Numerical study of identification of the main characteristics of air transport in the human nasal cavity

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Abstract— In this paper was considered the use of the numerical study of identification the main characteristics of air transport in the human nasal cavity. Investigation of air flow in the human nasal cavity is of considerable interest since breathing is done mainly through the nose. In this study conducted a two-dimensional numerical simulation of air transport in the cross-sections model of the nasal cavity to normal human nose based on the Navier-Stokes equations, the temperature transport equations and relative humidity equation. For the numerical solution of this system of equations is used projection method. The numerical solution of the equation system is divided into five stages. At the first step, it is assumed that the momentum transfer by convection and diffusion. The intermediate velocity field is solved by the 5-step Runge–Kutta method. At the second stage, the pressure field is solved by the found intermediate velocity field. The Poisson equation for the pressure field is solved by the Jacobi method. The third step assumes that the transfer is carried out only by the pressure gradient. The fourth and fifth steps of the temperature and relative humidity equations are also solved as momentum equations, with the 5-step Runge–Kutta method. This numerical algorithm fully parallelized using different geometric decompositions. The obtained data transfer numerical modelling air human nasal cavity was verified with known numerical results in the form of velocity, temperature and relative humidity profiles.

Keywords— Navier-Stokes equations, decomposition methods, alveolar state, heat transfer in the nasal cavity, projection method, finite volume method.

I. Introduction

THROUGH the nasal cavity there is a primary recognition of odours, through it we breathe in air, which passes into the alveolar state (it heats there to physiologically normal temperature and is completely saturated with water vapour). They serve as regulators of all air circulation, create a normal air temperature and are completely saturated with water vapour, cleaned and disinfected. Normally, the airflow passes through the nose at a speed of 6 litres per minute, this indicator can be increased to 10 litres per minute.

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However, the nasal cavity has, depending on the cause of occurrence, curvatures and can be divided as:

• Physiological
• Compensatory
• Traumatic

With the aforementioned character of curvature, they negatively affect primarily the difficulty of breathing. Nasal breathing is very important, a systemic part of our body's vital activity and any of its disturbances sooner or later cause negative consequences for the human body. Most often, the cardiovascular system suffers, bronchitis or regular colds develop. Also, negative consequences for health due to the nasal cavity can be attributed to such reasons:

• The difficulty with nasal breathing.
• Chronic Rhinitis.
• Allergic reactions.
• Headache.
• Dryness in the nose, discomfort and discomfort during nasal breathing.
• Nasal bleeding.
• Snoring at night
• Increased fatigue, reduced performance, reduced resistance to physical stress.
• Frequent infections with symptoms of ARI (a runny nose, coughing, sneezing), fever.
• Symptoms of chronic inflammation of the pharynx and larynx:
• Symptoms of inflammation in the middle ear:
• Violation of the shape of the nose.
• Deterioration of memory, thinking, the distraction of attention.

The main method of eliminating the curvature of the nasal cavity is a surgical operation - septoplasty. However, it should be noted that the success of a surgical operation at best does not exceed 80%, which leads to a repeated surgical operation. And also the surgical operation will depend on the experience and skill of the surgeon. Naturally, to increase the percentage of a surgical operation success, it will be necessary to accurately make nasal cavity corrections. Since before the surgical intervention due to X-ray images, it will be possible to evaluate the nature of the curvature and with the help of numerical modelling, it will be possible to correct and optimize the nasal cavity in advance. Knowing the preliminary accurate correction of the nasal sinus, the surgeon can increase the percentage of the surgical operation success that will accordingly reduce the percentage of the reoperation.

The nasal cavity balances the inhaled air with the internal state of the body with amazing efficiency. In the papers of Cole [2], Inglesstedt [3] and Webb [4], it was generally agreed that the inhaled air through the nasal cavity reaches up to the alveolar state (completely saturated with water vapour and at normal body temperature) by the time it reaches the pharynx. And it practically does not depend on a condition of ambient air which has arrived through nostrils. These results were also obtained in the paper of Farley and Patel [5] who collected data in natural conditions with air temperature readings along the upper respiratory tract, as well as Hannah and Scherer [6], reflecting measurements of local mass transfer coefficients on the gypsum model of the upper human respiratory tract. Nevertheless, McFadden [7] noted that the conclusions are valid for quiet breathing in some circumstances at high ventilation levels, conditioning of additional air should occur in the intrathoracic airways in order to completely determine the inhaled air in the alveolar state.

