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INFECTION CONTROL IN HOSPITALS

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Infection Control in Hospitals.

Abstract

The terrible statistics about hospital-acquired infections point out the necessity of improving the infection control in health care facilities. This implies that it is necessary to search for new methods and techniques of design.

The aim of this paper is to describe all known measures of the infection control and to consider a new approach in its optimizing – the use CFD modeling.

The CFD modeling possibilities are demonstrated by an analysis of one factor impact on the infection risk. The analyzed factor is the use of local exhaust unit in the airborne infectious isolation room. The report includes the detailed description of all steps of the simulation: collection of the initial data, the modeling process, setting the solver and analysis of the results.

The results of the simulation allow estimating the impact of the analyzed factor and giving certain recommendations for the design of airborne infectious isolation rooms.

Subject headings, (keywords)

Infection control, nosocomial infections, pathogenic microorganisms, airborne infectious isolation rooms, computational fluid dynamics, Eulerian multiphase model

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CONTENTS

1. INTRODUCTION

Everyone suppose that hospital is the place, where we recover from a disease. However, there is a high risk to acquire a serious infection instead of recovery. The term nosocomial infection or hospital-acquired infection (HAI) is used when a patient gets infected in hospital. Hospital is a place of concentration of infection and the main aim of designers and administration is to isolate and prevent the spread of the infection in order to protect patients. Unfortunately the statistics shows that this aim is not fully achieved. As a result of the collection and processing of the statistical data, provided in the Appendix A, the estimated morbidity associated with HAI for US and EU together is about 6 million per year, and the mortality is about 300.000 per year. This terrible statistics reveals the importance of the problem of nosocomial infections and suggests the necessity of a concerted approach to solutions of specialists from different fields: architects, engineers, health workers. More attention should be paid to designing health care facilities for maximum infection control.

This paper describes the causes of HAI and the measures of infection control in health care facilities. The engineering measures, such as ensuring the directional airflow, reducing the concentration, direct source technique, dilution and removal of the infection, filtering, ultra violet germicidal irradiation, etc. are described in more detail. Also an analysis of guidelines and technical recommendations is performed.

However, the main question of the paper is the CFD modeling approach in optimizing the infection control. In order to reveal the CFD modeling possibilities, an analysis of one factor impact using this technique is performed. The theoretical justification is followed by detailed description of all steps of simulation: collection of the initial data, the modeled process description, creation of the model, setting the solver and analysis of the results. The results of the simulation not only allow showing the power of CFD, but also allow giving a certain recommendation for the design of airborne infectious isolation rooms.

2. FEATURES AND HAZARDS OF HEALTH CARE FACILITIES

The main difference between health care facilities and conventional buildings is the character of processes carrying out inside the facility. Due to these processes there are biological, chemical, and radiation hazards to human health. Also contaminated supply air or water, substances generated by building materials or equipment, microbe growth sites within the building represent hazards for patients and staff.

However the most dangerous are pathogenic microorganisms released by patients suffering from contagious diseases. Due to a large variety of infection sources, health care facilities have rather larger concentration of pathogenic microorganisms than in the conventional buildings.

Another important feature is that exposed persons, besides visitors and health care workers, are patients – most susceptible to acquiring infection.

3. TRANSMISSION OF INFECTION

The following chapter is based on the ASHRAE HVAC Design Manual for Hospitals and Clinics. /1/

The infection can occur in two main ways: by direct contact and by airborne transmission. The way of infection depends on the type and source of pathogenic microorganisms.

The airborne transmission occurs when a person inhales particles of aerosol of small size. The small particles of infection can remain suspended in air for a long time and thus can be spread throughout the building environment. The small size of particles allows the infection to penetrate deeply into the lungs to alveoli – the most vulnerable part of respiratory tract.

However, pathogens don’t cause infection in all cases. Firstly, the concentration can be less than the infection dose. Secondly, the time of exposure can be not enough for the infection to occur. And thirdly, the infection can be not strong enough to over-

whelm the immune system of the host. The biological force of infection can be described by the formula:

$$\text{Infection} \cong \frac{\text{Dose} \times \text{Site} \times \text{Virulence} \times \text{Time}}{\text{Level of Host Defence}}$$

The virulence and level of host defence are parameters that can't be controlled. On the other hand the dose and time of exposure are parameters that are controlled by the infection control measures. /1, p.129/

3.1. **Sources of airborne pathogens**

The following chapter is based on the ASHRAE HVAC Design Manual for Hospitals and Clinics. /1/

There are several types of processes that produce airborne pathogens. The first type includes physiological processes: sneezing, coughing, talking, and respiration of an infected person. An infected person permanently releases a large amount of pathogens, especially when sneezes or coughs.

The second type includes growth and spread of pathogens through ductworks and air-handling equipment. The microbes grow and reproduce in areas of dust and moisture accumulation. Dust buildups contain large amount of organic matter: fungal spores, insects and plants matter, skin flakes and hair, etc., that serve as nutrition for microorganisms. The most vulnerable areas are filters, cooling coil drain pans, fittings of unfiltered duct systems, dampers.

And the third type includes the processes of releasing into air of microbes settled on the building materials, equipment, and furniture, when such activities as renovation, maintenance, cleaning, and bed-making are performed. The most dangerous from this list is duct cleaning. Duct cleaning requires placing the duct under negative pressure and mechanical brushing, washing, steam cleaning or contact vacuuming. Sometimes biocides are used for disinfection purposes. However, the expediency of duct cleaning and its efficiency in reducing contaminant concentration in health care facilities is equivocal. The lack of caution, insufficient negative pressure, insufficient time for

disinfection, careless coordination with the hospital staff and other reasons can lead to severe contamination of hospital environment. The Centers for Disease Control emphasize that duct cleaning is not an appropriate solution for reducing contaminant concentration in health care facilities and should be performed only in order to improve the ventilation system performance in cases of severe contamination of the ductwork. Furthermore the authorities strongly recommend that duct cleaning be carried out only by qualified personnel and all necessary safety measures be taken. /1, p.27-29, 97-98/

3.2. **Pathogens classification**

Pathogens are microorganisms that cause diseases, allergies or irritation. Respiratory pathogens are divided into three taxonomic groups:

- viruses
- bacteria
- fungi. /2, p. 34/

Depending on the ability of transmissibility of infection between patients in health care facility all pathogens fall into three categories:

- communicable
- non- communicable
- primarily nosocomial. /2, p. 35/

The list of the most widespread pathogens and the indication of their types and the disease they cause is presented in the Table 1 and Table 2.

TABLE 1.Communicable Respiratory Pathogens /2, p. 37/

Table 1: Communicable Respiratory Pathogens					
AIRBORNE PATHOGEN	MICROBIAL GROUP	DISEASE	SOURCE	Diameter microns	Notes
Adenovirus	VIRUS	colds	Humans	0.08	
Arenavirus	VIRUS	hemorrhagic fever	Rodents	0.18	F
Coronavirus	VIRUS	colds	Humans	0.11	
Coxsackievirus	VIRUS	colds	Humans	0.027	
Echovirus	VIRUS	colds	Humans	0.028	
Morbillivirus	VIRUS	measles (rubeola)	Humans	0.12	F, N
Influenza	VIRUS	flu	Humans, birds	0.1	F, N
Parainfluenza	VIRUS	flu	Humans	0.22	N
Paramyxovirus	VIRUS	mumps	Humans	0.23	F, N
Parvovirus B19	VIRUS	fifth disease, anemia	Humans	0.022	F
Reovirus	VIRUS	colds	Humans	0.075	
Respiratory Syncytial Virus	VIRUS	pneumonia	Humans	0.22	F, N
Rhinovirus	VIRUS	colds	Humans	0.023	
Togavirus	VIRUS	rubella (German measles)	Humans	0.063	N
Varicella-zoster	VIRUS	chickenpox	Humans	0.16	N
Chlamydia pneumoniae	BACTERIA	pneumonia, bronchitis	Humans	0.3	N
Mycobacterium tuberculosis	BACTERIA	TB	Humans	0.86	F, N
Yersinia pestis	BACTERIA	pneumonic plague	Rodents	0.75	F

TABLE 2.Primarily Nosocomial Respiratory Pathogens /2, p. 37/

Table 1: Primarily Nosocomial Respiratory Pathogens					
AIRBORNE PATHOGEN	MICROBIAL GROUP	DISEASE	SOURCE	Diameter microns	NOTES
Acinetobacter	BACTERIA	opportunistic infections	Environmental	1.3	E, N
Actinomyces israelii	BACTERIA	actinomycosis	Humans	1.0	E, N
Alkaligenes	BACTERIA	opportunistic infections	Humans	0.75	E, N
Bordetella pertussis	BACTERIA	whooping cough	Humans	0.25	E, N
Cardiobacterium	BACTERIA	opportunistic infections	Humans	0.63	E, N
Corynebacteria diphtheria	BACTERIA	diptheria	Humans	1.0	E, N
Haemophilus influenzae	BACTERIA	meningitis, pneumonia	Humans	0.43	E, N, F
Haemophilus parainfluenzae	BACTERIA	opportunistic infections	Humans	1	E, N
Klebsiella pneumoniae	BACTERIA	opportunistic infections	Environmental	0.4	E, N
Moraxella catarrhalis	BACTERIA	opportunistic infections	Humans	1.3	E, N
Moraxella lacunata	BACTERIA	opportunistic infections	Humans	1	E, N
Mycobacterium avium	BACTERIA	cavitary pulmonary dis.	Environmental	1.2	N
Mycoplasma pneumoniae	BACTERIA	pneumonia	Humans	0.25	E, N
Neisseria meningitidis	BACTERIA	meningitis	Humans	0.8	E, N, F
Pseudomonas aeruginosa	BACTERIA	opportunistic infections	Environmental	0.57	N
Pseudomonas mallei	BACTERIA	opportunistic infections	Environmental	0.77	N
Pseudomonas pseudomallei	BACTERIA	opportunistic infections	Environmental	0.57	N
Serratia marcescens	BACTERIA	opportunistic infections	Environmental	1.3	E, N
Staphylococcus aureus	BACTERIA	opportunistic infections	Humans	1	E, N
Streptococcus pneumoniae	BACTERIA	pneumonia, otitis media	Humans	0.9	E, N, F
Streptococcus pyogenes	BACTERIA	scarlet fever, pharyngitis	Humans	0.9	N
Pneumocystis carinii	Protozoa / Fungi	pneumocystosis	Environmental	2	S, N
Cryptococcus neoformans	FUNGI	cryptococcosis	Environmental	5.5	S, N

NOTES:
E = Endogenous, common as human flora
F = Fatalities occur (excluding nosocomial)
HP = Hypersensitivity Pneumonitis
N = Nosocomial, common as (purple blocks)
EAA = Extrinsic Allergic Alveolitis
S = Spores
VOC = Volatile Organic Compounds produced
References: 1, 3, 4, 5, 8

The most important classification for reason of infection control is the classification by size, because there are many characteristics dependent on the size of pathogens. The most significant are filtration efficiency and place of deposition in the respiratory tract. /1, p.129-131/

The filtration efficiency of HEPA-filters is 99.97% for 0.3µm particles. The filtration efficiency of ULPA-filters is up to 99.999% for 0.1 – 0.2µm particles. The size range

of bacteria is 0.2 – 5 μm, thus it can be filtered quite easily. On the other hand, the size range of viruses is 0.005 – 0.3 μm, thus the filtration efficiency drops down and can't be precisely estimated. Therefore the filtration can't be the basic method of infection control in the case of viruses. /1, p.131-132/

The probability of particles deposition in certain part of respiratory tract is dependent on the particles size. This relationship is presented on the Figure 1.

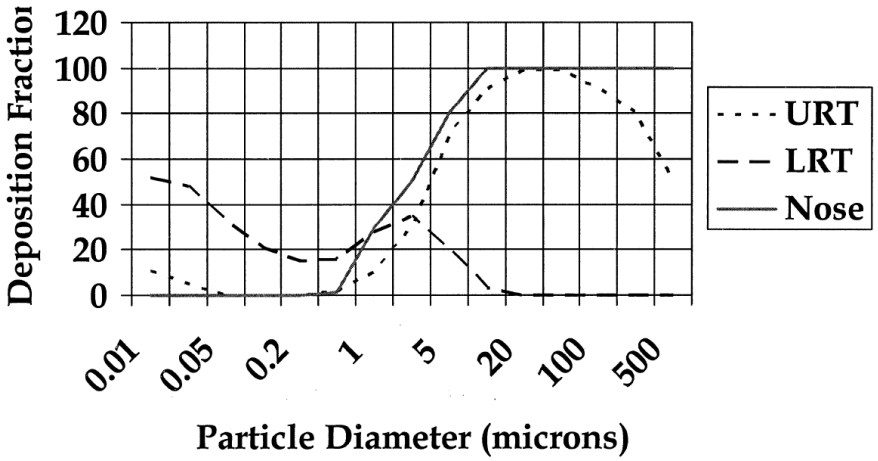

FIGURE 1.Primarily Nosocomial Respiratory Pathogens /1, p.131/

From this figure it can be noticed that nose and upper respiratory tract (URT) protect the lower respiratory tract (LRT), what is more vulnerable for infection.

Also it can be noticed that for the size range of bacteria (0.2 – 5 μm), the deposition fraction in URT strongly decreases, that allows the infection to be deposited deep into the lungs and cause disease. Potentially dangerous bacteria of this size range are tuberculosis, diphtheria, streptococcus, anthrax and others. /1, p.131-132/

The knowledge of types of pathogens, their origin and the mechanism of transmission and infection is fundamental for the infection control in health care facilities.

As it was emphasized before every pathogen has its unique characteristics and requires individual approach. Therefore the infection control measures should be determined by the type of pathogen most likely to be present in a certain space of the facility.

One of the most dangerous pathogens is Mycobacterium tuberculosis (TB), which causes serious and hard treatable disease and can lead to death. It is also characterized by high level of infectivity due to the infection dose is very low and it is enough only 1 bacteria to get infected. Therefore this work is focused upon the infection control measures by the example of tuberculosis bacteria.

4. INFECTION CONTROL MEASURES

High level of pathogens concentration within health care facilities and the associated risk require strict infection control measures in order to protect patients, health care workers, and visitors. There is a wide variety of techniques, practices, engineering controls and equipment for this purpose.

