Input parameters for development of pneumatic system, for simulating the breathing cycle of human occupants in indoor environment

Martin Ivanov, Dimitar Staykov, Emanuil Georgiev

Abstract:

This paper presents the input parameters, required to develop a 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. These thermal manikins represent modern, highly complex tools used to evaluate the thermal comfort of occupants in enclosed environment, as well as for analyses of the indoor air quality perception.

The presented work is part of the activities under a "Perspective leaders" project, supported by "НИС" 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

Входни параметри за създаване на пневматична система, симулираща процесът на дишане при хората, обитатели на затворени помещения

Мартин Иванов, Димитър Стайков, Емануил Георгиев

Резюме:

Настоящата публикация представя входните параметри, необходими за създаване на пневматична система, симулираща процесът на дишане при хората. Предложената система намира приложение при анализът и оценката на параметрите на микроклимата в затворените помещения. В частност, тази система е допълнение към високотехнологичните топлинни манекени, които представляват модерни инструменти, използвани за оценка на топлинния комфорт и усещането за качество на въздуха при обитателите на затворени помещения.

Представената работа е част от дейностите по проект към НИС на ТУ-София, финансиран по направление „Перспективни ръководители", с Договор № 151ПР0002-02, на тема: „Схемно решение за създаване на пневматична система, симулираща процесът на дишане при хората, обитатели на затворени помещения".

Ключови думи: затворена климатична среда, качество на въздуха в затворените помещения, топлинни манекени, експериментални изследвания, дихателен цикъл

Introduction:

Through the past years, the "World Health Organization" reveals that, 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 [2, 6, 7]. 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 [6, 7]. Considered as a distinctive complex research tools, the development of their functionality has particular importance for the entire field of environmental engineering science.

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. Thermal manikins are actually quite expensive measurement equipment, capable of simulating various processes related to human physiology. They can be equipped with additional 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.

Historically, some 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. [6]. 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 [8,9].

On the other hand, 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 [3,7]. On Figure 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.

Figure 1. Breathing thermal manikin, owned by ICIEE at Denmark Technical University

All this shows 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 purpose of the presented work in the paper.

Project objective:

The global objective of the presented project 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 addition to the aim, the following tasks are defined:

1. Conducting a thorough review of the existing research literature, in order to point out and analyze the parameters, connected with the respiratory cycle in humans, from a physiological point of view.
2. Review of the existing research information, about the general design of the thermal manikins, including the overall geometrical dimensions and functionalities.
3. Development of schematic solution for pneumatic system, simulating with high precision the respiratory cycle in humans.
4. Optimization of the established schematic design, in order to implement the developed pneumatic system, as additional functionality inside thermal manikin body.
5. Development of precise 3D model of the proposed pneumatic system, as well as flexible and easily accessible database with the designing information.

The presented paper concerns mostly the results from tasks 1 and 2. The results from the rest of the implemented tasks will be presented elsewhere.

Human respiratory system:

Basically, the 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 O_2 to break down glucose. In this way CO_2 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 O_2 into its cells and get CO_2 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 O_2 and CO_2 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.

In 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.

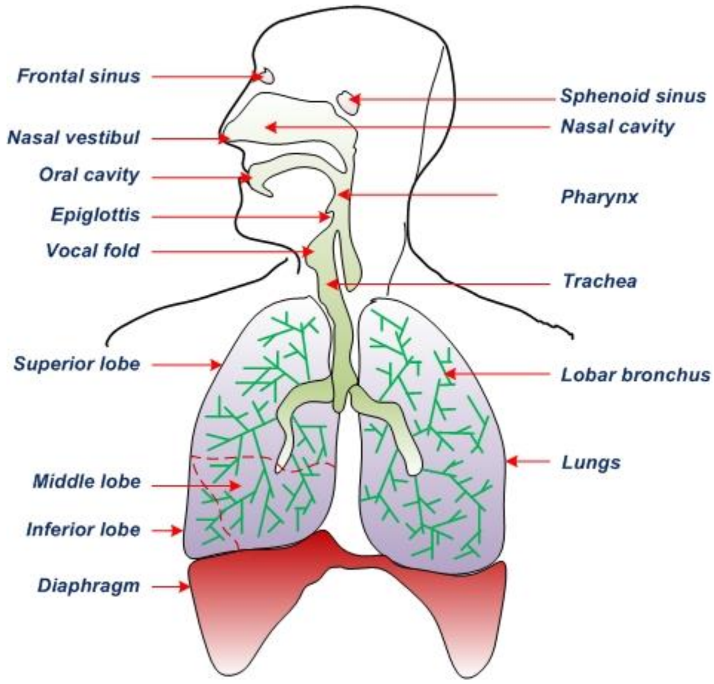

Figure 2. Basic diagram of the human respiratory system

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 lug 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**.**

All the mentioned components of the human respiratory system are shown schematically on Figure 2.