Numerous studies have been aimed at assessing the hydration and temperature regulation of the nasal cavity. However, mathematical models were based on axisymmetric tubes or occupied quasistationary flows [1]. As a rule, these studies confirmed the opinion that under normal conditions there is enough time for heating and humidifying the air in the nasal cavity. In addition, medications, as well as surgical procedures, are being used with increasing speed to restore the structure and functions of the nasal cavity [8]. For example, aromatic inhalations are used to improve airflow and to reduce congestion, as well as rhinoplasty procedures, are used to overcome trauma or aesthetic deformities. These artificial interventions cause local changes and can affect the efficiency of air transport phenomena. However, precise intranasal characteristics and distribution of transport phenomena are not yet known even for a normal (or healthy) state [19, 20, 21].

Experimental examination of the nasal cavity is practically impossible, due to the complex internal structure and dimensions, i. e. The introduction of any measuring device or probe causes additional disturbance of the flow. Therefore, mathematical modelling is one of the only approaches to studying the air flow in the nasal cavity.

II. Statement of the Physical Problem

Air flow through the structure of the nasal cavity is a very difficult path. The complex structure of the nasal cavity and complete three-dimensional analysis of the steam flow, heat transfer in the inner part of the nasal mucosa requires significant computational resources that prevent a systematic analysis of the relevant factors (Figure 1).

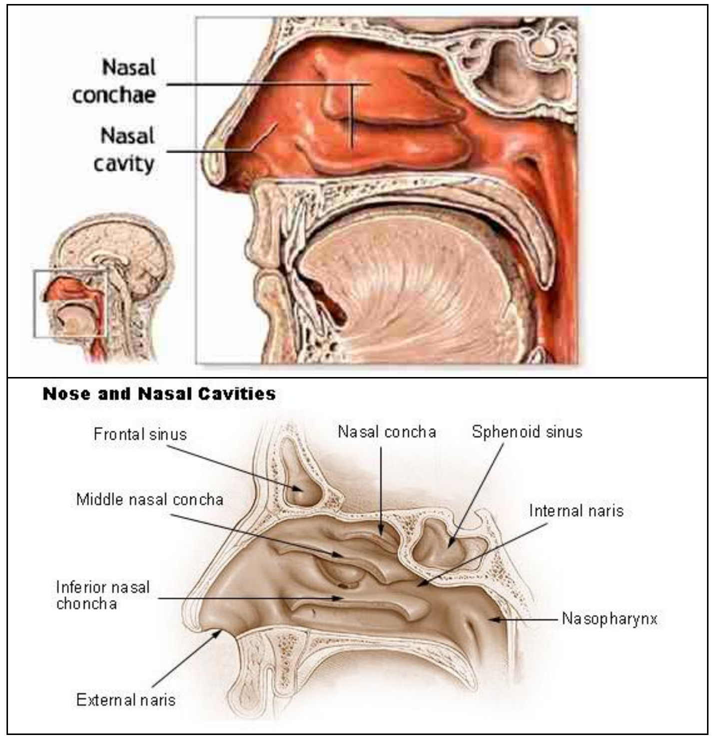

Figure 1 - Model of the nose with a longitudinal section.