The hierarchy of control measures includes four groups of measures:

1) use of airborne infectious isolation rooms (AII) – to separate the infected patients from other persons;
2) engineering measures –reducing the concentration and prevention of the spread of infection;
3) administrative measures – reducing the risk of exposure to infection;
4) use of personal respiratory protective equipment –reducing the risk of exposure to infection in high risk areas, particularly in isolation rooms. /3/

4.1. **Airborne Infectious Isolation rooms**

Airborne infectious isolation room is a room for patients with suspected or confirmed infectious diseases. The main purposes of an AII room are:

- to separate the infected patients from other persons;
- to provide a favorable environment for efficient reduction of concentration of pathogens in the room generated by the infected patient;
- to prevent the escape of pathogens out from the AII room. /3/

For these purposes two ventilation criteria are applied:

- directional airflow by sustenance of negative air pressure with respect to all adjoining spaces;

- air distribution pattern by providing good mixing and direction of airflow from clean areas to less clean areas. /1, p. 133-136/

The number of isolation rooms should be enough to ensure an appropriate isolation for all patients with suspected and confirmed infectious diseases. The results of risk assessment of the hospital should be used to estimate the required number of AII. However there should be at least one AII room in the hospital. /3/

Regardless of the number of isolation rooms, they should be grouped together in one area of the hospital. Firstly, this measure allows reducing the risk of infection spread. Secondly, it simplifies the installation, maintenance and control of the ventilation system for AII rooms. And thirdly, it facilitates care of infected patients. /3/

According to the number of patients in one space, AII rooms can be classified as:

- single-patient rooms,
- multibed rooms. /4, p. S2/

A study of the Facility Guidelines Institute (FGI) Research committee assessed the benefits of single-patient rooms and the most important are the following:

- reduction of cross-infection risk;
- reduction of room-to-room transfers;
- more flexibility in operation;
- enhancement in patient care;
- enhancement in patient comfort;
- enhancement in privacy/noise abatement. /4, p. S2-S5/

Moreover it can be assumed that the peak concentration in single-patient room is lower than in multibed-room. Thus the risk for health care workers and the possibility of infection escape is also lower.

The only one disadvantage of single-patients AII rooms is the higher initial costs. However, the wide list of advantages of such design easily compensates the initial investment.

Another important design element is the anteroom. The guidelines don't require an anteroom to be present. However it can be very useful in infection control. The anteroom decreases the potential of infection escaping out of the AII room, especially when a health care worker opens the door to enter the room. The air pressure in the anteroom obligatory should be positive with respect to isolation room and it is recommended to be negative with respect to corridor. /3/

Moreover anterooms play an access control role. As an example, food is usually delivered by untrained personnel, thus there is additional risk while entering the isolation room. The anteroom allows leaving patients' trays there without entering the high risk area. Also anteroom can be used as a storage for isolation materials, such as masks, gowns, gloves, etc. /1, p. 218-219/

A sample worksheet of an AII room with anteroom is presented in the Table 3.

TABLE 3.Sample Worksheet of an AII room. /1, p. 135/

Room Floor Area	11.2 m^2
Room Volume	27.2 m^3
Room Leakage Area	225.8 cm^2
Room Supply Volume	87.3 l/s
Anteroom Supply Volume	35.4 l/s
Differential Air Volume (for P=2.5 Pa)	47.2 l/s
Toilet Exhaust Volume:	47.2 l/s
Room Exhaust Volume	122.7 l/s
Room Air Change Rate (ACR)	16.25

4.2.**Engineering measures**

Engineering control of infection in health care facilities is performed by HVAC systems and it is the most effective among the hierarchy of control measures. There is a variety of demands that the HVAC systems of health care facility should meet. Health care facility HVAC systems must be at the highest standard of performance and reliability. It is a specific case when the HVAC systems are so important and integral part

of the building processes. All these features make the design of health care facility HVAC systems the most sophisticated and unique.

Along with the AII rooms HVAC systems intend to achieve the following aims:

1) Prevention of infection escape out of the isolation room;
2) Health care workers protection;
3) Reducing patient care waiting time;
4) Providing comfort for patients;
5) Reducing energy consumption. /5, p. 1322-1323/

In order to achieve these aims the following measures must be taken:

1) Ensuring directional airflow inward the AII room by providing appropriate pressure difference with respect to all adjoining spaces;
2) Reducing infection concentration in all areas of the AII room by contaminant dilution, filtration, exhausting and ultraviolet germicidal irradiation (UVGI);
3) Providing appropriate air temperature and humidity and avoiding high velocities in occupation zone;
4) Providing appropriate local ACR in occupation zone by ensuring good mixing of air and avoiding formation of stagnant zones;
5) Reducing air flow setting time by improving control system ;
6) Minimizing air flow volumes for energy saving.

The detailed description of these measures is provided in following chapters.

4.2.1.Guidelines and recommendations

There are many guidelines and design recommendations related to ventilation and air conditioning in AII rooms. The most significant are:

- ASHRAE Handbook – HVAC Applications;
- AIA Guidelines;
- Guidelines for Preventing the Transmission of Mycobacterium tuberculosis in Health-Care Facilities;
- HVAC Design Manual for Hospitals and Clinics.

The requirements in each particular document differ, therefore a summary of "best practice" recommendations provided by HVAC Design Manual for Hospitals and Clinics is presented in the Table 4. It must be emphasized that these are only recommendations and the real design must be firstly in accordance with the local legislation. /1, p. 32/

TABLE 4.Best practice recommendations. /1, p. 33-38/

Space	AII Room	Isolation Anteroom
Pressure Relationship to Adjacent Areas	N	P/N
Minimum Air Changes of Outdoor Air per Hour	2	2
Minimum Total Air Changes per Hour	12	10
All Air Exhausted Directly to Outdoors	Yes	Yes
Air Recirculated Within Room Units	No	No
Relative Humidity	-	-
Design Temperature	21-24	-
Differential pressure between space and corridors	2.5 Pa	-

4.2.2.Ensuring directional airflow inward the AII room

Directional air flow inward the AII room is achieved by creating negative pressure in the room in dependance with the adjacent spaces, because air always flows from area with a higher pressure to a lower pressure area. Negative pressure is achieved by providing a certain volume flow differential between exhaust and supply (exhaust flow rate higher than the supply flow rate). /3/

The required level of negative pressure to ensure an appropriate air flow inward the AII room primarily depends on the configuration of ventilation system and room design. However, according to the guidelines, the minimal level of pressure difference must be at 2.5 Pa (0.01 w.g.). A higher level of pressure difference may be an advantageous factor, but it leads to more energy consumption and in some cases is excessive. /1, p. 30/

Generally,in normal cases in order to achieve minimal level of pressure difference of 2.5 Pa it is necessary to set the flow differential at a level of the highest of two values: 10% of supply air flow rate or 25-50 l/s. However, this is just an approximate value and the required rate of flow diference depends also on airtightness of the AII room. /1, p. 30-31/

Airtightness is characterized by the area of all cracks and gaps in walls, ceiling, floor, and door. This charateristic ia called the leakage area. Generally, the infiltration of an AII room is a function of the pressure difference and leakage area. In order to estimate the allowable leakage area the following formula is used:

$$A_L = 10{,}000 \cdot \frac{Q_r \cdot \sqrt{(\frac{\rho}{2\Delta p_r})}}{C_D \cdot \Delta p_r},$$

$where: A_L = air\ leakage\ area, cm^2;$

$Q_r = air\ leakage\ volume, \frac{m^3}{s};$

$\rho = air\ density\ at\ normal\ room\ temperature, \frac{kg}{m^3};$

$\Delta p_r = reference\ pressure\ difference, 2.5Pa;$

$C_D =\ discharge\ coefficient$

$(depends\ on\ the\ gaps\ through\ which\ the\ air\ flows)$. /6, p. 26.12/

If the minimum pressure difference can't be achieved, then the room must be inspected for leakage. If it is possible all leaks must be sealed. However an air gap must be provided for a controlled airflow path. The recommended size is about 0.3 – 1.3 cm with the placement at the bottom of the door. /3/ The Centers of Disease Control and Prevention with reference to Andrew J. Streifel, MPH, Registered Environment Health Specialist, mention a total leakage area of 460 cm^2 (0.5 ft^2). /7, p. 30/

If the ventilation system can't provide required differential flow rate, alternative methods must be used to increase exhaust air flow rate and in this way to achieve required pressure difference.

There are several solutions to increase exhaust air flow rate:

1) Fixed room-air recirculation systems – can be set up to discharge air outside the AII room;
2) Portable room-air recirculation units – can be designed to discharge air outside the AII room;
3) Exhaust fan mounted in the window or outside wall – can blow air to the outside if there are no restrictions;
4) Positive pressurizing of the corridor and other adjacent areas – increases the pressure difference:
    - by increasing the supply air flow rate of adjacent areas (preferably);
    - by decreasing the exhaust air flow rate of adjacent areas.

    This measure has also some restrictions:
    - pressurization of the corridor shouldn't compromise the pressure balance of the facility;
    - the exhaust air flow rate shouldn't be decreased below the acceptable value. /3/

Despite the pressure difference, there are some factors that can disturb directional air flow and allow infection to escape out of the AII room. The most significant factor is opening the door. When the door opens, the leakage area increases instantly and the pressure difference decreases in a flash. That causes the dispersion of infectious air out of the AII room. This effect can be quantified by air volume migration (AVM) value, which means the amount of air escaped out of the AII room. The AVM value depends mostly on the air volume flow differential and according to some studies varies from 1.0 m^3 to 1.8m^3. The most effective measure to reduce the impact of door opening and reduce the amount of infection escape is to design an anteroom. /1, p. 134/

The importance of an anteroom can be demonstrated by a simple calculation. Assume that the AVM value when opening the door is about 1.5 m^3. The volume of anteroom is about 12m^3. The concentration of infection in anteroom before opening the door is assumed to be zero. The escaped infectious air substitutes the anteroom air. Then as a result of dilution of escaped infectious air and clean anteroom air, the infection concentration in anteroom will be set at a certain value according to formula:

$$C_{mixed} = \frac{C_e \cdot V_e + C_a \cdot V_a}{V_a},$$

$where: C_{mixed} = infection\ concentration\ of\ the\ mixed\ air;$
$C_e = infection\ concentration\ of\ the\ escaped\ air;$
$C_a = infection\ concentration\ of\ the\ anteroom\ air;$
$V_e = volume\ of\ the\ escaped\ air;$
$V_a = volume\ of\ the\ anteroom.$ /1, p. 134/

For the considered example:

$$C_{mixed} = \frac{C_e \cdot 1.5 + 0 \cdot 12}{12} = \frac{1}{8} C_e = 0.125 C_e$$

The result show that the concentration after dilution decreased with 87.5%. Even without exhaust ventilation in the anteroom, a significant reduction of infection escape is obtained. An exhaust ventilation can reduce the risk almost to zero.

Monitoring of pressure difference is no less important. A pressure sensing device can be used for several purposes:

- to ensure that the ventilation system works properly and required pressure difference is maintained;
- to prevent leaving the door open: an audible warning can be used to alert, when the door was left opened. The signal must have a time delay to offer enough time for health care workers to enter the room without activating the warning;
- to measure the adjusting pressure difference, when a variable air flow system are used. In this case the pressure sensing device is an important part of control system and affects its efficiency. /3/

The position of pressure sensing device is essential. The device must be located inside the airflow path into the room. Due to variations of air flow pattern within the room, the pressure can vary a lot for different locations. The best point for sensor location is the bottom of the door. If it is not possible to measure pressure across the airflow path, then another point with equal pressure as that across the air flow path must be chosen. The possible location of pressure sensor is shown on the Figure 2. /3/

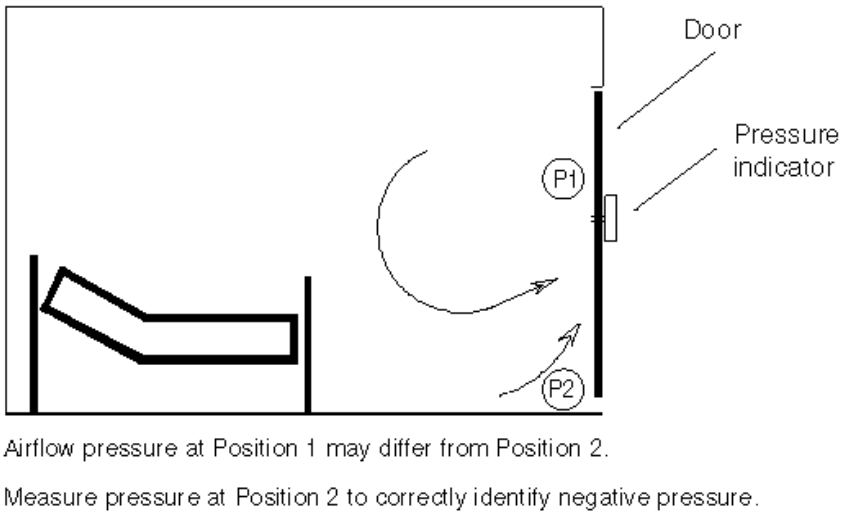

FIGURE 2.Location of pressure sensing device /3/

However the use of pressure sensors is not enough to ensure sufficient safety. For a higher safety the pressure difference must be verified by using other methods: visualization with smoke tubes or manual measurements. /3/

4.2.3.Reducing concentration of infection

Infection concentration control is performed for two purposes:

- to reduce the concentration of pathogens in the door zone, thus reducing the number of pathogens escaped, when the door is opening;
- to protect health care workers and visitors, who enters the AII room.

The risk of being infected is a function of pathogens concentration and the time of exposure. Reducing the concentration, the chance of infection is reduced. The major role in reducing concentration plays the ventilation system. Unfortunately there is no single effective solution, because there are too many factors that influence the efficiency of the infection concentration control, such as room design, the type of pathogens, ventilation system performance, the health care facility general infection control strategy, etc. Therefore engineers have to develop control strategies for each individual case, considering all available controls. The list of such controls includes:

- direct source control: using local exhaust ventilation;
- dilution and removal of contaminated air;
- controlled direction of airflow: from the health care worker operational zone to the infection source and then to the exhaust;

- filtration of air;
- ultraviolet germicidal irradiation (UVGI). /3/

One of the disadvantages is the inability of the ventilation control system to respond to infection concentration variations, because it is impossible to measure particles concentration in real-time. Ventilation system can respond only to basic parameters: temperature, relative humidity, pressure, and the door opening event. Thus the control system is indirect and this leads to a lower efficiency.

The essential point in infection concentration control is the recognition of the factors that affect the local concentration in the AII room, such as:

1) the rate of pathogens generation by the infected person – each disease is characterized by individual rate of infectivity. The concentration of pathogens in the sputum of infected person can vary from a thousand to millions of pathogenic microorganisms per 1 ml. Also the stage of disease should be taken into account.
2) the air change rate – directly influence the dilution and removal efficiency;
3) the filtration efficiency;
4) the air flow pattern within the room – can favor or compromise the dilution and removal.
5) the air temperature – high values of temperature can lead to patient sweating, thereby increasing the rate of pathogens generation;
6) relative humidity value – pathogenic microorganisms are more viable at very low or very high values of relative humidity (it depends on the nature and species of the pathogen). Pathogens are the least viable in the range of relative humidity about 40-70%. Excessively dry conditions allow large infectious aerosol particles to evaporate and their droplet-nuclei to remain suspended in the air, thus decreasing the settling rate of infectious aerosols. Moreover dry conditions lead to decreasing of deposition fraction in upper respiratory tract and increasing of the deposition fraction deeply into the lungs, thus increasing the risk of being infected. /1, 8/

4.2.4.Direct source control technique

The following chapter is based on the Guidelines for Preventing the Transmission of Mycobacterium tuberculosis in Health-Care Facilities. /3/

The purpose of direct source control technique is to capture airborne pathogens at the source of their production. This technique prevents or at least reduces the spreading of infection through the room. The direct source control is the most efficient when the patient is coughing or sneezing.