Human breathing cycle mechanism:

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 Figure 3. The figure also shows the possible lung volumes with respect to the time.

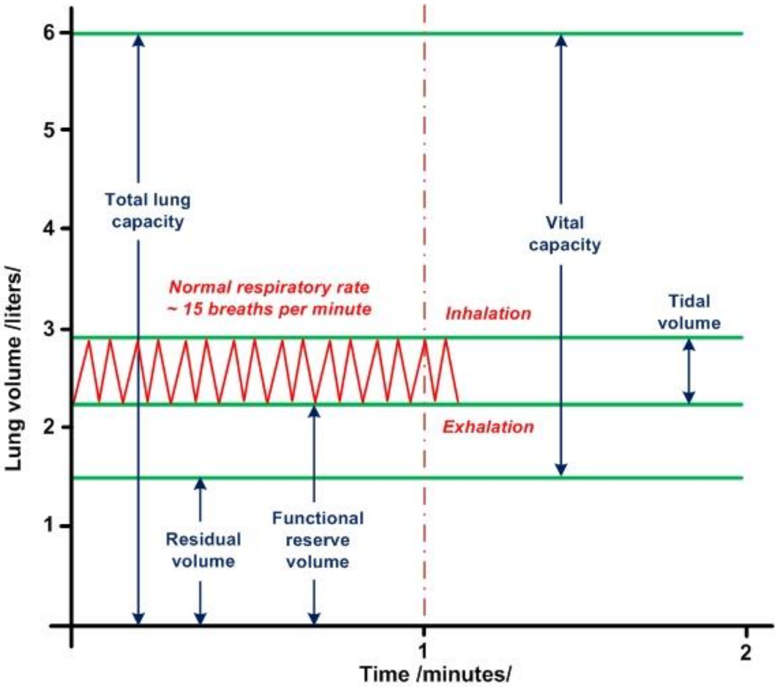

Figure 3. Schematic diagram of the lungs volume change with respect to time

The lungs of an average person have a ***total lung capacity*** of about 6 liters. 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***.

General geometrical dimensions of thermal manikin:

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.

Concerning 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.

There are several reasons why, a female model thermal manikins are mostly used for thermal comfort and clothing insulation measurements. 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. [5] suggest that this can most easily be obtained with female model.

The external geometrical dimensions of all high precision thermal manikins are based on the anthropometric measurements of real humans. These measurements are taken and standardized for the different nations all over the world, and are usually used for design of clothing [5, 3]. For instance, the two manikins, of Denmark Technical University (presented on Figure 1) and the simple one, owned by the Aalborg University in Denmark (described in Bjorn at al. [3]), are based on the average Scandinavian woman – size 38, height 168 cm.

Input parameters of the suggested pneumatic system:

As it was mentioned the main objective of the presented project is to develop schematic solution for compact pneumatic system, which simulates the breathing cycle of human occupants, suitable for implementation inside standard thermal manikins. Here, the basic input parameters for the system design will be described briefly.

The overall geometrical dimensions of the system should be 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 [1], 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 and are schematically presented on Figure 4. 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.

Considering 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 won't be possible to fit inside these dimensions a cylinder with 6 liters capacity as well as electric motor, wiring, hoses, controllers and so on. This will be the first limitation of the proposed system, namely the simulated maximum lung capacity will be restricted to ½ of the maximum real capacity and will be 3 liters. This capacity will be 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 should be 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 should be adjustable from 0 to maximum 3 liters. The frequency of the breathing cycle should be adjustable from 1 to 60 breaths per minute. The directions and the sequence of inhalation and exhalation should be controllable as well. These parameters are described in Table 1.

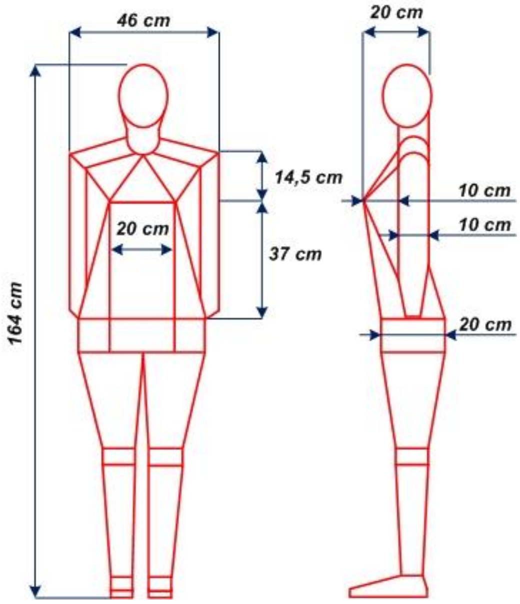

Figure 4. Overall approximate external dimensions of thermal manikin body, with the size of typical Bulgarian women

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

One of the most important properties of the suggested pneumatic system should be the "Sampling" function. This means that, at certain time, the inhaled volume of air should be redirect 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 should also be programmable.

