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Compact Breathing Simulation System, Developed as Additional Functionality for Thermal Manikins

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Abstract: *The presented work reveals the development of a compact pneumatic system, which simulates the breathing process in humans. The proposed system could be used for analysis and assessment of indoor environment parameters. In particular, this system is in addition to the thermal manikins' functionality. Thermal manikins represent modern, highly complex tools for evaluation of the occupants' thermal comfort, as well as for analyses of the indoor air quality perception in the enclosed environment. The small overall dimensions of the suggested pneumatic system allow it to be implemented inside a thermal manikin body, which is one of the main system advantages. The presented work is part of the activities under a "Perspective leaders" project, supported by "RDS" at TU-Sofia, with Contract № 151ПР0002-02, entitled: "Schematic solution for development of pneumatic system, for simulating the breathing cycle of human occupants in indoor environment".*

Key words: Indoor Environment, Indoor Air Quality, Thermal Manikins, Experimental Studies, Breathing Cycle

1. Introduction

The thermal manikins represent accurate models of the human body, and are designed for analysis and assessment of the indoor environment parameters. Also, they are used to study the free convection flow around the human body, in different conditions, without unnecessary exposure risk to the human occupants themselves [1, 2, 3]. In addition, thermal manikins are quite expensive measurement equipment, capable of simulating various processes related to human physiology [3, 4]. They can be equipped with supplementary devices that mimic human activities such as breathing, sweating, sneezing, coughing and others. But the experience with the recently developed breathing thermal manikins show that breathing functionality is quite an expensive and inflexible system and there is a need for further research and optimization in this area.

The "World Health Organization" reveals that, through the past years, in the modern society in the developed countries, people spend more than 90% of their lifetime indoors. In numerous scientific studies worldwide, it has been proven that all indoor environment parameters have significant influence over the occupants' health, comfort, productivity and performance [3, 5, 6]. That is why all the experimental studies in this area, conducted in laboratory or in filed conditions, have an extensive impact in improving the quality of life of people and the degree of their productivity and performance. And nowadays, the thermal manikins have very important place in these research studies [3, 6]. Considered as a distinctive complex research tools, the development of their functionality has particular importance for the entire field of environmental engineering science.

One of the first thermal manikins were developed by the US Army in the 1940s, and had a single thermal zone without any additional functions. But today's manikins are often made of over 30 individually controlled thermal zones simulating the physiology of the individual human body parts, like arms, hands, fingers, feet, etc. [3]. In most of them, each zone contains a heating element and temperature sensors inside the "skin" of the manikin. This allows the control software to precisely heat the manikin body parts and to reach the normal temperature of the human body, depending on the simulated activity [7, 8].

Figure 1. Breathing thermal manikin, owned by ICIEE at Denmark Technical University (Picture taken with permission)

Unfortunately, all the additional functionalities, such as simulating breathing, sweating, sneezing and coughing, are complex systems external to the body of the manikins. Usually, the linking of the "nose" and the "mouth" of the manikins with these systems is implemented by multiple rubber hoses and extra wiring. This, and the very fact that the “breathing” system is outside the body of the manikin, significantly complicates the operation with these measurement devices [6, 9]. On Fig. 1 it is shown the breathing thermal manikin, owned by the International Center of Indoor Environment and Energy (ICIEE) at Denmark Technical University (DTU). On the right side of the picture, it is shown the breathing system, also called “artificial lungs”. Obviously, the system is quite large and heavy, and causes significant effort within the operation work.

The mentioned facts above suggest that, there exist a need for development of a breathing simulation system, compact enough for implementation inside the body of a standard thermal manikin. This need determines the global objective of the presented work.

2. Objective and tasks of the presented study

The project global objective is to develop schematic solution for compact pneumatic system, which simulates the breathing cycle of human occupants in indoor environment. This system should be suitable for implementation as additional functionality in standard thermal manikins.