Local exhaust ventilation allows capturing the largest portion of the generated air-borne pathogens near the source before their dispersion. There are two types of local exhaust devices:

- enclosing type – represents a hood that partially or fully encloses the patient;
- exterior type – also represent a hood, but the patient is outside.

The exterior type hoods are less efficient, but more handy. However, it is required that patient to face directly into the hood. That is needed to direct the path of a cough or sneeze into the hood. Moreover maintenance of high velocities at the patient's breath-ing zone is recommended. /3/

4.2.5.Dilution and removal of the infection

The following chapter is based on the Guidelines for Preventing the Transmission of Mycobacterium tuberculosis in Health-Care Facilities. /3/

The next step in the infection control hierarchy is the dilution ventilation. The target of the dilution ventilation is to remove the pathogens, which had not been captured by the local exhaust ventilation. This step consists of two processes: dilution and removal of the airborne infection. The dilution is performed by supplying the clean air, mixing with the room contaminated air and removing by the exhaust ventilation. In such way the clean air replaces the contaminated one and the infection concentration in the room gradually decreases.

The efficiency of dilution and removal of the infection depends on several parameters:

- the mixing factor, which depends on the pattern of air flow distribution;
- the air change rate value;
- the exhaust units' location.

The supply air can be totally fresh outdoor air, or a mixture of fresh and filtered recirculated air. The recirculation is applied to reduce the energy consumption and maintain a high air change rate at the same time.

The recirculation system can be:

- a part of general ventilation system;
- fixed room-air HEPA recirculation system;
- wall- or ceiling-mounted room-air HEPA recirculation system;
- portable room-air HEPA recirculation system. /3/

4.2.6.Controlled direction of air flow

The following chapter is based on the Guidelines for Preventing the Transmission of Mycobacterium tuberculosis in Health-Care Facilities. /3/

The purpose of controlling the direction of airflow within the AII room is to reduce the exposure of health care workers or visitors to the generated by patient infection. For this purpose an optimal air flow pattern must be provided in such way that clean air flows firstly to the operational zone of health care worker, then across the infection source and then to the exhaust. One of the possible solutions is presented on the Figure 3.

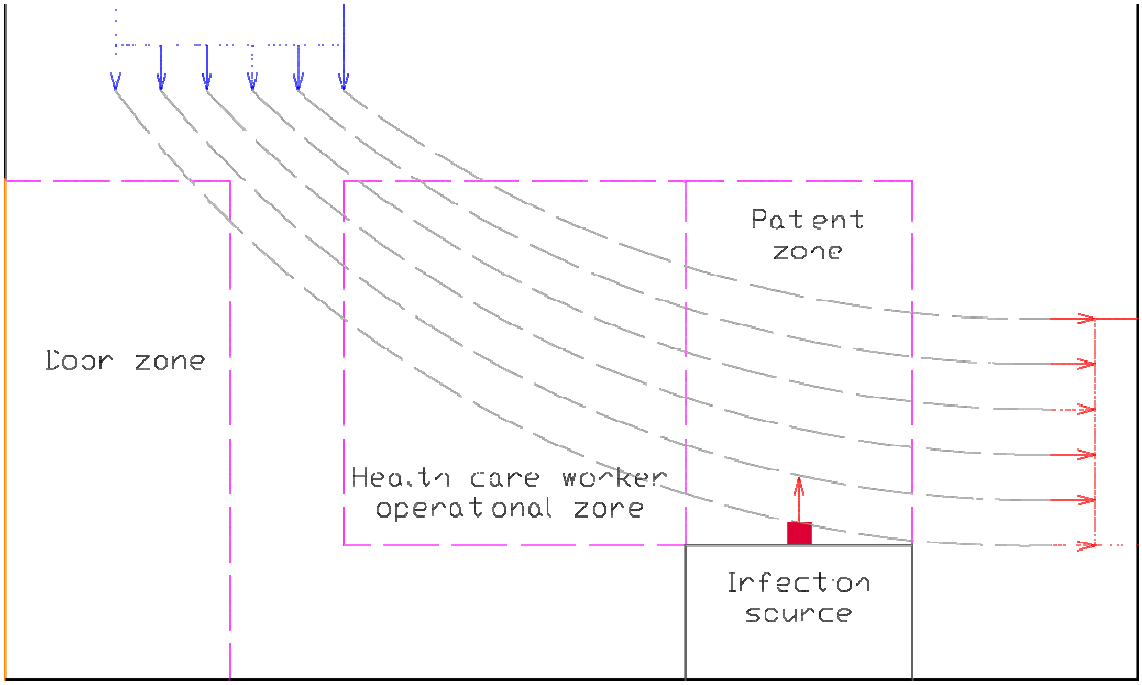

FIGURE 3.Directional air flow

Another solution is to supply cool air near the ceiling and exhaust it near the floor. This method is similar to laminar flow systems of the clean-rooms, but in the described method the flow is not laminar. Laminar flow systems are not suitable for AII rooms, because require very high rates of flow and consume a lot of energy. Turbulent flow systems can ensure satisfactory efficiency of contamination removal with significantly lower consumption of energy, thereby, it is not necessary to achieve a laminar flow.

The goal of turbulent flow systems is maximum mixing of air and, thereby, maximazing the efficiency of concentration reduction. Maximum mixing can be achieved only if stagnation zones and short circuiting is avoided. Also diffuser type and location, temperature differentials, geometry of the room and the location of furniture are the parameters that significantly affect the mixing efficiency.

In order to analize the airflow patterns within the AII room, smoke tubes can be used for visualization. A more demonstrative alternative method is CFD modeling. /3/

4.2.7.AIR Change rate (ACR)

The following chapter is based on the Guidelines for Preventing the Transmission of Mycobacterium tuberculosis in Health-Care Facilities. /3/

As was mentioned before the recommended minimum value of ACR for AII rooms is 12 changes per hour. The minimum changes of fresh outdoor air is recommended to be at least 2 changes per hour. Thus, 10 changes per hour can be obtained by recirculation through HEPA filters. Should be noted that the ACR in the AII rooms must be calculated on the basis of the exhaust air flow rate.

If a greater reduction of the infection concentration is required, then a higher ACR can be set. The increase of ACR leads to reducing the time needed to remove the infection, which in turn means reduction of the time of exposure and, thereby, reduction of the risk of being infected.

However, a high value of ACR of the AII room is not an absolute guarantee of high infection removal efficiency. Evaluating the ACR, the mixing factor should be taken into account as well. Uneven distribution of air flow can lead to lowering of local ACR in certain areas. It is necessary to ensure a high value of ACR primarily in risk areas of the AII room, such as health care worker operational zone and door zone.

The effect of ACR in the reducing the required time for removing the infection is presented in the Table 5. The mixing is assumed to be perfect. /3/

TABLE 5. Effect of ACR in the reducing the required time for removing the infection /3/

ACR	Minutes required for a removal efficiency of:		
	90%	**99%**	**99.9%**
1	138	276	414
2	69	138	207
6	23	46	69
12	12	23	35
15	9	18	28
25	6	11	17
50	3	6	8

If the general ventilation system is incapable to provide the required ACR, then alternative methods should be used:

1) Fixed air recirculation system – the air is exhausted into a duct through a HEPA filter and returned back into the room. The air can be conditioned or not, but the main process is filtering. Also the system can be wall-mounted or ceiling-mounted. The scheme of such systems is presented on the Figure 4 and Figure 5.
2) Portable air recirculation unit – can be used to increase local or general ACR of the room. The main aim of such units is also to filter the air through an embedded HEPA filter. However, the efficiency and reliability of these units less than of the fixed recirculation system. Therefore the expediency of use of the portable air recirculation units should be evaluated for each particular case.

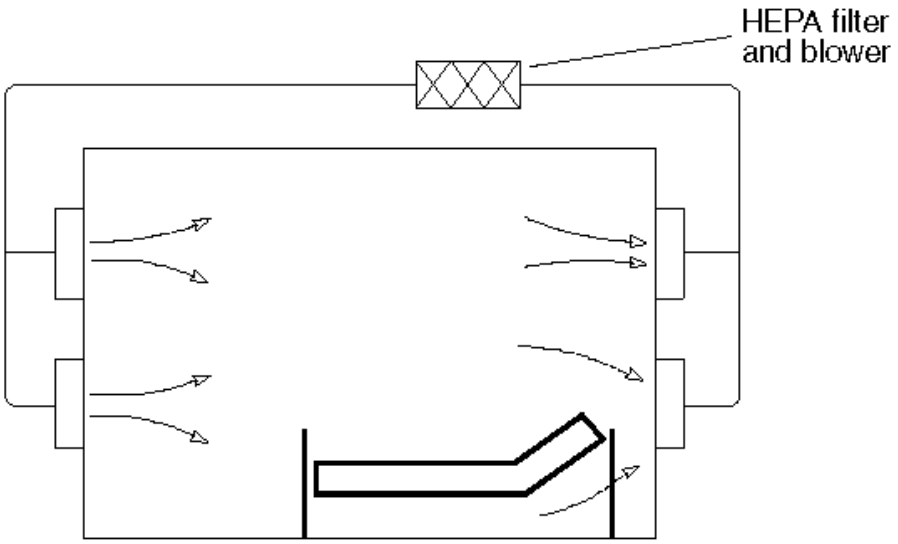

FIGURE 4.Fixed ducted air recirculation system. /3/

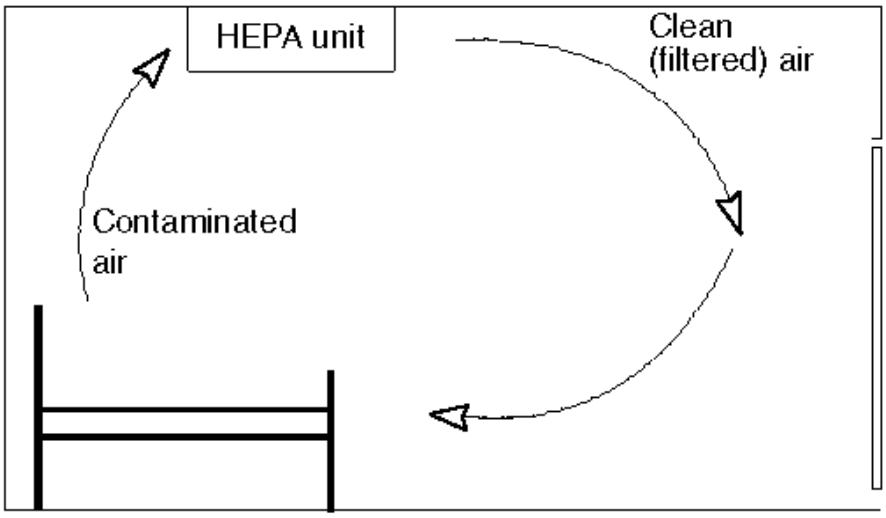

FIGURE 5.Fixed ceiling-mounted air recirculation system. /3/

4.2.8.Filters

The essential purpose of filters is removing the contaminants from the air. In terms of the infection control, filtration is the basic method of reducing the pathogens concentration. For this purpose filters can be used in:

- air-handling units to limit the concentration of particles entering from outdoors and keep the ventilation system components clean;
- exhaust ducts to remove pathogens before the air is discharged to the outside;
- ducts discharging air from AII room into the general ventilation system;
- fixed or portable recirculation systems. /3, 8/

Usually there are three stages of filtration:

1) Pre-Filters – to remove the lint, dust, and other large particles from the air. The efficiency of such filters is about 70% for particles of 10µm.
2) Fine-Filters – to remove smaller particles and provide a higher air quality for special spaces of health care facility. The efficiency of such filters is about 99% for particles of 5µm.
3) HEPA-Filters – to remove dangerous microorganisms. The efficiency of such filters is 99.97% for particles of 0.3µm. These filters are the most important in reducing infection concentration and will be discussed in more detail. /9, p. 231-232/

Generally, filters are classified by their overall and local efficiency against their most penetrating particles. The classification of filters according to the EN 1822:2009 is shown in Table 6.

TABLE 6 EN 1822:2009 classes for EPA, HEPA and ULPA filters. /10, p. 19/

Filter Class	Overall		Local	
	Efficiency (%)	Penetration (%)	Efficiency (%)	Penetration (%)
E10 (H10)	85	15	-	-
E11 (H11)	95	5	-	-
E12 (H12)	99,5	0,5	-	-
H13	99,95	0,05	99,75	0,25
H14	99,995	0,005	99,975	0,025
U15	99,9995	0,0005	99,9975	0,0025
U16	99,99995	0,00005	99,99975	0,00025
U17	99,999995	0,000005	99,9999	0,0001

The selection of certain filter type should be based on the type of particles present in the air. Proper filter types for different air impurities are presented in the Figure 6.

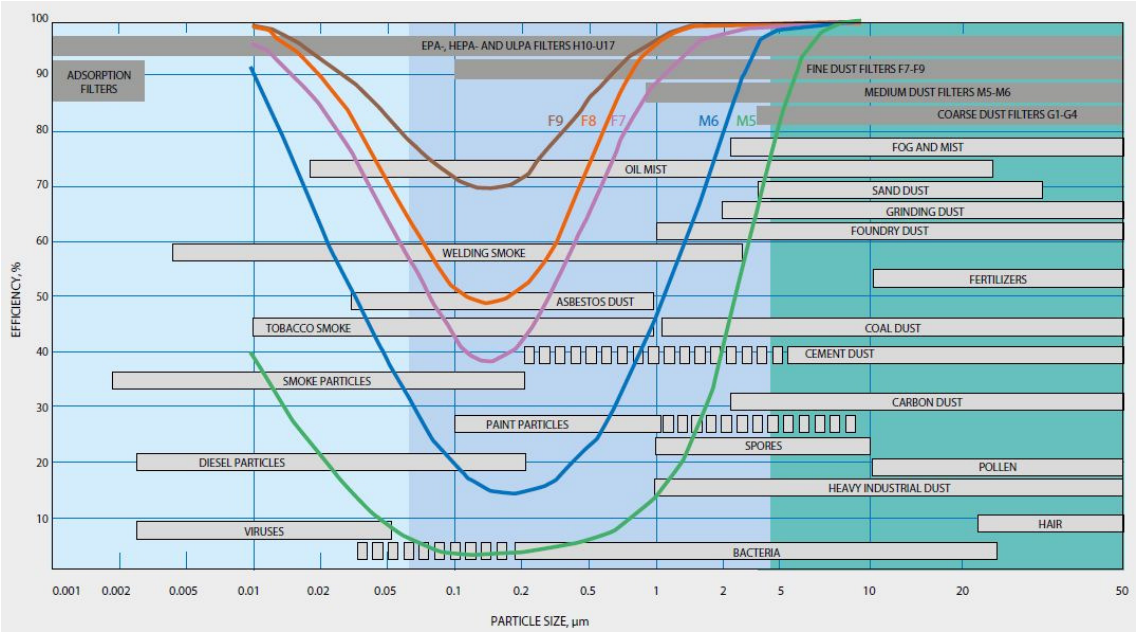

FIGURE 6. Typical air impurities, particle sizes, and filter types. /10, p. 6/

The construction of high efficiency filters can be of two types: deep-pleated and mini-pleated. /11, p. 104/

The following seven paragraphs are based on the “Cleanroom Design” book. /12, p. 157-165/

Deep-pleated filters consist of rolls of filter paper of 15 or 30 cm length, which are assembled into a frame. The frame is ussualy made of plastic, wood or metal. There are two methods to give the filter strength:

- to use a crinkled sheet of aluminum foil as a separator;
- to corrugate the filter media and fold it directly into a pack in such a way, that corrugations support the pleats.