Direction and sequence of inhalation and exhalation ***Table 1***

Inhalation trough	Exhalation trough
Right nostril	Right nostril
	Left nostril
	Right nostril + Left nostril
	Mouth
Left nostril	Right nostril
	Left nostril
	Right nostril + Left nostril
	Mouth
Right nostril + Left nostril	Right nostril
	Left nostril
	Right nostril + Left nostril
	Mouth
Mouth	Right nostril
	Left nostril
	Right nostril + Left nostril
	Mouth

Finally, in order to use the thermal manikin as a pollution source, the suggested system should be able of dosing a CO_2 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 should take place during exhalation, in order to keep the inhaled air clean. The CO_2 or tracer gas bottles could be external to the manikin, or small bottles could be implemented in the manikins’ legs.

Conclusion:

Input parameters, for the development of pneumatic system, which simulates the breathing process in humans, is presented and discussed. This system will be additional functionality to the thermal manikins, used for the analysis and assessment of the indoor environment.

The presented system “assignment” is based on the physiology and the mechanism of the human breathing cycle. The overall dimensions of the proposed system should be compact enough to fit inside the body of a female model thermal manikin, based on the average size of typical Bulgarian woman.

The suggested work is innovative and will add significant value to the presented research area. The developed scheme of the proposed pneumatic system will be published elsewhere.

References:

[1] БДС EN 13402-3:2013, “Size designation of clothes - Part 3: Body measurements and intervals”, 2013;

[2] ISO Standard 7730-2005, “Ergonomics of the thermal environment -- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria”, International Organization for Standardization, 2005;

[3] Bjørn E., „Simulation of human respiration with breathing thermal manikins“ Proc. of the 3rd inter. meet. on thermal manikin testing 3IMM, Sweden, 1999;

[4] Bohm M., “Factors affecting the equivalent temperature measured with thermal manikins”, Proceedings of the 3rd international meeting on thermal manikin testing 3IMM, Stockholm, Sweden, 12–13 October, 1999;

[5] Madsen T., “Development of a breathing thermal manikin”, Proceedings of the 3rd international meeting on thermal manikin testing 3IMM, Stockholm, Sweden, 12–13 October, 1999;

[6] Melikov A., "Breathing thermal manikins for indoor environment assessment: important characteristics and requirements". Europ. J. of Applied Physiology 92 (6): 710–713, 2004;

[7] Melikov A., Kaczmarczyk J., Cygan L., “Indoor air quality assessment by a “breathing” thermal manikin. In: Awbi H (ed) Air distribution in rooms: proc. of Roomvent 2000, vol I. Elsevier, London, 101–106, 2000;

[8] Nielsen P.V. “The importance of thermal manikins as a source and obstacle in full-scale experiments”, In: Proceedings of the 3rd inter. meet. on thermal manikin testing 3IMM, Sweden, 1999;

[9] Nilsson H., Holmer I., “Comfort climate evaluation with thermal manikin methods and computer simulation models”, Indoor Air 13:28–37, 2003;

[10] White I., “The respiratory system”, AS Biology, Module 1, Chapter 5 – “Breathing”, (www. biologymad . com, *last visit: July.2015*), October, 2005;

Acknowledgements:

The presented study is supported by “НИС” at TU-Sofia, as part of the activities under the "Perspective leaders" project, with Contract № 151ПР0002-02, entitled: "Schematic solution for development of pneumatic system, for simulating the breathing cycle of human occupants in indoor environment".

Senior Assist. Prof. Dr. Martin IVANOV, PhD, Department of Hydrodynamics and Hydraulic Machines, Technical University of Sofia, Bulgaria, e-mail: martin_ronita@yahoo.com

Dimitar STAYKOV, MSc, PhD Student, Department of Hydrodynamics and Hydraulic Machines, Technical University of Sofia, Bulgaria, e-mail: i.dimitar.staykov@gmail.com

Emanuil GEORGIEV, MSc, PhD Student, Department of Hydrodynamics and Hydraulic Machines, Technical University of Sofia, Bulgaria, e-mail: ev1l@abv.bg