In the presented paper, the achievement of the following tasks is discussed:

- Review of research literature, in order to point out and analyze the parameters, connected with the respiratory cycle in humans, from a physiological point of view.
- Review of research information, about general design of thermal manikins, including geometrical dimensions and functionalities, in order to establish the system input parameters.
- Development of schematic solution for compact pneumatic system, simulating with high precision the respiratory cycle in humans.

3. Respiratory system and breathing cycle in humans

The main function of the human respiratory (breathing) system is to get oxygen into the human body and to take out waste gases [10]. The function itself is called "respiration" (breathing), and it is vital function of all living organisms. Respiration occurs at two different levels. The first one is at the level of the cell. There, in the mitochondria of Eukaryotic cells, aerobic respiration needs O2 to break down glucose. In this way CO2 and water are released, and also large amounts of adenosine three phosphate (ATP) is produced. This process is known as "cellular respiration". The other level is in the level of the organism. The living organism must get O2 into its cells and get CO2 out. This process is known as "external respiration", because the exchange of gases takes place with the external environment [10].

The human respiratory system is a group of organs working together to ensure the exchange of O2 and CO2 with the external environment. The system includes the nose, nasal cavity, pharynx, larynx, trachea, bronchi, bronchioles, and alveoli. The last two organs together are forming the lungs. The respiratory system is divided into upper and lower respiratory tracts. The upper respiratory tract comprises all structures before the lungs, and the lower respiratory tract consists of the lungs themselves and the structures within them.

During the normal breathing process, the air enters the human body through the nose or through the mouth. The air entering the nose passes into the nasal cavity, which is richly supplied with arteries, veins, and capillaries. After that, the air goes into the pharynx. The pharynx is the back of the mouth and serves as a passageway for both air and food or drinks. When food or drinks are swallowed, a flap of cartilage, called the epiglottis, presses down and covers the opening to the air passage. From the pharynx, the air moves through the larynx and into the trachea which leads directly into the lungs.

All these passageways provide the connection between the outside air and the human lungs. That is why, these passageways should filter out dust particles, smoke, bacteria, and a huge variety of other contaminants found in the air. They also provide heating and humidifying of the inhaled air.