The construction of deep-pleated filters is shown on the Figure 7 and Figure 8.

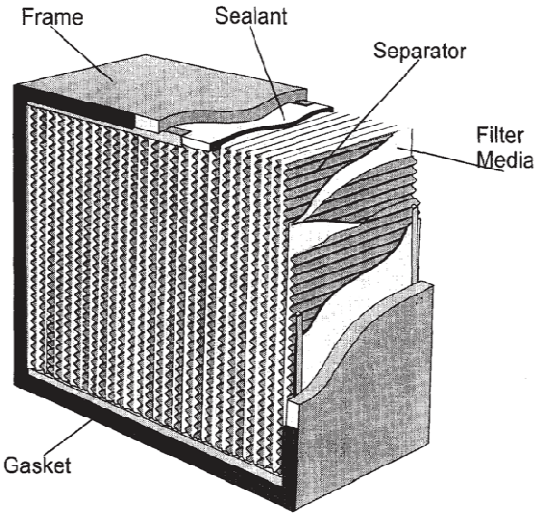

FIGURE 7. Deep-pleated high efficiency filter with separators. /12, p. 158/

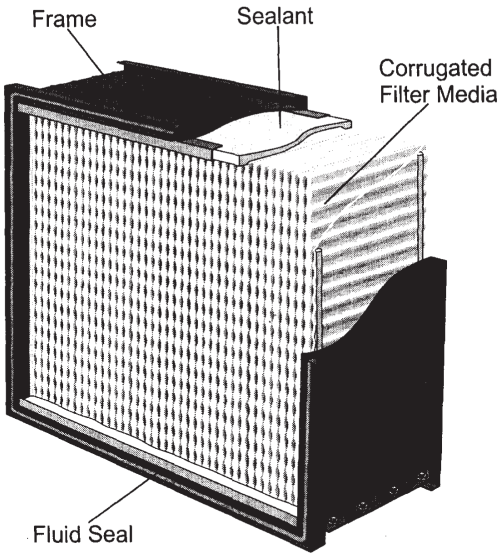

FIGURE 8. Deep-pleated high efficiency filter without separators. /12, p. 159/

In mini-pleated filters the media is folded over ribbons or glued strings and compactly assembles into a frame. This method allows assembling 2-3 times more pleats in the same size of frame, thus these filters contain much more media per unit area and are more compact. Moreover, the lower pressures drop than in a deep-pleated construction is also an advantage. The construction of mini-pleated filters is shown on the Figure 9 and Figure 10.

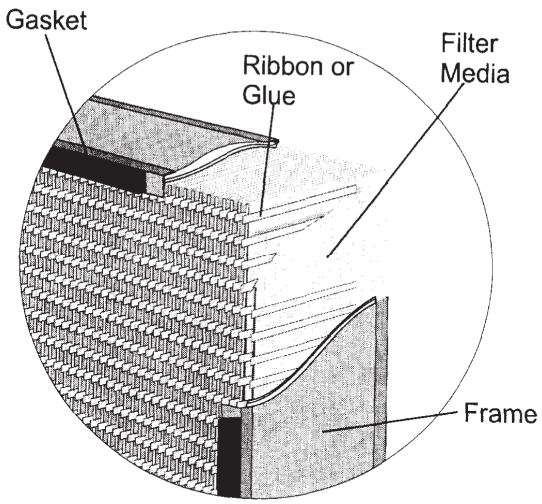

FIGURE 9.Mini-pleated high efficiency filter with separators. /12, p. 160/

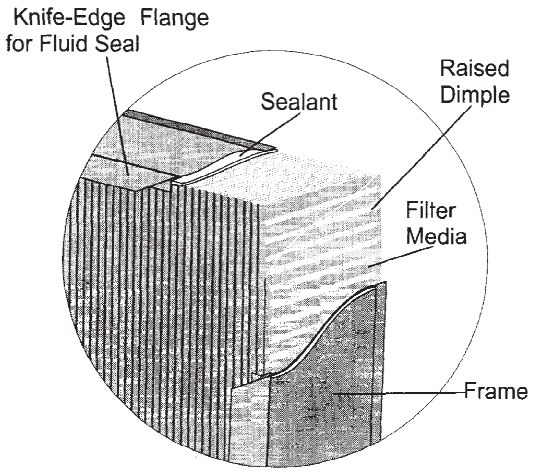

FIGURE 10.Mini-pleated high efficiency filter without separators. /12, p. 160/

If the efficiency of HEPA filters is not sufficient, then ULPA filters should be used. The efficiency of such a filter is 99.999% for particles of 0.1 – 0.2 μm. The construction of ULPA filters is the same as that of HEPA filters and the difference is only in fibers of the filter media – they have a higher fraction of smaller fibers. This distinction leads to a higher resistance and hence slightly higher pressure drop in comparison with HEPA filters.

The filter media of a high efficiency filter is made of glass fibers of 0.1 – 10 μm. The spaces between fibers are random and relatively large in comparison with the particles captured. A photograph of filter media is shown on the Figure 11.

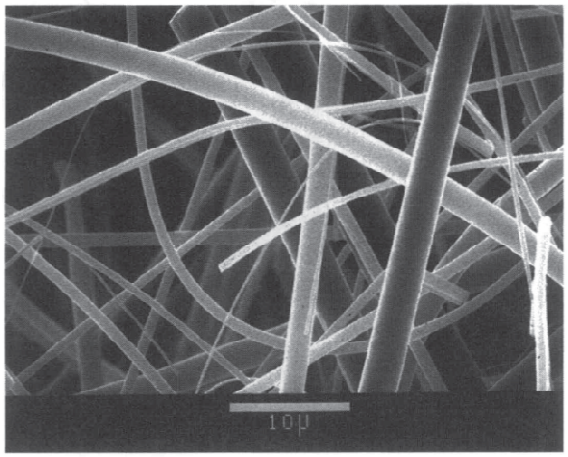

FIGURE 11.Photograph of high efficiency filter media. /11, p. 106/

There are four basic mechanisms of capturing the particles by filter media:

1) Impaction – when a particle has enough mass and momentum, it leaves the air stream and strikes a fiber;
2) Diffusion – smaller particles constantly and randomly move about and touch the fibers;
3) Interception – when a particle strikes a fiber tangentially;
4) Sieving (screening) – when a particle is larger than the space between certain fibers. However this mechanism is the least important.

The captured particles are retained due to the Van der Waal's forces, which are established between the fiber and captured particle. The illustration of the filtration mechanisms is shown on the Figure 12.

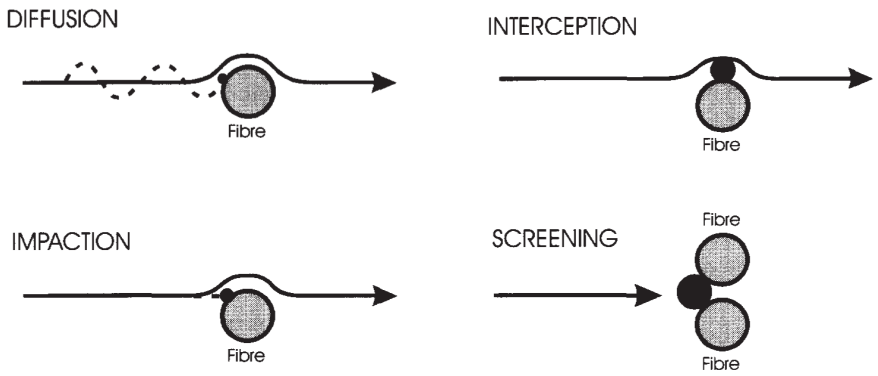

FIGURE 12.Particle capturing mechanisms. /11, p. 107/

The efficiency of each mechanism primarily depends on the particle size. A classical efficiency curve is shown on the Figure 13.

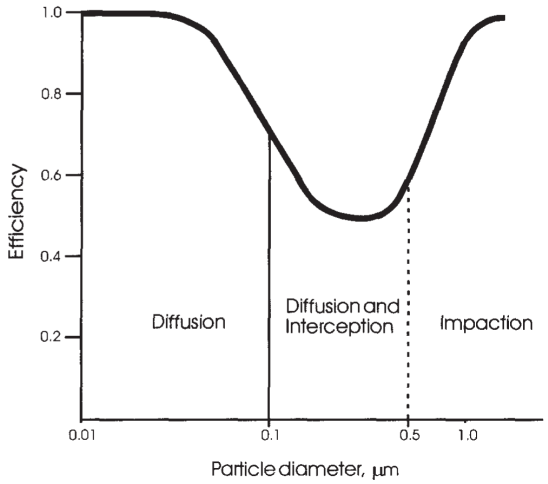

FIGURE 13.Classical efficiency curve of high efficiency filter. /11, p. 109/

However, the filtration efficiency depends also on other parameters, such as:

- velocity of the particle;
- mass (density) of the particle;
- thickness of the filter media;
- size of fibers of the filter media;
- pressure, velocity and temperature of the air. /12/

All HEPA filters must be tested after manufacture and their efficiency should be checked. The best known tests are the following:

- Military Standard 282;
- Sodium Flame Test (Eurovent 4/4);
- IEST-RP-CC007;
- European Standard EN 1822;
- etc. /11, p. 109-111/

The installation of HEPA filter must be performed with maximal care to avoid the damage of filter media and ensure the right position. The filter must be sealed and tested. The main aim is to avoid bypass leakage that can significantly spoil the efficiency of the filter. All HEPA filters must be provided with pressure-sensing device in order to determine when the filter should be replaced. /3/

4.2.9.Ultraviolet Germicidal Irradiation (UVGI)

The following chapter is based on the Guidelines for Preventing the Transmission of Mycobacterium tuberculosis in Health-Care Facilities. /3/

The purpose of UVGI is killing or inactivating pathogenic microorganisms. Studies have demonstrated the effectiveness of this method, thus it is recommended as a supplement to other infection control measures.

Ultraviolet radiation is a portion of the electromagnetic spectrum of 100 – 400 nm wavelengths. It is classified into three wavelength bands:

- long wavelengths (UV-A): 320 – 400 nm;
- midrange wavelengths (UV-B): 290 – 320 nm;
- short wavelengths (UV-C): 100 – 290 nm.

Usually the low-pressure mercury vapor lamps of UV-C range are used.

The UVGI can be used carefully and without exposing persons to UV-irradiation. Generally, it is used in two ways:

1) Duct irradiation – UV lamps are installed in exhaust ducts to disinfect the air before recirculation or exhausting to the outside. This method allows producing high levels of UV radiation without any risk for patients.
2) Upper-room irradiation – UV lamps are mounted under the ceiling or on the wall and the radiation is directed by a shield upward. It allows minimizing radiation exposure to persons in the space. The efficiency of this method is highly dependent on the air mixing rate in the room.

The effect of UVGI can be expressed as an equivalent ACR magnitude. This magnitude is estimated to 10-40 ACR-s. Theoretically the use of UVGI can replace a certain amount of ACR-s. However, it was demonstrated that UVGI efficiency depends on the ACR a lot. Too low air change rates drop down the efficiency of irradiation. On the other hand too high ACR leads to decreasing the length of time the air is irradiated, thus decreasing the efficiency of UVGI. So, there is an optimal relationship between the ACR value and UVGI, which is not known yet.

Due to the variations of the UVGI efficiency, there are several limitations of application:

1) UVGI should not substitute the HEPA filters in the ducts, which transfer the air from AII rooms to other areas of a facility;
2) UVGI should not substitute the HEPA filters of the local exhaust systems;
3) UVGI should not substitute the maintaining of negative pressure in AII rooms.

The International Agency for Research on Cancer classified the UV-C as “probably carcinogenic to humans”. Some studies show that UV-C radiation can induce skin cancer, DNA damage, activation of HIV gene promoters, etc. It means that over-exposure to UVGI is potentially dangerous both for patients and health care workers. Therefore the use of UVGI requires special safety measures in operation and maintenance. So, the expediency of the UVGI use should be evaluated in each particular case. /3/

4.2.10.CAV/VAV systems

The following chapter is based on the ASHRAE HVAC Design Manual for Hospitals and Clinics. /1, p. 47-54/

The ventilation systems fall into two basic categories: constant air volume systems (CAV) and variable air volume systems (VAV).

Constant air volume systems provide the simplest design approach and a high level of reliability. On the other hand they involve higher operational energy costs and less flexibility. The scheme of a common CAV system with terminal reheat is presented on the Figure 14.

