Mina Nishi, "Breathing of Humans and its Simulation", Friedlich-Alexander-University Erlangen-Nuremberg, 2004

[6] P.Höppe (1981), "Temperatures of Expired Air under Varying Climatic Conditions", Int.J.Biometeor vol.25, no.2, pp.127-132

[7] Erik Bjorn, "Simulation of human respiration with breathing thermal maniki", Aalborg University

[8] P. O. Fanger, Calculation of Thermal Comfort: Introduction of a Basic Comfort Equation, Asgrae Transactions 1967

[9] Glent Ventilation

[10] Jitendra K. Gupta, Chao-Hsin Lin, Qingyan Chen, "Flow dynamics and characterization of a cough", Indoor Air 2009

[11] Peter V. Nielsen, Ewa Jakubowska, "The performance of diffuse Ceiling Inlet and other Room Distribution Systems", Aalborg University

[12] http://en.wikipedia.org/wiki/

[13] H. Qian, Y. Li, P. V. Nielsen, C. C. Hyldgaard, T. W. Wong, A. T. Y. Chwang, "Dispersion of exhaled droplet nuclei in a two-bed hospital ward with three different ventilation systems."

[14] T. A. Khan, H. Higuchi, D. R. Marr, M. N. Glauser "Unsteady Flow Measurements of Human Micro Environment Using Time Resolved Particle Image Velocimetry"

[15] Shengwei Zhu, Shinsuke Kato, "Investigating How Viruses Are Transmitted by Coughing"

[16] Julian W. Tang, F.R.C Path, Gary S. Settles "Coughing and Aerosols"

[17] Li Liu, Yuguo Li, Peter V. Nielsen, Rasmus L. Jensen, Michal Litewnicki, Jan Zajas, "An Experminetal Study of Human Exhaltion during Breathing and Coughing in a Mixing Ventiloated Room", Aalborg Universitet, 2008

[18] Ines Olmendo et al. "Study of the human breathing flow profile in a room with three different ventilation strategies"

[19] Piotrek Grzelecki, "The Examination of Comfort and Cross Infection in a Displacement Ventilated Room", Aalborg Universitet, 2010

[20] "Contaminant flow in the Microenvironment Between People Under Different Ventilation Conditions ", Peter V. Nielsen, F.V. Winther, M.Buss, M. Thilageswaran, Aalborg University, Denmark

[21] Henrik Brohus, "CFD Models of Personal Evaluated by Full-scale Wind Channel Experiments", Aalborg University

[22] Michal Litewnicki, Jan Zajas, "Microenvironment around human body", 9th semester project, Aalborg University 2009

[23] Peter V. Nielsen, Rasmus L. Jensen, Michal Litewnicki, Jan Zajas, "Experiments on the Microenvironment and Breathing of a Person in Isothermal and Stratified Surroundings", Aalborg Unieversity 2009