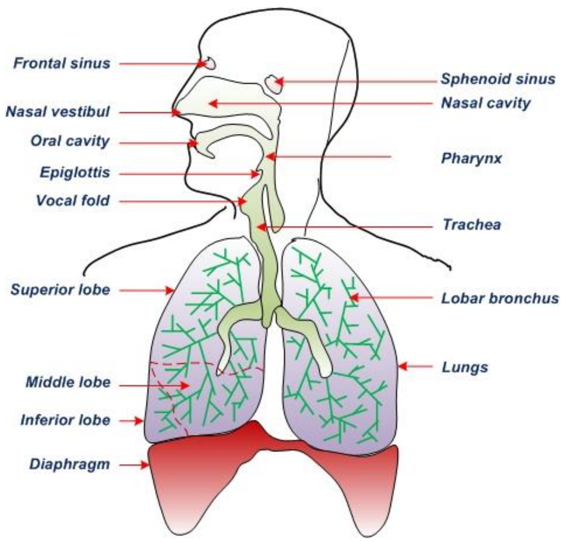

Figure 2. Scheme of the human respiratory system

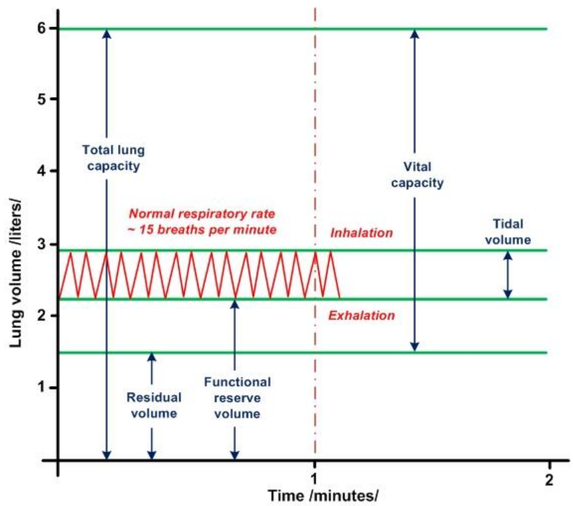

Figure 3. Lungs volume change, with respect to time

The lungs are basically the organs, which provide the gas exchange between the atmospheric air and the blood. The right lung consists of three lobes, and is slightly larger than the left lung. The left lung has two lobes, but the extra space in the human chest is taken up by the heart. The lungs are situated inside the thoracic cavity, surrounded by the rib-cage and the diaphragm. There are also two pleural membranes, which are lining the entire cavity and encase the lungs. These components of the human respiratory system are shown schematically on Fig. 2.

Breathing is considered to be the movement of air into and out of the lungs. Healthy adult human beings normally breathe 10 to 15 times per minute, depending on the activity level. Children breathe between 18 and 20 times per minute. During hard exercise, a professional athlete could breathe over 50 times per minute.

Each breathing cycle involves two stages – “inhalation” and “exhalation”. Inhalation (also called inspiration) occurs when the lungs expand and the air is pulled into them. Exhalation (also called expiration) occurs when the lungs reduce in volume and air leaves the lungs. Actually the lungs are not directly connected to any muscle, so they cannot expand or contract by themselves. Inhalation and exhalation are produced by the movements of two sets of muscles – the diaphragm and the muscles between the ribs, known as the intercostal muscles.

The diaphragm lies along the bottom of the ribcage and separates the thorax from the stomach. Before inhalation the diaphragm is curved upwards into the chest. During inhalation, the diaphragm contracts and moves down, causing the volume of the thorax to increase. The pressure inside the thorax therefore decreases, which leads to sucking air in. When the diaphragm relaxes, it returns to its curved position, assisted by contraction of the muscles of the stomach wall. This causes the volume of the thorax to decrease, and the pressure to rise, which forces the air back out of the lungs.

The intercostal muscles work in almost the same way. The external intercostal muscles contract which leads to swinging the ribs upwards and outwards. This movement increases the volume of the thorax, and causes the human beings to inhale.

Exhaling, or breathing out is easier, because the gravity pulls the ribs down and also the natural elasticity of the lungs helps them to collapse and to take the air out. Humans generally breathe with the diaphragm and external intercostal muscles only. Only during exercising, there could be used other muscles to force the air out, like the internal intercostal muscles, or the muscles of the stomach wall.

Human breathing is based on the atmospheric pressure so that, the lungs can only work if the space around them is completely sealed. This fact is very important, because if there is a hole in the thoracic cavity, the lung collapses and the breathing cycle stops. This may happen for example, due to a broken rib. That is why each lung is separately sealed, in order to reduce the risk from such injury.

Breathing function is very important for human beings. That is why the human body will not let the people to have complete control of it. Breathing cycle is controlled by the “medulla oblongata”, situated in the lower part of the brain. Human beings can only temporarily suppress this breathing reflex.

Simplified scheme of the human breathing cycle mechanism is shown on Fig. 3. The figure also shows the possible lung volumes with respect to the time. The lungs of an average person have a “total lung capacity” of about 6 liters. But, only about 0.6 liters is exchanged during normal breathing. This volume is called the “tidal volume”. During exercise, deep breathing forces out much more of the total lung capacity and up to 4.5 liters of air can be inhaled or exhaled. This is called “vital capacity”. The vital capacity is always from 1 to 1.5 liters less than the total capacity because of the air trapped in the trachea and bronchi. This air is known as the “residual volume”.

4. Geometrical limitations and design parameters of the proposed system

The thermal manikins intend to represent human beings in full-scale experiments, as accurate as possible. They could be used as flow obstacle, a heat source, a contaminant (pollution) source, or as a heat loss, or contaminant exposure measurement tool. Therefore, the external geometry, the emissivity, the total heat output, the temperature distribution and the respiration flow should be made as realistic as possible.