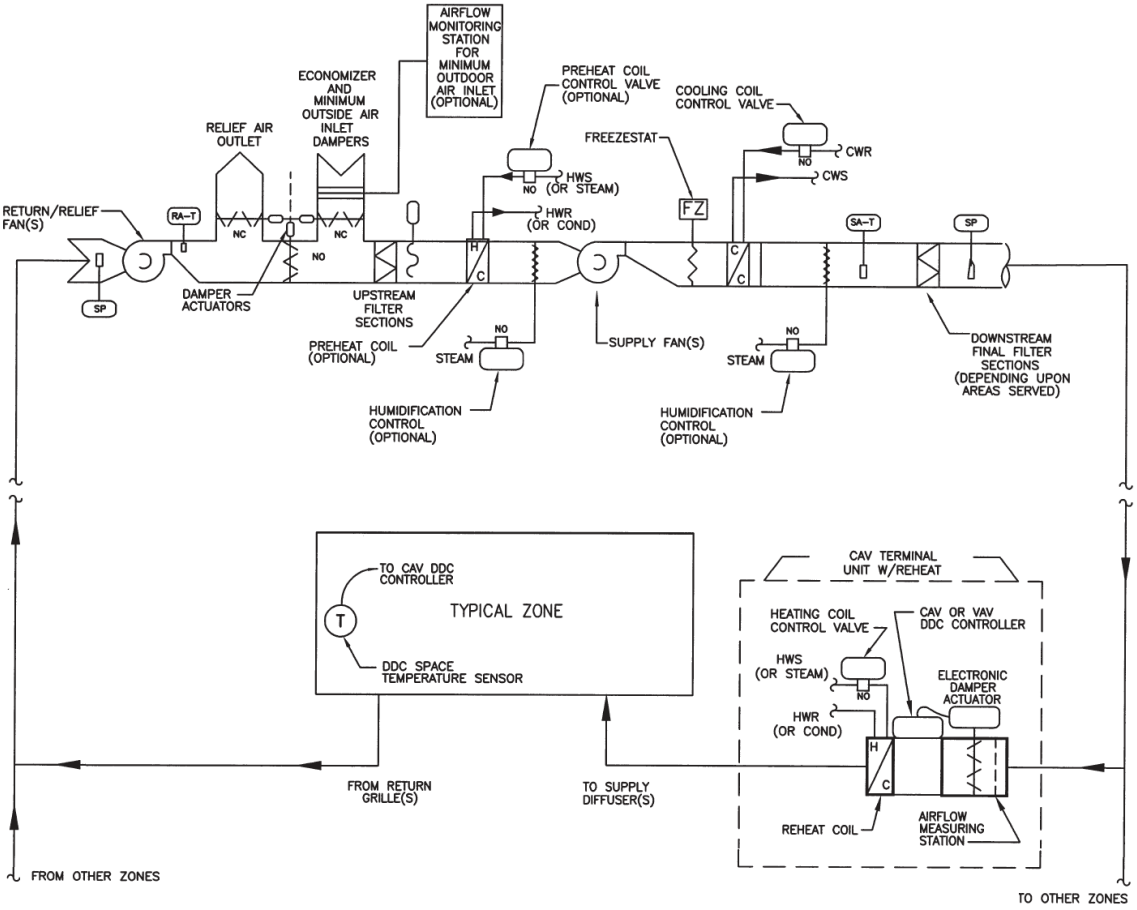

FIGURE 14.Constant volume air-handling system with terminal reheat. /1, p. 50/

Variable air volume systems allow regulating the air volume flows, temperature and humidity of the air in response to space conditions. These systems involve less operational energy costs in comparison with CAV systems, because they can reduce the air flow or air temperature, if necessary. Fan capacity is varied using the variable speed motor drives in response to the reading of pressure-sensors. Another strategy is the control of dampers position. The VAV systems have certain limitations of use in spaces that have specific pressure requirements. That is attributed to insufficient control reliability. However, recent studies demonstrated that modern control systems allow operating of VAV systems at a high level of reliability even in the spaces with stringent requirements, such as AII rooms.

Dual-duct systems distribute air with different air characteristics through two parallel ducts. Then the air streams are mixed in certain proportion, thereby adjusting the required air parameters (temperature, humidity). These systems can be either CAV or VAV. Also these systems can be divided into two categories: single fan dual duct sys-

tem (SFDD) and dual fan dual duct system (DFDD). The scheme of a common dual duct system is presented on the Figure 15.

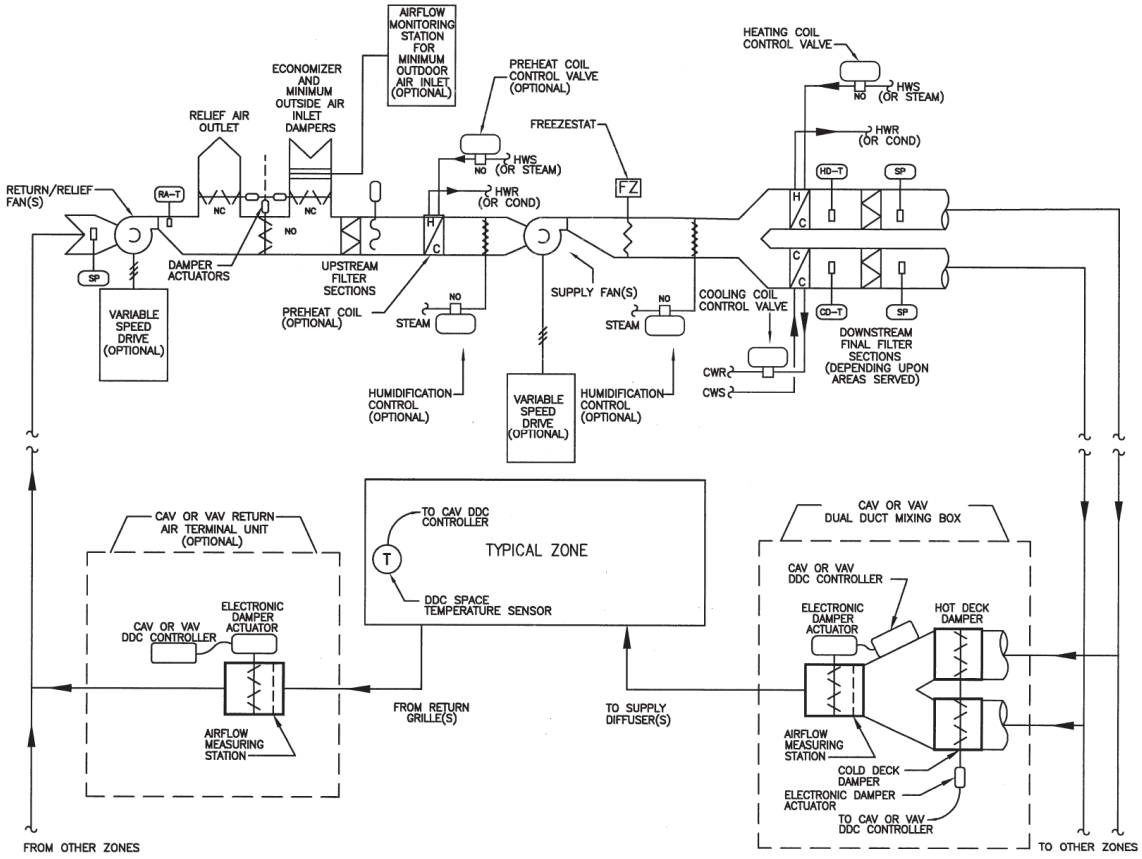

FIGURE 15.Dual duct system. /1, p. 52/

A comparison of advantages and disadvantages of all mentioned above systems is presented in the Table 7. /1/

TABLE 7.Advantages and disadvantages of different ventilation systems.

Parameter	CAV	VAV
Adjustment of air parameters	-	+
Flexibility	-	+
Reliability	+	-
Ease of maintenance	+	-
Easy of design	+	-
Investment costs	+	-
Operational costs	-	+

Acoustic characteristic	+	-

4.2.11.Control systems

The following chapter is based on the ASHRAE HVAC Design Manual for Hospitals and Clinics. /1, p. 105-110/

Control system is intended to maintain at a designed set-point a set of parameters, such as air flow rate, pressure, temperature, humidity. It reacts in response to changes in environment and makes adjustments. Control system is an integral part of the HVAC system. It contributes to infection control, reduces energy consumption, and provides a favorable environment for patients.

There several types of control systems:

1) Pneumatic control systems – use compressed air to operate actuators, relays, and sensors. These systems are the simplest. They are pretty reliable, but not very functional.
2) Electric control systems – are powered by low or line voltage and can perform on-off, proportional, derivative and analog control. However, they are most commonly used for on-off control. One of the advantages is the possibility to function within broad environmental limits.
3) Electronic control systems –amplifies the analog sensor signal and compare it to a set-point to actuate operations. The main advantage of electronic control systems is the remote set-point adjustment, because sensor can be located far from the controller.
4) Microprocessor or Direct Digital Control (DDC) – the sensor signal is converted to digital form and then certain algorithms are applied for control. Besides stand-alone option, DDC can be incorporated into a building management system (BMS). DDC is the most functional type of control system.

There are two basic pressurization criteria: volumetric flow rate (VFR) and room differential pressure (RDP). VFR is based on the calculation of differential air flow. VFR criterion is used in CAV systems. RDP criterion requires permanent pressure measurement. If there is a decrease of pressure difference for some reason (for example leaving the door open), then the control systems reacts by activating an alarm and if

possible increasing the exhaust air flow. So, in the case of AII rooms and VAV system, only RDP criterion is allowed. /1/

4.3. **Administrative measures**

The following chapter is based on the Guidelines for Preventing the Transmission of Mycobacterium tuberculosis in Health-Care Facilities. /3/

Besides engineering measures, there are also administrative measures of the infection control, which are not less important. The most significant are:

1) Developing and implementing effective polices and protocols for early identification and isolation of infected patients.
2) Implementing effective work practices among health care workers.
3) Educating and training health care workers.
4) Screening health care workers for infections.

The most important practices include:

- education of infected patients about the mechanisms of infection transmission, the reason of isolation and measures to reduce infection spread;
- obligatory wearing of respiratory protection for all persons entering the AII room;
- minimizing the number of persons entering the AII room;
- giving general instructions about infection transmission to all visitors;
- prohibition of leaving the AII room for infected persons;
- keeping the door of the AII room closed;
- etc.

Studies show that the administrative measures can significantly reduce the risk of infection in health care facilities. At the first sight these measures seem to be simple and easy, but unfortunately the neglecting these measures lead to serious consequences. The administration and health care workers are primarily responsible for stringent respect of these measures. /3/

4.4. **Personal respiratory protective equipment**

The following chapter is based on the Guidelines for Preventing the Transmission of Mycobacterium tuberculosis in Health-Care Facilities. /3/

Personal respiratory protection is the third measure of infection control and very important as well. It is the last step in the hierarchy of control measures and must be discussed in more detail.

Personal respiratory protection should be used in the following cases:

- by any person entering the AII room;
- by health care workers present during cough-inducing or aerosol-generating procedures;
- by any person present in a space, where engineering controls don't ensure a protection from inhaling airborne pathogens.

There are two types of respirators:

1) Positive-pressure respirators – the positive pressure inside the facepiece is maintained by a blower that forcibly blows the air through a HEPA filter inside the facepiece. The flow rate of the blower exceeds the flow rate of inhalation; thereby a positive pressure is sustained.
2) Negative-pressure respirators – the negative pressure inside the facepiece is created every time when the person inhales.

The efficiency of personal respiratory protective equipment is determined by face-seal leakage and filter leakage.

Face-seal leakage compromises the respirator efficiency, because a certain portion of air passes through leaks of the respirator instead of passing through the HEPA filter. Face-seal leakage is mostly essential for negative-pressure respirators, and can reach up to 20% leakage. The improvements in design, widening the variety of available sizes and proper fit testing can reduce the leakage to less than 10%. For positive-pressure respirators, face-seal leakage is not so critical, and can reach up to 2% leakage.

Filter leakage usually is less significant than face-seal leakage, when high efficiency filters are used. The HEPA filter efficiency is almost 100% and the leakage through such a filter can be disregarded in comparison with face-seal leakage. However, in general for all types of filters, the efficiency depends on following factors:

- type of the filter;
- size distribution of particles in the air;
- velocity of air through the filter media;
- filter loading;
- electrostatic charges.

Generally, the respiratory protective equipment should meet certain standard performance criteria:

1) filter efficiency for 1 μm particles and flow rate of up to 50 l/min: ≥ 95%;
2) face-seal leakage: ≤ 10%;
3) available sizes of respirators: ≥ 3;
4) the ability to check the facepiece fit each time of use (according to the standards of Occupational Safety and Health Administration). /3/

So, it may be concluded, that the simplest negative-pressure respirator, which meets the performance criteria, reduces the risk by 90% × 95% = 85,50%. The best positive-pressure respirator reduces the risk by 98% × 99,97% = 97,97%. These are really significant figures and must be taken into account at the infection risk assessment. The administrations of health care facilities should consider the difference of 12,5% risk, when take the decision of what type of respirators to use.

5. CFD – NEW TREND IN VENTILATION SYSTEM DESIGN

From the previous chapters it can be concluded that the design of ventilation system of an AII room is very sophisticated and there are a lot of parameters that must be taken into account. This is explained by the complexity of air movement and infection spread. In general, the design of AII room ventilation is based on the experience of engineers and the rules of thumb. The new technologies allow finding an alternative approach to the design of such complex systems. One of the most perspective techniques is the computational fluid dynamics (CFD).

“Computational fluid dynamics is the use of computers and numerical techniques to solve problems involving fluid flow.” /13/ The most important equations of fluid dynamics represent conservation laws of mass, momentum, energy, and additional constituents. /14/

Because the equations are highly nonlinear, approximate methods are used. There are three methods: finite volume method, finite difference method, finite element method. /1, p. 244-246/

The most popular method in fluid mechanics is the finite-volume method. The advantages of this method are: strict enforcement of conservation, geometric flexibility, variety of fluid phenomena, etc. /13/

For all methods, at first the domain is divided into a set of cells and nodal points are defined. This is followed by three steps:

1) The flow field variables (velocity, pressure, temperature, concentration) are approximated by their values at each node.
2) The equations of motion are approximated in terms of values at nodes.
3) The resulting system of equations is solved and values at the nodes are obtained. /13/

The CFD study consists of three stages:

1) Pre-processing – includes the creation of computational mesh and setting the boundary conditions and governing equations;
2) Solving – includes finding the numerical solution of the governing equations;
3) Post-processing – plotting, visualization and analysis of results. /15/

The advantages of CFD modeling are:

+ the ability to simulate real systems;
+ the ability to describe the conditions very precisely;
+ the ability to simulate any environmental conditions;
+ the ability to study the impact of any number of variables;
+ the ability to change the boundary conditions very easy and fast;
+ the ability to measure any parameter in unlimited number of points;
+ the ability to measure any parameter in any modeled environment conditions;

+ the ability to measure any parameter with very small time steps;
+ relative much less time resources spending in comparison with experiments;
+ relatively much less cost in comparison with experiments. /1, p. 244-246/

The disadvantages of CFD modeling are:

- the necessity of a comprehensive understanding of the fluid mechanics and heat transfer;
- sophisticated CFD software;
- high computational resources requirements;
- CFD modeling can't fully replace physical experiments, because in some cases boundary conditions are not known;
- any CFD simulations must be based on experimentally proved models. /1, p. 244-246/

So, it can be concluded that CFD is a very powerful tool. It allows considerable reduction of the expenditures of time and money and possibility for more accurate research. The use of CFD allows increasing by an order the number of alternative designs for consideration and avoidance of need for building multiple prototypes. Regarding to HVAC systems in health care facilities, the CFD modeling can be used to improve the performance of the systems, to reduce the energy consumption and the risk of infection spread. The CFD modeling is the key tool for optimization and some of the possibilities are demonstrated in the following chapters.

5.1. **Infection control optimization**

One of the measures of solving nosocomial infection problem is improving the AII room. It can be achieved by the use of optimization approach, which means the selection of the best alternative from all possible.

For an AII room the following parameters should be optimized:

- infection escape risk;
- health care worker infection risk;
- patient care waiting time;
- patient comfort;
- energy consumption.

However there are a lot of factors that influence the parameters to be optimized, such as: room geometry, location of the door, location of the patient bed, location of terminal units, number of terminal units, types of terminal units, sizes of terminal units, initial velocities for each terminal unit, volume flow rate for each terminal unit, total volume flow difference, supply air temperature, design temperature, supply air relative humidity, design air relative humidity, use of a local exhaust device, use of an anteroom, type of the control system, etc.