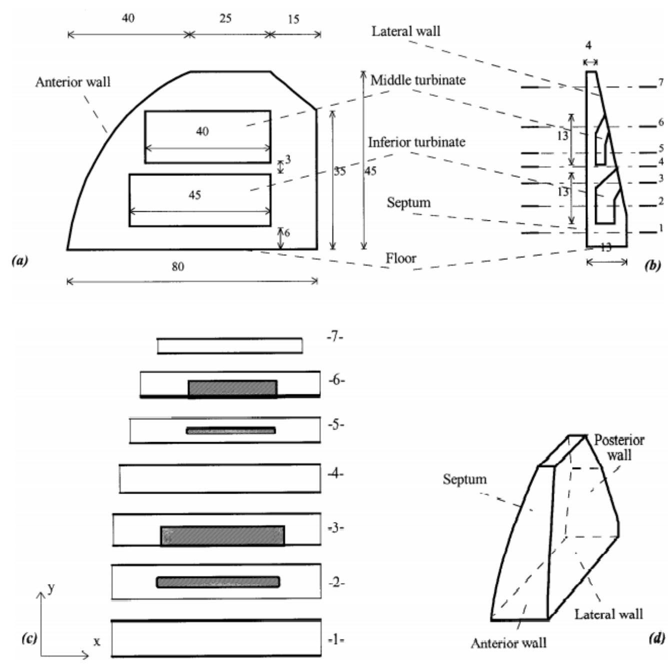

Figure 2 - Simplified nose model: a) longitudinal section, b) coronary section, c) cross sections at height h = 3, 13, 17, 20, 26, 33, 40 mm from the bottom point of the nasal cavity, d) perspective view.

Given the available computational resources, a complex study of transport mechanisms was carried out in two-dimensional form, through the cross sections of the nose.

In addition, the following assumptions are made for numerical modelling:

• The walls of the nasal cavity and nasal concha are assumed to be immovably hard.

• The air flow in the nasal cavity is considered as a laminar flow, and the air as an incompressible medium (since the Reynolds and Mach numbers are very small).

• The velocities on the cavity walls are taken as zero ($u=0$, $v=0$).

• The nasal cavity walls are considered fully saturated with water vapour and the temperature near the body due to the moist mucous layer reaches the vascular vessels of the nasal wall.

Thin features of the nose do not have exact dimensions because there are differences in the structure of the nasal cavity in healthy people, so it is almost impossible to determine the exact model of a "normal nose". Thus, a simplified the nose model is developed, where the main essential signs of the nasal cavity are revealed. The dimensions are taken from the averaged data of the human nasal cavity (Figure 2). The physical area of the problem is the second cross-section (Figure 2 (c) "-2-"), which is important for the study, because it is in this area that a significant proportion of the air flow takes place, and also has a complex structure, through which the basic functions of the nasal cavity are performed.

The mathematical model is constructed on the basis of the Navier-Stokes equations, including the continuity equation, the momentum equation, and also the energy (temperature) transport equation and relative humidity equations are used in addition [11, 12, 13].

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho c_p}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)$$

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right)$$

where u,v - velocity components, t - time, p - pressure, ν - kinematic viscosity, T - temperature, C - humidity, c_p - medium specific heat at constant pressure, k - thermal conductivity coefficient, ρ - density, D - molecular diffusion coefficient.

The instantaneous velocity at the inlet in each cross section is assumed to have a parabolic profile with a maximum velocity $(U_{in}^M)_{\max}$ that varies during the breathing cycle. In the work of Khirardin et al. [18] measurements were made using laser anemometry in the human nose model and it was found that the field flow basically has layered parabolic velocity profiles in any cross section. At rest, a normal adult breathes a volume about $V_T=0.5L$ (inhaling and exhaling) once a minute at an average flow rate of about 0.125 L/s to each nostril. Accordingly, the instantaneous velocity distribution at the input U_{in}^M in the direction is given in the following form (Figure 3):

$$u_{in}(t,x=0,y)=(U_{in}^M)_{\max}\left[2\sin^2\frac{\pi t}{2}-1\right]\times\frac{(12y-y^2)}{36}$$

The input boundary conditions for the temperature and relative humidity of the external air are given in the following form:

$$T_{in}(t,x=0,y)=25°C,$$
$$C_{in}(t,x=0,y)=0.0047\ kg\,H_2O/m^3$$

On the nasal cavity walls and nasal concha:

$$u_{wall}(t,x,y)=0,\qquad v_{wall}(t,x,y)=0,$$
$$T_{wall}(t,x,y)=37°C,\ C_{in}(t,x,y)=0.0438\ kg\,H_2O/m^3$$