Most of the commercially known manikins consist of a hollow shell (body) with thin walls made of different materials, like aluminum, fiberglass, resins or even carbon fibers. On the outer side of the shell, wiring is implemented, for heating the different segments and for the measurement purposes. The wiring position is usually less than 0.5 mm below the surface, in the manikin skin, which gives a very fast response on the changes in the thermal environment.

Regarding the thermal manikins' outlook, they could be composed entirely of simple geometrical shapes. This is relatively easy and inexpensive to produce solution. However, for more accuracy and precision, some of the thermal manikins have components with complex shapes, which reproduce exactly the human body elements. Nevertheless of which type it is, the surface area of the manikin is usually between 1.5 and 2 m^2, like the normal adult human being.

Female model thermal manikins are mostly used for thermal comfort and clothing insulation measurements, and there are several reasons for that. The first one is that the ladies are more sensitive to the thermal environment changes. Additionally, there is more variation in female than in male clothing. Another reason is that the female model is smaller and lighter and therefore it is easier to operate with. Also it is very important for the measuring accuracy that the total heated surface is independent of the position of the manikin, seated or standing respectively. Madsen at al. [11] suggest that this can most easily be obtained with female model.

The anthropometric measurements of real humans are used for external geometrical dimensions of all high precision thermal manikins. These measurements are taken and standardized for the different nations all over the world, and are usually used for design of clothing [9, 11]. For instance, the two manikins, of Denmark Technical University (presented on Fig. 1) and the simple one, owned by the Aalborg University in Denmark (described in Bjorn at al. [9]), are based on the average Scandinavian woman – size 38, height 168 cm.

That is why the overall geometrical dimensions of the presented pneumatic system are compact enough, to fit inside the body of a female thermal manikin model, based on the average Bulgarian woman size. According to the standards for clothing design [12], the outer size of typical Bulgarian woman is 44 (Bulgarian system): 164 cm height, chest circumference 88 cm, waist circumference of 69.1 cm, hip circumference of 96 cm. The distance from the seventh "cervical vertebra" to the waist is approximately 39.7 cm rear length and approximately 51.5 cm front length. All these measures are forming the external size of the hollow manikin body. It should be noted, that these dimensions are external, and the thickness of the body walls could vary significantly, depending on the different materials used.

Bearing in mind the specifics of the described above human breathing cycle mechanism, it will not be possible to simulate with pneumatic hardware the "total lung capacity". It is not possible to fit inside these dimensions a cylinder with 6 liters capacity as well as electric motor, wiring, hoses, controllers and so on. That shows the first limitation of the proposed system, namely the simulated maximum lung capacity is restricted to ½ of the maximum real capacity and is 3 liters. This capacity is suitable for applications where thermal manikins simulate light sedentary activities (office work) and also "sleeping". These activities by definition do not suggest a high degree of stress, accompanied by deep breathing. These are the most widely simulated cases in the indoor environment experimental studies.

All system functionality is controllable, in order to simulate human beings at different ages and within different activity levels. It means that the tidal volume and the vital capacity are adjustable from 0 to maximum 3 liters. The frequency of the breathing cycle is adjustable from 1 to 60 breaths per minute. The directions and the sequence of inhalation and exhalation are controllable as well, and are schematically shown in Fig. 4.

The suggested pneumatic system is able to simulate sneezing and coughing. This means that the air inhaled inside the cylinder is able go out very quickly. This function is programmable, in order to achieve different rates of sneezing and coughing.

One of the most important properties of the suggested pneumatic system is the "Sampling" function. This means that, at certain time, the inhaled volume of air could be redirected towards a gas analyzer system. The gas analyzers may differ in sizes and functionality, that's why they will be external to the manikins. The “Sampling” function is also fully programmable.