Considering that each factor is described by a few variables, it can be assumed that the total number of variables is about several dozen. That means that the number of alternative designs is too large to model each one of them. The only way is to analyze the impact of each factor separately, using the guidelines as a basis.

6. ANALYSIS OF ONE FACTOR IMPACT USING CFD MODELING

In order to demonstrate the CFD modeling possibilities in optimizing the infection control strategies, the impact of one factor will be analyzed in this paper. The factor to be analyzed is the use of local exhaust ventilation of exterior type. The guidelines don't oblige to use a local exhaust in the AII room. In this paper the expediency of such measure will be investigated. For this purpose a tuberculosis (TB) AII room was chosen. The reason of TB choice was discussed in "Pathogens Classification" chapter.

Thus, two models were created:

1) TB AII room without any local exhaust ventilation;
2) TB AII room with a local exhaust ventilation of exterior type.

All other parameters of the models were equal.

6.1. **Infection generation process definition**

Generally, the infected person in a TB AII room generates airborne pathogens by three processes:

- speaking;
- coughing;
- sneezing. /16, p. 471/

The most dangerous of these processes is sneezing and there are several reasons of this conclusion:

1) The velocity of a sneeze is the highest from all mentioned activities – that allows particles to be spread faster.
2) The photometric measurements showed that the mean droplet diameter decreases as the velocity increases. That means, that sneezing produce smaller droplets, that are more dangerous due to they can penetrate deeply into the lungs of the exposed person.
3) Sneezing produce much more droplets than any other activity. J.P. Duguid in his investigation measured the size of droplets produces by speaking, coughing and sneezing by direct micrometry after the recovery of droplets from the air on to the oiled slides. The results of that investigation for droplet diameter range of 1-8 μm are presented in the Table 8.

TABLE 8. Number of droplets expelled for droplet diameter range of 1-8 μm /16/

Droplet diameter, μm	One sneeze	One cough	Counting loudly "1-100"
1-2	26,000	50	1
2-4	160,000	290	13
4-8	350,000	970	52
Total	536,000	1,310	66

It was assumed that droplets are distributed equally by diameter over each size range. Thus the mean volume of a size range was calculated by the formula:

$$V = \frac{\frac{1}{6} \cdot \pi \cdot \frac{1}{4} \cdot (d_2^4 - d_1^4)}{(d_2 - d_1)},$$

$where\ V = mean\ volume\ of\ droplets\ of\ certain\ size\ range;$
$d_1 = minimum\ diameter\ of\ the\ size\ range;$
$d_2 = maximum\ diameter\ of\ the\ size\ range.$ /16, p. 476/

The calculation results are presented in the Table 9.

TABLE 9. Mean volume of droplets

Diameter			Number of droplets			Volume of one droplet (ml)
d1	d2	Mean	Sneeze	Cough	Speaking	
1	2	1,5	26 000	50	1	2,0E-12
2	4	3	160 000	290	13	1,6E-11
4	8	6	350 000	970	52	1,3E-10

As was mentioned before, the concentration of bacteria in the sputum of infected person varies a lot, thus for the purpose of calculation a maximum value of 1 million bacteria per 1 ml was chosen. The results of bacteria number and droplets concentration calculation are presented in the Table 10.

TABLE 10. Bacteria concentration calculation

Diameter			Mean number of bacteria in one droplet	Mean number of bacteria for activities			Concentration
d1	d2	Mean		Sneeze	Cough	Speaking	
1	2	1,5	2,0E-06	0,1	0,0	0,0	5,1E-11
2	4	3	1,6E-05	2,5	0,0	0,0	2,5E-09
4	8	6	1,3E-04	44,0	0,1	0,0	4,4E-08

The results demonstrate that the largest concentration corresponds to the droplets size range of 4-8 μm. In order to improve performance of the modeling, the size range of 4-8 μm was chosen and smaller sizes were neglected. Moreover too small droplets evaporate very fast, therefore are less hazardous. Also for the purpose of more accurate solving, the concentration of sputum droplets will be used and then the recalculation to the number of bacteria will be performed at the post-processing stage of CFD modeling.

The next parameter to be determined is the velocity and air volume flow rate of a sneeze. According to the Big Medical Encyclopedia edited by Petrovskii, the initial air velocity at the glottis point is about 50-120 m/s. /17, p. 337-338/ However, the initial velocity of droplets at the mouth or nose point is significantly less. Recent slow-motion camera experiment performed by Adam Savage and Jamie Hyneman showed that the initial velocity of droplets expelled by a sneeze is about 16.5 m/s. /18/ Grace M. Hwang in his work “An analysis on the Detection of Biological Contaminants

Abroad Aircraft" mention air volume flow rate of a sneeze of 3.56 l/s and the duration of 0.55 s. /19/

Ultimately, the initial data required for modeling a sneeze is the following:

- concentration of monitored droplets in the air expelled: 4.4E-08;
- diameter of monitored droplets: 6 µm;
- Initial air velocity: 16.5 m/s;
- Air volume flow rate: 3.6 l/s;
- Duration of expelling: 0.55s.

6.2.**TB AII room definition**

For the purpose of improving the performance of solving, the room geometry was simplified, but with the respect to guidelines recommendations. The anteroom is not present in the design, because its affect was discussed separately. The worksheet of the room model is presented in the Table 11.

TABLE 11.Room Model Worksheet

Room Floor Area	9 m^2
Room Volume	27 m^3
Air Gap Leakage Area	400 cm^2
Room Supply Volume	100 l/s
Room Supply Velocity	0.15 m/s
Room Exhaust Volume	115 l/s
Room exhaust Velocity	0.20 m/s
Differential Air Volume (for P=0.5 Pa)	15 l/s
Room Air Change Rate (ACR)	15.0

The pressure difference was set at 0.5 Pa despite the guidelines requirement of 2.5 Pa, because the requirement of 2.5 Pa is quite new and the earlier value was 0.25 Pa. Thus, the most of health care facilities HVAC systems are designed to maintain lower pressure differentials. They are incapable to increase the pressure difference up to 2.5

Pa with the means of general ventilation system. Thus, the general ventilation system of the model is meant to be an old one. And in order to achieve the required pressure differential alternative measures are used. This question was discussed in “Ensuring directional airflow inward the AII room” chapter.

Due to low computational performance available, the model was built in 2D space. The layout of the AII room model is presented on the Figure 16.

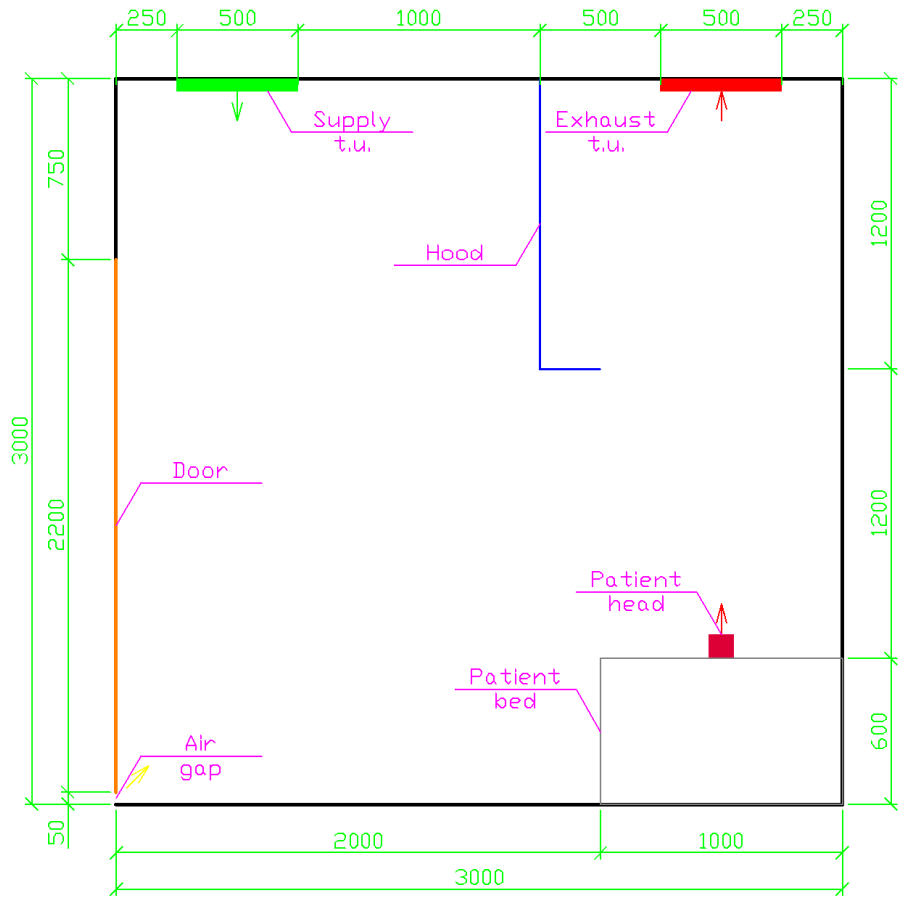

FIGURE 16.Layout of the TB AII room model

6.3.**Mesh generation**

The mesh for both alternative models was created in the Ansys Gambit 2.4.6 pre-processor in three steps:

1) creation of the geometrical model;
2) creation of the mesh;
3) specification of boundary and continuum types.

For the purpose of improving solving accuracy and due to the type of the model, the rectangular type of the mesh was chosen. The mesh size varied from 2.5x1.0 cm to 5.0x5.0 cm. A denser mesh was created in the infection injection zone and at the bottom of the door, where the air gap is located. The highest aspect ratio was 5:1. The total number of faces was 13,584 for the model without a hood and 13,613 for the model with a hood. The image of the grid (for model with a hood) is presented on the Figure 17.

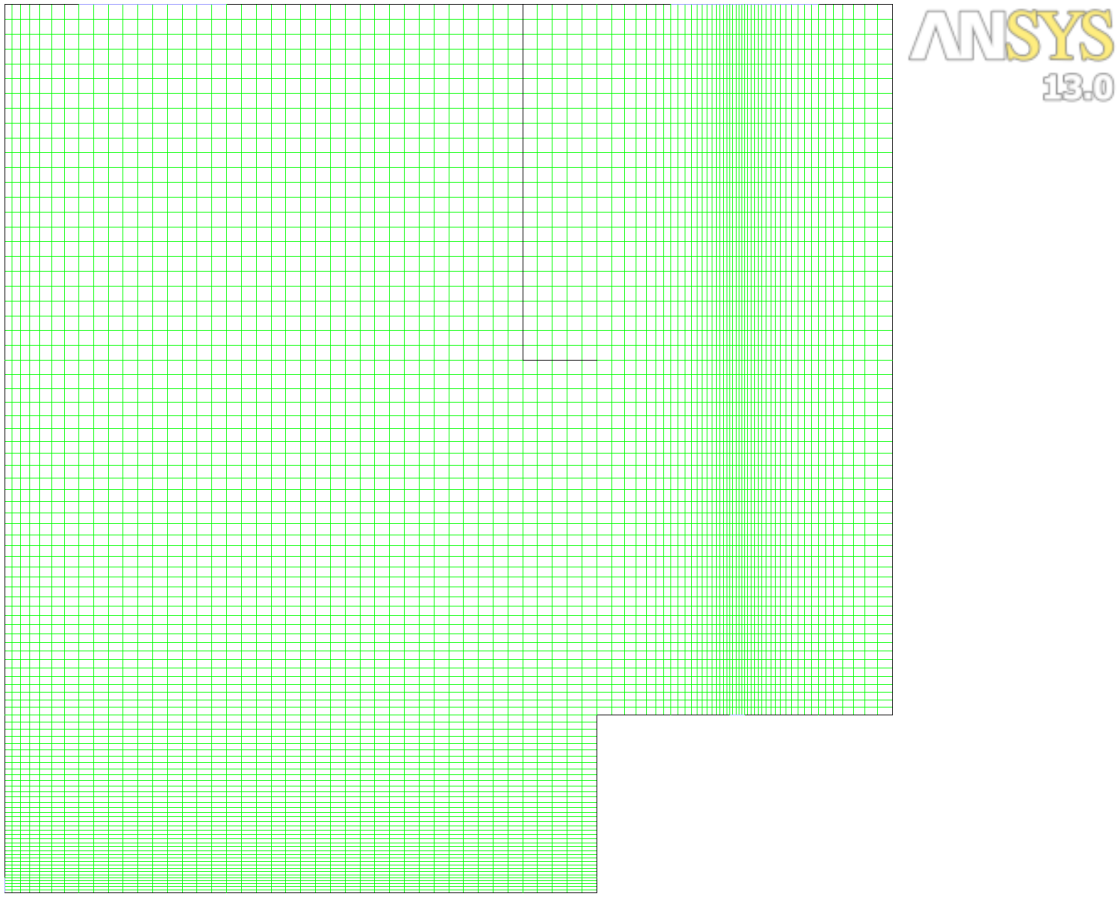

FIGURE 17.Mesh of the TB AII room model

Then the boundary types for each element of the model were specified according to the Table 12.

TABLE 12.Boundary types for the elements of the model

Element	Boundary Type
Walls, floor, ceiling	WALL
Patient Bed	WALL

Door	WALL
Hood	WALL (for one model only)
Supply Terminal Unit	VELOCITY_INLET
Exhaust Terminal Unit	VELOCITY_INLET
Infection Source	VELOCITY_INLET
Air Gap	INLET_VENT

Then the mesh was exported to Ansys Fluent 13.0 solver.

6.4.**Air gap local loss coefficient calculation**

In order to describe the model more realistic and to have the ability to analyze the risk of infection escape, the air gap at the bottom of the door was specified as INLET_VENT boundary type element. That allows to specify a certain hydraulic flow resistance coefficient for the air gap and to find the exact differential air volume for designed pressure differential. Moreover it allows analyzing the airflow pattern in the door zone throughout the process, thereby evaluating the risk of infection escape.

A separate model was created in order to determine the hydraulic flow resistance coefficient of the air gap in question. The hydraulic flow resistance coefficient was calculated by the formula:

$$K = \frac{Total\ Pressure\ Loss}{Dynamic\ Pressure} = \frac{p_1 - p_2}{p_d},$$

$where\ K = hydraulic\ flow\ resistence\ coefficient;$
$p_1 = total\ pressure\ before\ obstacle;$
$p_2 = total\ pressure\ after\ obstacle.$

The results of solving are presented on the Figure 18 and Figure 19.

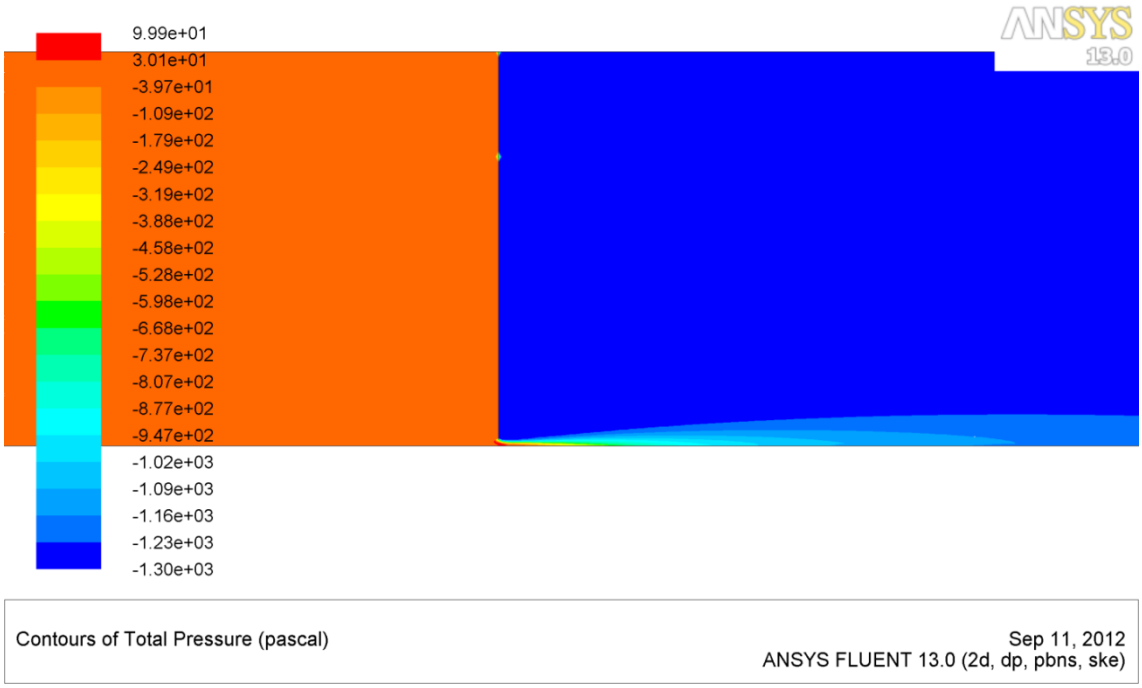

FIGURE 18.Contours of total pressure

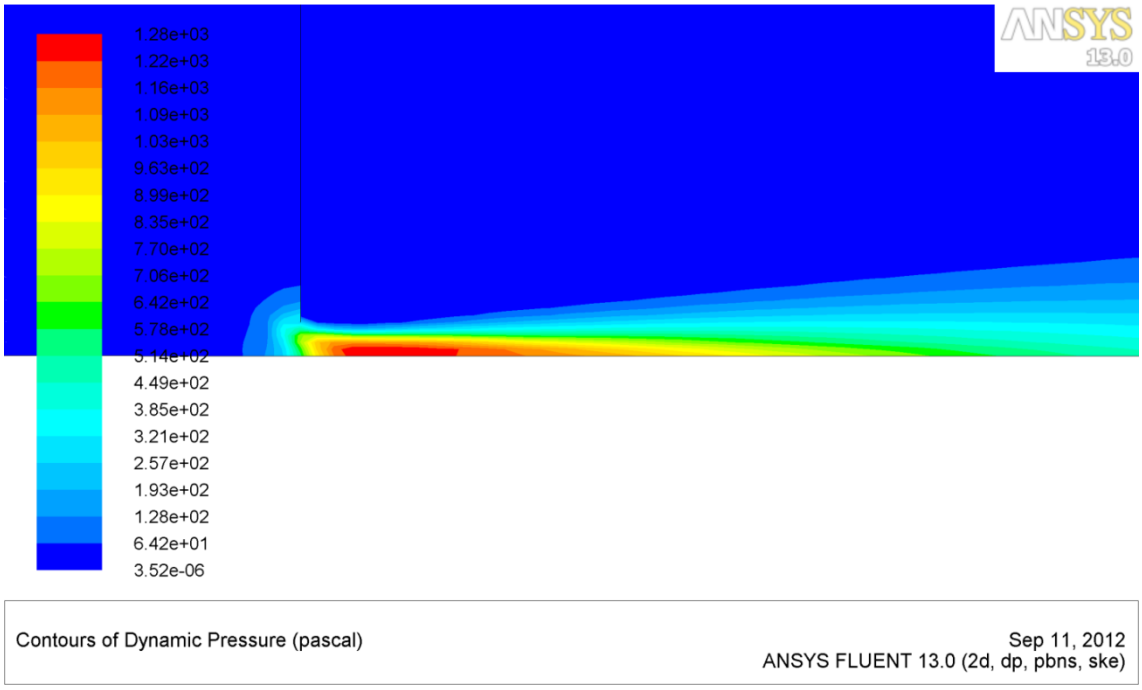

FIGURE 19.Contours of dynamic pressure (zoomed in)

Using the results of the simulation, the hydraulic flow resistance coefficient was calculated:

$$K = \frac{35Pa - (-1260Pa)}{670Pa} = 1.93$$

The resulting value of 1.93 was used for both AII room models.

6.5. **Determination of the differential air volume**

The differential air volume was determined also by the simulation method. As initial data were used:

- the calculated flow resistance coefficient;
- the designed air change rate;
- the volume of AII room;
- the designed pressure difference.

Firstly the exhaust air volume flow rate was calculated by the formula:

$$q_{v,exhaust} = ACR \cdot V_{room},$$

$where: q_{v,exhaust} = exhaust\ air\ volume\ flow\ rate;$
$ACR = designed\ air\ change\ rate;$
$V_{room} = the\ volume\ of\ AII\ room.$

According to the initial data:

$$q_{v,exhaust} = 15 \cdot \frac{1}{h} \cdot 27m^3 = 405\frac{m^3}{h} \approx 115\frac{l}{s}$$

Then different supply air volume flow rates were used in simulation, until the designed pressure difference was achieved. Finaly, the supply air volume flow rate of 100 l/s was determined. Thus, the differential air volume equals to 15 l/s. The contours of pressure for this case are presented on the Figure 20 and Figure 21.

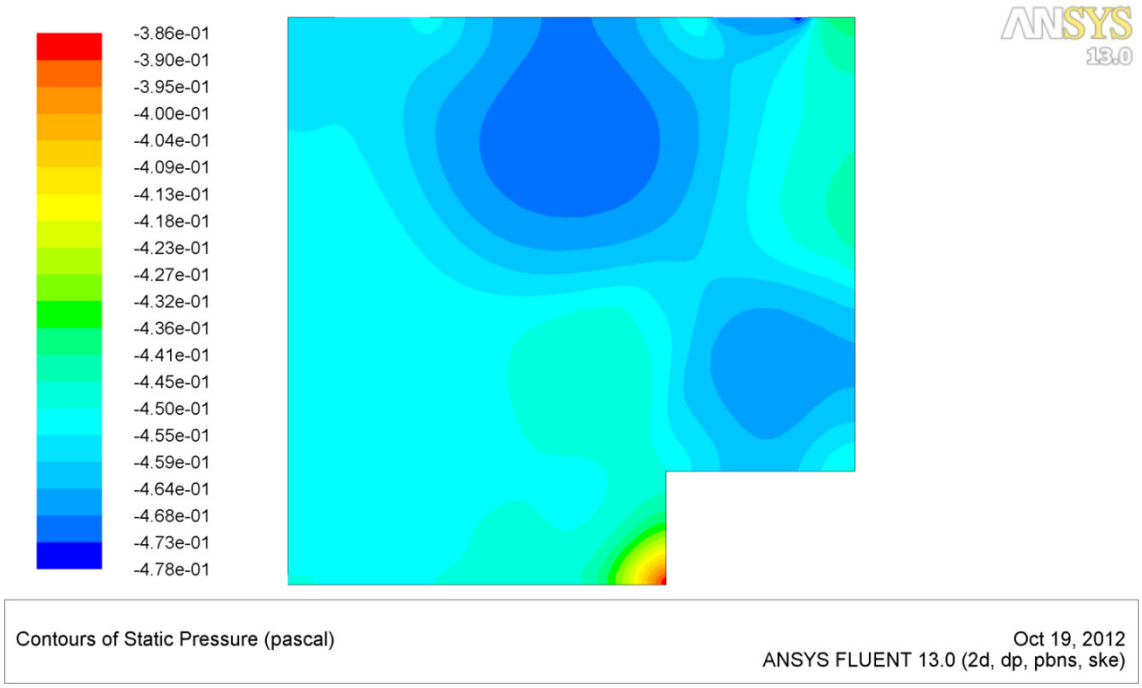

FIGURE 20.Contours of static pressure (AII room without hood)

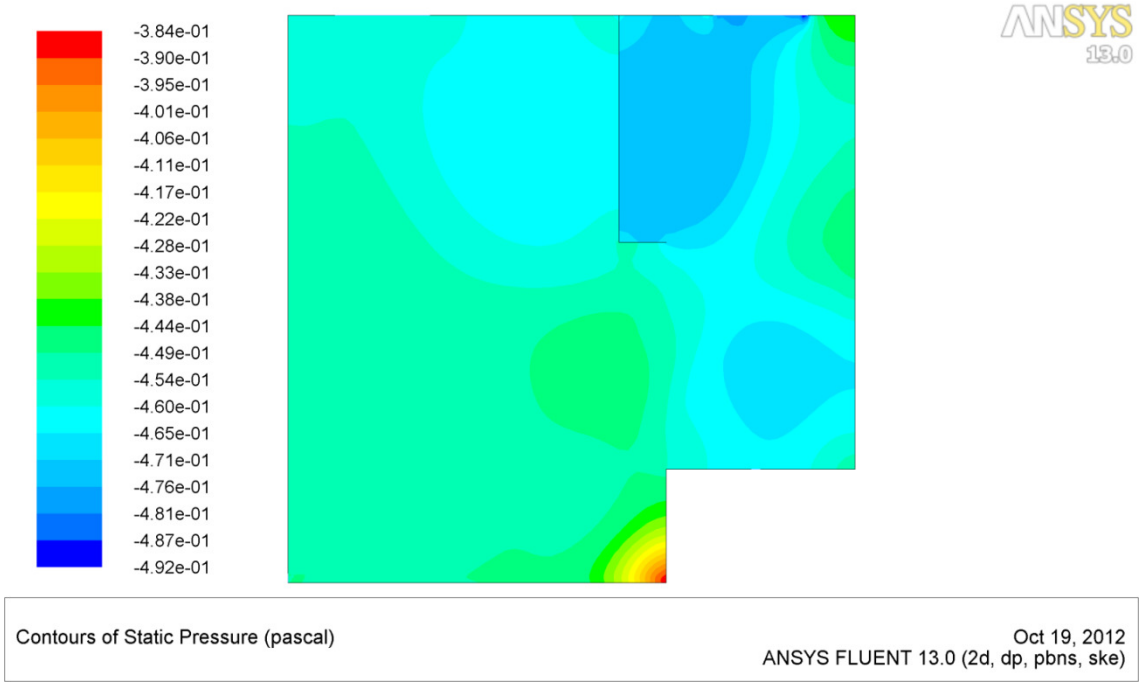

FIGURE 21.Contours of static pressure (AII room with hood)

6.6.**Eulerian multiphase model**

In order to observe the infection spread, a two-phase model was used for air and sputum droplets. Generaly, there are three multiphase models: volume of fluid (VOF) model, mixture model and Eulerian model. The VOF model is applicable for stratified/free-surface flows and cannot be applied in the case of study. The mixture

model is a simplified alternative of the Eulerian model. In constrast to the mixture model, the Eulerian model has no restrictions placed on either the velocity differential between the phases or the volume fraction of any phase, so it is more preferable. In order to confirm the expediency of selection of Eulerian model, an analysis of velocity fields was performed. A velocity differenial between two phases was observed, which means that the mixture model is less accurate and the Eulerian model is the best choise. The Eulerian model requires more computational effort, because it solves a larger number of ecuations, but on the other hand it provides more accurate results. It should be mentioned that the case of study doesn't fall under the limitations of Eulerian model, so it can be used. /20, 21/

The Eulerian model is used to model dispersed phase (droplets) in continuous phase (gas). The continuous phase is considered the primary phase (air) and the dispesed phase is considered secondary phase (sputum droplets). The conservation laws of mass, momentum and energy are defined for each phase and coupled via interfacial terms, which are modeled. The interfacial terms depend on particle diameter and due to they determine the accuracy of the model, the knowledge of particles diameter is very important. Therefore it was estimated very detailed in the "Infection Generation Process Definition" chapter. /22/

6.7.**Solver settings**

As was mentioned before, the simulation was performed by Ansys Fluent 13.0 solver. After all preliminary preparation, the solver was set according to the recommendations for Eulerian model. The key settings are presented in the Table 13.

TABLE 13.Solver settings

Parameter	Setting
Solver	Type: Pressure-Based
	Time: Transient
Multiphase Model	Eulerian (2 phases)
Viscous Model	k-epsilon Standard
Phases	Primary phase: air

	Secondary phase: water (the most realistic)
Solution Methods	Scheme: Multiphase Coupled
	Gradient: Least Squares Cell Based
	Momentum: First Order Upwind
	Volume Fraction: First Order Upwind
	Turbulent Kinetic Energy: First Order Upwind
	Turbulent Dissipation Rate: First Order Upwind
Solution Controls	Courant Number: 40
	Momentum: 0.5
	Pressure: 0.5
Under-Relaxation Factors	Density: 1
	Body-Forces: 1
	Volume Fraction: 0.4
	Turbulent Kinetic Energy: 0.8
	Turbulent Dissipation Rate: 0.8
	Turbulent Viscosity: 1

The time step size was calculated according to the formula:

$$\Delta t = \frac{L_{cell} \cdot Cu_{max}}{v_{max}},$$

$where: \Delta t = time\ step\ size;$

$L_{cell} = the\ smallest\ cell\ edge;$

$Cu_{max} = maximum\ Courant\ number, Cu \leq 0.25;$

$v_{max} = maximum\ velocity.$

According to the initial data:

$$\Delta t = \frac{0.025m \cdot 0.25}{16.5m/s} = 0.00038s$$

$Round\ downward\ to: \Delta t = 0.00025s\ (for\ more\ exact\ time\ slices)$

Number of steps for injection is calculatedaccording to the formula:

$$N = \frac{T}{\Delta t},$$

$where: N = number\ of\ steps;$

$T = injection\ duration;$

$\Delta t = time\ step\ size.$

According to the initial data:

$$N = \frac{0.55s}{0.00025} = 2200$$

And the last step before solving is setting the control points. The control points are defined separately for four zones according to the Table 14.

TABLE 14.Control points

Zone	X-Step (m)	Y-Step (m)	Total points
Door	0.20	0.05	135
HCW Operational	0.25	0.05	105
Bed	0.20	0.05	68
Hood	0.20	0.05	102

The scheme of the zones and the control points location is presented on the Figure 22.