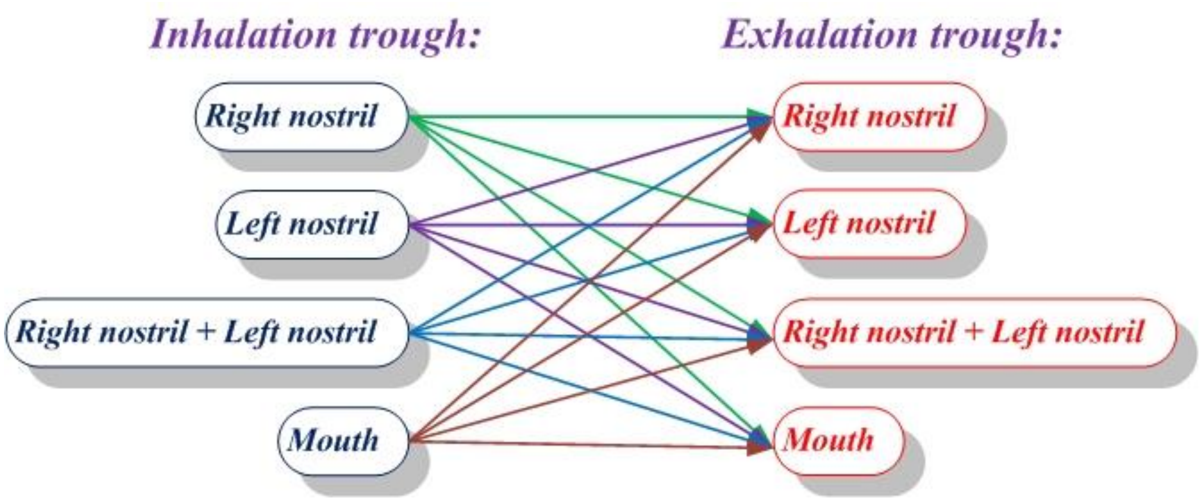

Figure 4. Direction and sequence of inhalation and exhalation

In order to use the thermal manikin as a pollution source, the presented system is capable of dosing a CO2 or any other tracer gas, such as Freon for example. This functionality is used in simulation of "cross-contamination" or in measurements of "ventilation effectiveness" and “exposure effectiveness”. The dosing takes place during exhalation, in order to keep the inhaled air clean. The CO2 or tracer gas bottles could be external to the manikin, or small bottles could be implemented in the manikins’ legs.

5. Scheme and description of the functionality of the developed pneumatic system

The scheme of the developed compact pneumatic system, simulating the human breathing process, is presented on Fig. 5. All the used pneumatic elements are commercially available, except the main cylinder and piston mechanism.

The servo motor “SM” is used to drive the piston of the excessive volume compressor “ECC1”. This is the main system compressor and it is selected with excessive volume, in order to accommodate the heater “H1”, which is used to heat up the “exhaled” air, as in the real exhaled air by the humans. The proportional valves “PV1”, “PV2” and “PV3”, which are controlled by the solenoids “S1”, “S2” and “S3”, are used to direct the inhalation and exhalation air through the nostrils or through the mouth. The discrete valve “DV1”, controlled by the solenoid “S4”, redirects the “inhaled” air towards external gas analyzer.

The two small compressors “CS1” and “CS2”, which are driven by the step motor “StM”, accomplish the dosing of CO2 or other tracer gases through the system. The system allows the use of internal CO2 storage bottle “CO2A1”, controlled by the accumulator block “AB1” and the pressure sensor “PS2”. It also allows the use of external gas storage source, accomplished by the valve “V1”, controlled by the solenoid “S5”. The main compressor is equipped with pressure and temperature sensors, “PS1” and “TS1” respectively, which are used to ensure the correct operating conditions.

The servo motor has a maximum shaft rotation angle of 160 degrees. This defines the end positions of the maximum stroke of the main compressor’s piston. The main excessive volume compressor has a maximum volume of 3.5 liters and maximum working volume of 3 liters. The servo motor allows the main volume to be regulated, as well as the excess volume, but the excess volume cannot be less than 0.5 liters. The reason is that, a heater is situated in this volume. This heater is used to heat the “exhaled” air, and to ensure temperature of about 37 oC at the nostrils or mouth region. Also, the thermal probe of the temperature sensor and the pressure sensor are situated in this volume. The temperature sensor registers the “exhaled” air temperature and controls the heater.