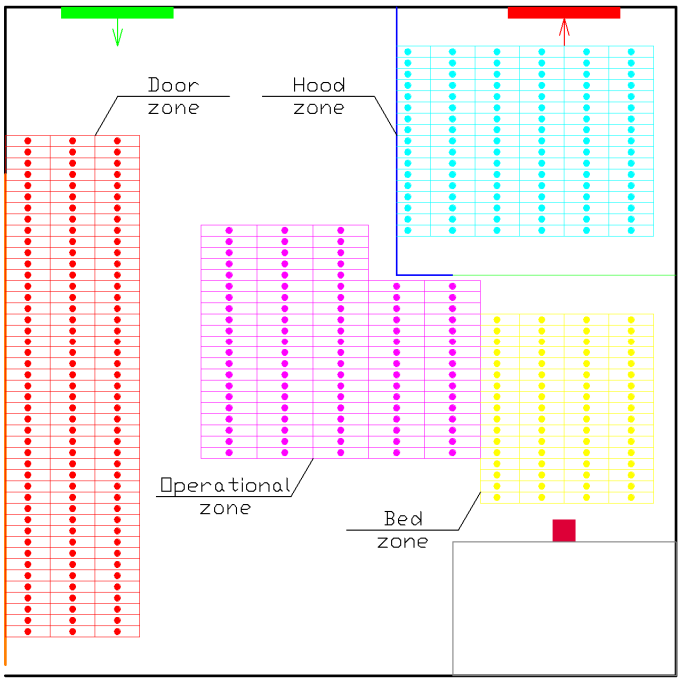

FIGURE 22. Scheme of the zones and the control points location

For all these points the concentration was measured during the whole simulation.

6.8.**Solving**

The solving process consists of four phases:

1) Preliminary stationary simulation;
2) Preliminary transient simulation without infection;
3) Injection of infection;
4) Infection removing observation.

The first phase is required to check the model and obtain the initial conditions for transient computation. Then the solver is changed to transient and run for 2s. The time step for this phase was set to 0.002s.

Then, the boundary conditions are changed to infection injection position. The time step is also changed to the calculated value. The duration of the phase was 0.55s. The contours of droplets concentration were saved every 0.05s during the injection to observe the path of infection spread. The slices at 0.05s, 0.15s, 0.25s, 0.35s, 0.45s and 0.55s are shown on the Figure 23 for the model with a hood and on the Figure 24 for the model without a hood.

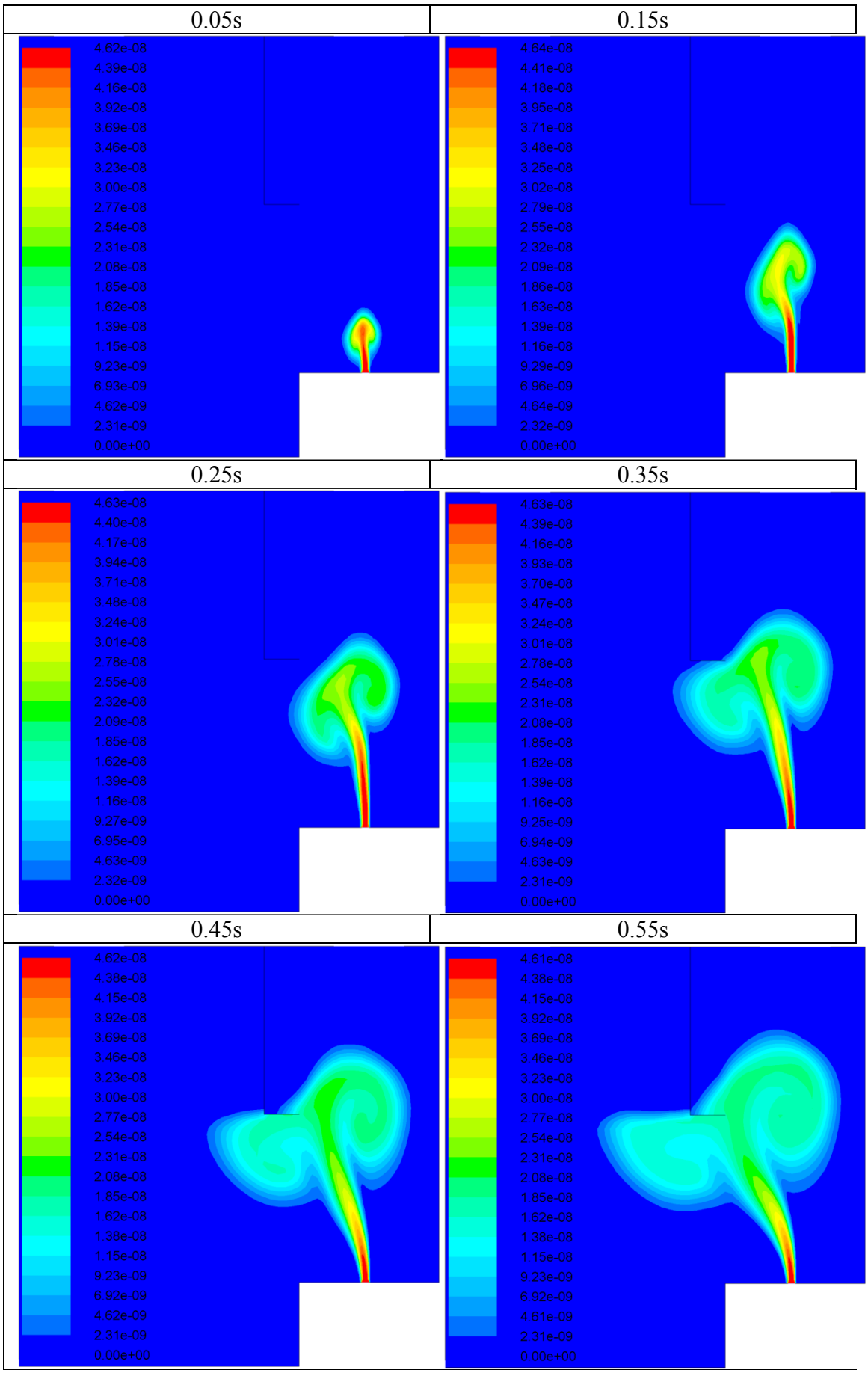

FIGURE 23. Contours of droplets concentration (model with a hood)

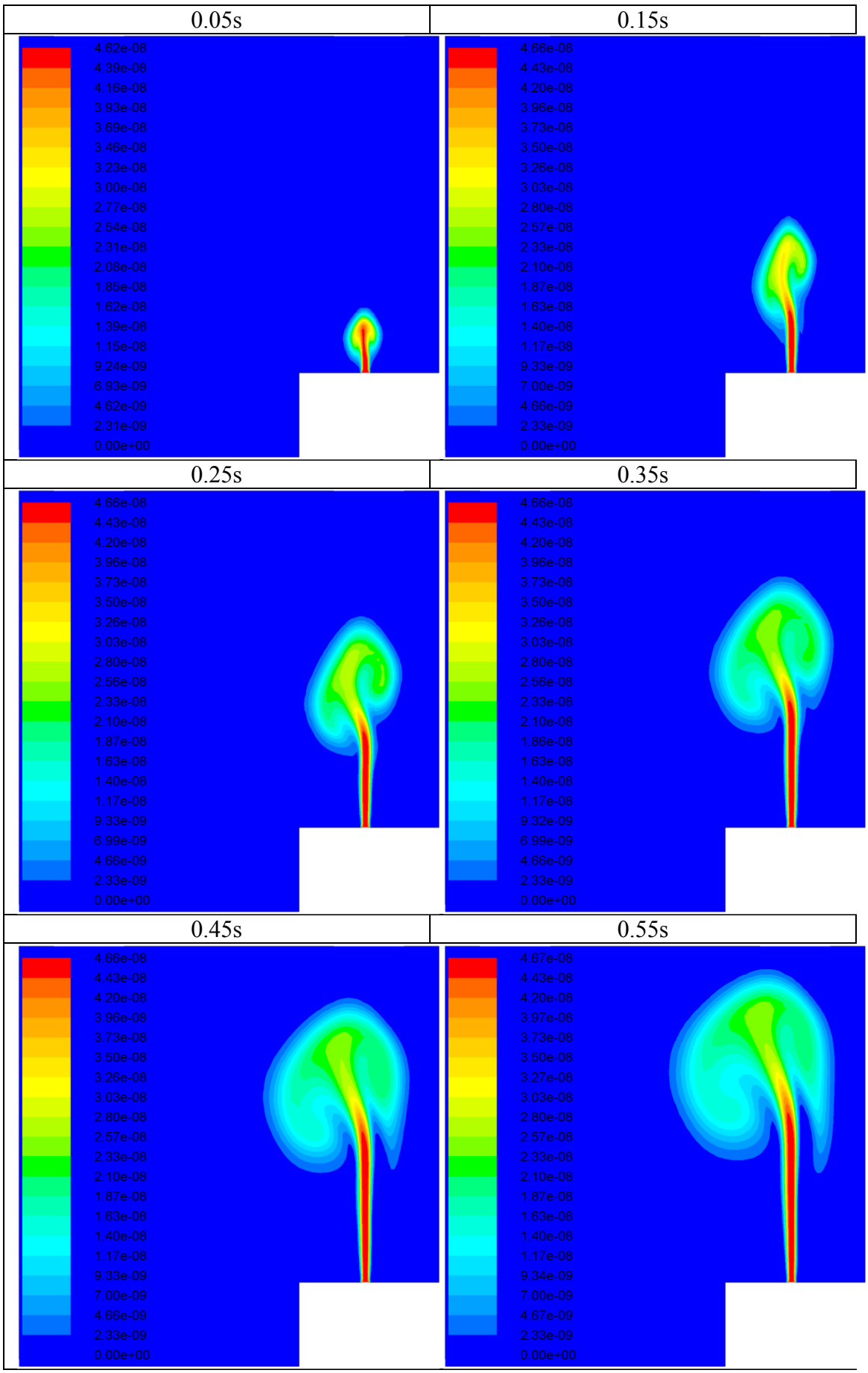

FIGURE 24. Contours of droplets concentration (model without a hood)

Then the infection injection is stopped and the last phase of simulation started. The duration of the third phase was almost 5 minutes (299.45s) of simulation time. The time step was decreased gradually accordingly to the maximum velocity. During this phase the contours of droplets concentration were saved only for the first 10s. However, the values of concentration at control points were saved permanently.

Ultimately, the total time for each model was 302s. In order to avoid mistakes and to improve accuracy, the simulation of both models was performed by2 different computers with the parameters according to the Table 15. It took about 50 hours of computational time on average for solving of each model. So, the total time spent was about 200 hours.

TABLE 15. Computers parameters

Parameter	Computer 1	Computer 2
OS	Windows Vista 32 bit	Windows 7 64 bit
CPU	Intel Core 2 Duo E6600 2.4 GHz 4Mb L2 Cache	Intel Core 2 Duo E6700 2.66 GHz 4Mb L2 Cache
RAM	4GB	2Gb

6.9.**Results**

As a result, the plots of the concentration function over time were created. The plots were created for each zone separately (bed, hood, door, HCW operational) and divided into 3 time periods:

1) 10s (time step of 0.5s)
2) 60s (time step of 2.5s)
3) 300s (time step of 15s)

The division into three time periods provides a more detailed data for analyzing at the start of simulation. It should be mentioned that the value on the plots is the ratio between the mean value of the concentration in all control points of the zone and the injection concentration value. All plots are presented in the Appendix B.

The most important are the results for the HCW operational zone and the door zone. The conclusion of the impact of use of a local exhaust device is presented in the Table 16. The impact was estimated by the comparison of two models.

TABLE 16. The local exhaust device impact

Parameter	Impact
Concentration in the door zone – 10s	**-47%**
Concentration in the door zone – 60s	**0%**
Concentration in the door zone – 300s	**+100%**
Concentration in the HCW operational zone – 10s	**-32%**
Concentration in the HCW operational zone – 60s	**-96%**
Concentration in the HCW operational zone – 300s	**-87%**
Time required to reduce the concentration with 90% in the door zone	**-10%**
Time required to reduce the concentration with 90% in the HCW operational zone	**-85%**

So, it may be concluded, that the use of local exhaust device significantly decreases the infection concentration in HCW operational zone, thus decreasing the risk. However, the concentration in the door zone eventually increases. The increase of concentration in the door zone can be explained by the portion of droplets escaped out of the hood and by the absence of additional exhaust terminal unit beyond the hood. That can be observed on the contours of concentration. Thus, the escaped droplets are more difficult to dilute and remove. An additional terminal unit would solve this problem. The use of anteroom also is a good solution.

Moreover, the problem is not very significant, because the values of concentration are very low for both models. It can be demonstrated by comparison with the guidelines values. According to the guidelines, the time required to reduce the concentration with 90% for the ACR value of 15 must be 9 minutes. For the model with a local exhaust device the values were less than 1 minute both for the door and HCW operational zones. For the model without a local exhaust device the values were about 4 minutes

and 1 minute for the door and HCW operational zones respectively. This fact emphasizes the importance of local exhaust device.

It was observed, that it is difficult to achieve 12 ACR in all regions of the room, as the guidelines require. That means that the room is not perfectly mixed according to the guidelines criteria. However, the results of the efficiency of infection removing show that the ventilation system operates pretty well: the infection is removed fast and the risk zones are good enough protected.

The position of supply terminal unit near the door region is meant to be like an air-lock, which prevents the infection cloud to penetrate into the door region – the most critical zone of the room.

It may be concluded that the perfect mixing is not the best criterion to consider in the design. Contaminant removing efficiency, which can be expressed, for example, in time of removing infection from critical zones, perhaps, could be a more adequate one.

Generally, the guidelines don't provide a particular ventilation strategy to achieve required values of certain parameters. Moreover, there should be not the only one strategy, because of the diversity of risk types. The ventilation control system could be configured in way to respond to different types of risk. There should be several regimes of operation, such as stand-by, preparation for opening the door, health care worker operation, emergency regime, etc. And for each of the regimes the particular priorities should be set. For example, before opening the door, the primary parameter for control is concentration in the door region; during health care worker operation - the primary parameter for control is concentration in the health care worker area; stand-by – patient comfort and energy saving. And for the purpose of these strategies developing, CFD can be used very effectively.

6.10.**Conclusion**

This paper describes the causes and measures of control of a serious problem – hospital acquired infections. The main engineering and administrative measures of infection control were discussed and the possibilities of CFD modeling in solving the problem of HAI were presented.

It was demonstrated that the design of ventilation systems in AII rooms can be optimized by the use of simulations based on the computational fluid dynamics. CFD allows predicting of all air parameters throughout the room for a variety of design alternatives. Such variables as room geometry, location of the door, patient bed, furniture, and terminal units, initial velocities, volume flow rates, supply air temperature, use of a local exhaust device and anteroom, etc., can be assesed and on the base of certain criteria, the most optimal design alternatives can be found.

In this paper only one factor was assessed – the expediency of use of local exhaust in AII rooms. And the results are very significant –the concentration of infection in the health care workers operational zone can be decreased down to about 85%, if a local exhaust device is used. However, even this figure can be optimized.

Purposeful investigations should be performed by design teams in cooperation with health care specialists and the most progressive and efficient tools should be used in order to enhance the life safety, comfort and reduce the energy costs. Only in this way the HAI problem can be solved.

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