In order to simulate realistic inhalation and exhalation, three proportional valves are used. Two of them simulate the nostrils, and one is for the manikin’s mouth. These proportional valves allow very precise control of the airflow through the nostrils. For example, the system could be set in that way, that 30% of the airflow to pass in both direction through the one nostril and 70% through the other. This is quite typical situation in the normal human breathing process. Also, after inhalation, no matter from where, the three proportional valves could be closed and at the beginning of the exhalation the discrete valve goes open. In that way, all the inhaled air is redirected towards external gas analyzer system. This function allows the thermal manikins to be successfully used in wide range of indoor air quality experimental studies.

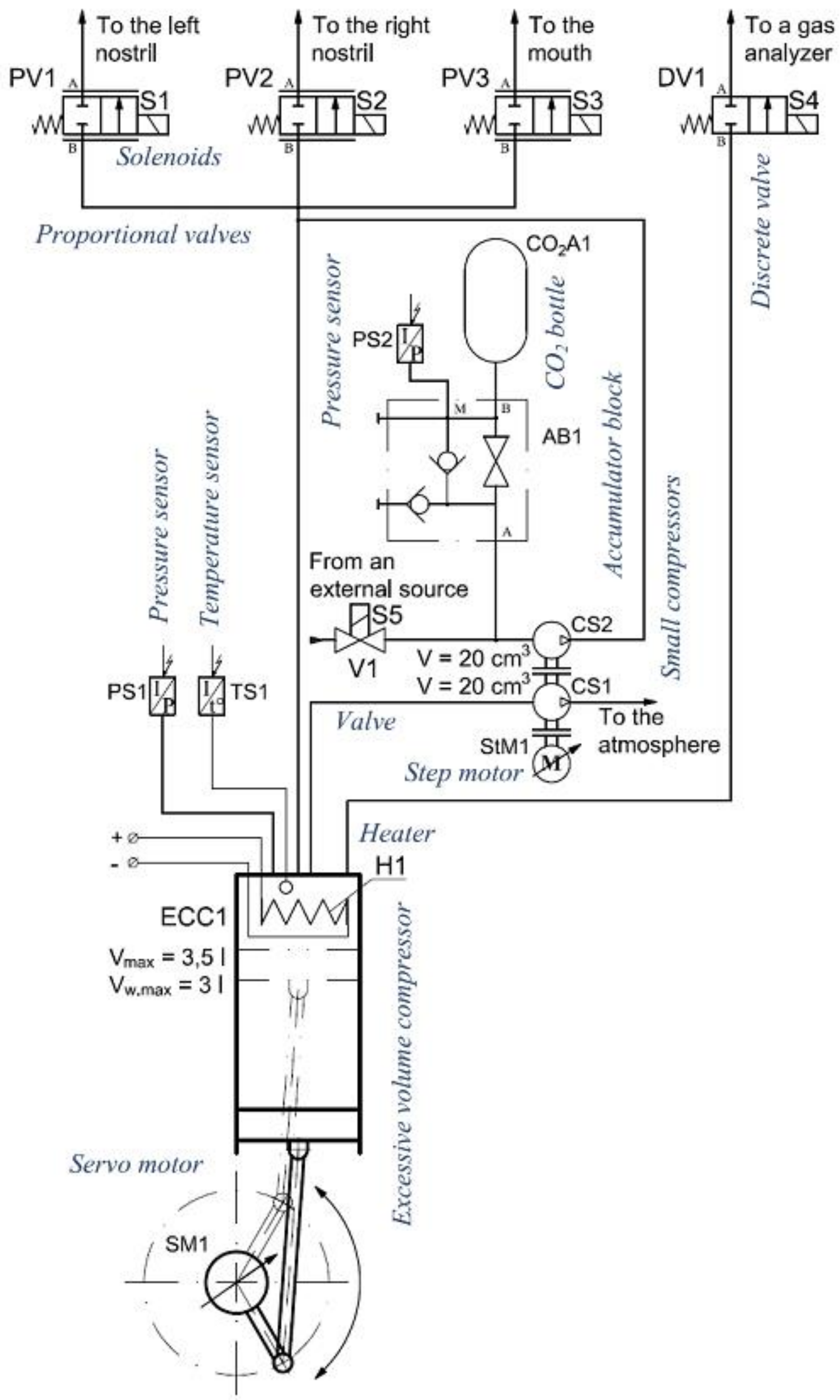

Figure 5. Scheme of the developed compact pneumatic system

The CO_2 or other tracer gas dosing system is controlled by a step motor, connected to a double volume compressor. Each of the two volumes are 20 cm3 in order to ensure removal of maximum 120 mm3 air, and to replace it with the same amount of CO_2 or tracer gas. One of the compressors sucks air from the main cylinder and throws it in the atmosphere. At the same time, the other sucks CO_2 or tracer gas and sends it towards the nostrils or the mouth. The CO_2 or other tracer gas could come from external or internal storage bottle, and the system allows the simultaneous use of both. This means that, two different tracer gases could be used during the experiments, if it is needed. Sometimes, the manikin design allows small pressurized bottle to be installed somewhere in the body, for example in the manikin's leg. The entrance for the external source is controlled by discrete electronically regulated valve. However, each external source should have own pressure sensors installed, like the one of the accumulator block AB1.

Considering that, all used compressors are volume compressors and are controlled by servo or step motors, additional discrete valves are not required in order to regulate the flow direction. Also, additional pressure safety system is not required as well, because the main compressor cannot make pressure above 1.8 atm. This is due to the fact that, all air entrances (like nostrils or mouth) are also exits to the system, and because the sucked in air is after that retuned into the atmosphere. The step motor is small, with low power and cannot achieve high pressure levels. Also it will not break down, if it stops rotating due to some system failing.

The simulation of sneezing and coughing is preconditioned by the closing of all proportional and discrete valves. In that way, the pressure inside the main cylinder is increased to sufficient level, which will ensure the fast air release trough the nostrils and/or the mouth. The features of the entire system allow the sequence and the frequency of the sneezing and coughing to be completely controllable.

One of the most important reasons, why such minimum number of devices for the pneumatic system is used, is that the system should be implemented inside thermal manikin's body. The space inside is very much restricted, due to the thermal function installations, as well as from the joints of the manikin's body parts. Obviously, the main cylinder and the piston are the devices with the biggest geometrical sizes here. If their size is decreased it will reflect to the simulated total lung capacity. Nevertheless, the presented system will still work properly, even if only the tidal volume of 0.6 liters is simulated, as it is during normal breathing. That way, the system will have the most compact overall dimensions. This will only limit the application of the thermal manikin, concerning the simulated activity level of the occupants.

6. Conclusions

A compact pneumatic system, which simulates the breathing process in humans, is designed and presented schematically. This system serves as additional functionality to the thermal manikins, which are used for analysis and assessment of the indoor environment parameters.

The presented system is based on the mechanism of the real human breathing cycle. It allows controllable simulation of total lung capacity, tidal volume and vital capacity, all of which may be adjusted from 0 to maximum 3 liters. The directions and the sequence of inhalation and exhalation (through the nostrils and/or the mouth) are also controllable, and the breathing frequency can be adjusted from 1 to 60 breaths per minute.

Important features of the presented system are the “Sampling” mode, the sneezing and coughing simulation and the possibility of dosing CO2 or any other tracer gas. The overall dimensions of the proposed system are compact enough to fit inside the body of a female model thermal manikin, based on the average sizes of typical Bulgarian woman.

It is considered that, the described pneumatic system is innovative and will add significant value to the presented research area.

7. Acknowledgements

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