The initial conditions are given in this form:

$$u_0(t=0)=0,\qquad T_0(t=0)=32°C.,$$
$$C_0(t=0)=0.0235\ kg\,H_2O/m^3.$$

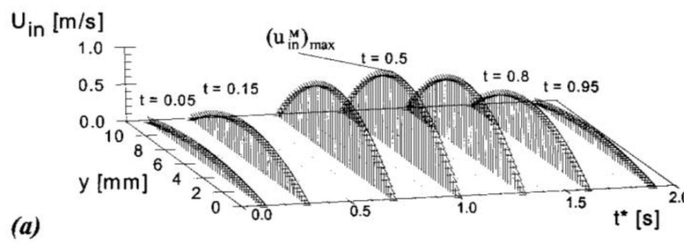

Figure 3 - Air velocity at the inlet in the cross section.

III. THE NUMERICAL ALGORITHM

For a numerical solution of this system of equations, the projection method is used [14, 17, 22-28]. Equations are discretized by the finite volume method [9, 10, 14]. At the first stage, it is assumed that the momentum transfer is carried out only through convection and diffusion, and an intermediate velocity field is calculated by the 5-step Runge-Kutta method [13, 15]. In the second stage, according to the found intermediate velocity field, there is a pressure field. The Poisson equation for the pressure field is solved by the Jacobi method. In the third stage, it is assumed that the transfer is carried out only due to the pressure gradient. In the fourth stage, the temperature transport equation is calculated by the 5-step Runge-Kutta method. In the fifth stage, the relative humidity equation is calculated, and also solved by the 5-step Runge-Kutta method [13, 15, 16].

I. $$\int_{\Omega} \frac{\vec{u}^{*} - \vec{u}^{n}}{\tau} d\Omega = -\oint_{\partial\Omega} (\vec{u}^{n} \vec{u}^{*} - \upsilon \nabla \vec{u}^{*}) n_i d\Gamma$$

II. $$\oint_{\partial\Omega} (\nabla p) d\Gamma = \int_{\Omega} \frac{\nabla \vec{u}^{*}}{\tau} d\Omega$$

III. $$\frac{\vec{u}^{n+1} - \vec{u}^{*}}{\tau} = -\nabla p.$$

IV. $$\int_{\Omega} \frac{T^{n+1} - T^{n}}{\tau} d\Omega = \oint_{\partial\Omega} \left(\frac{k}{\rho c_p} \nabla T - u^{n} T\right) n_i d\Gamma$$

V. $$\int_{\Omega} \frac{C^{n+1} - C^{n}}{\tau} d\Omega = \oint_{\partial\Omega} (D \nabla C - u^{n} C) n_i d\Gamma$$

IV. RESULTS OF NUMERICAL SIMULATION

As a numerical modeling result of the human nasal cavity aerodynamics, the following data were obtained. Also, to verify this numerical algorithm, we used the calculation data from the paper [1], which describes the profiles of the velocity longitudinal component and temperature in three cross sections: at a distance x_1= 17mm, x_2= 49mm and x_3= 80mm from the entrance (Figure 4). For the numerical simulation, the corresponding parameters for air constants were used: $\rho = 1.12\, kg/m^3$, $\mu = 1.9 \times 10^{-5}\, kg/ms$, $c_p = 1005.5\, J/kgK$, $k = 0.0268\ W/mK$, $D = 2.6 \times 10^{-5} m^2/s$.

Figure 5 shows the comparison of profiles for x_1, x_2 and x_3 cross sections for longitudinal velocity component of the calculation results and data from the paper Naftali et al. [1]. Figure 6 shows a comparison of temperature profiles for cross sections x_1, x_2 and x_3 with data from the paper [1]. Figure 7 shows the relative humidity profiles for cross sections x_1, x_2 and x_3. In all the figures, numerical results were shown in the dimensionless form.

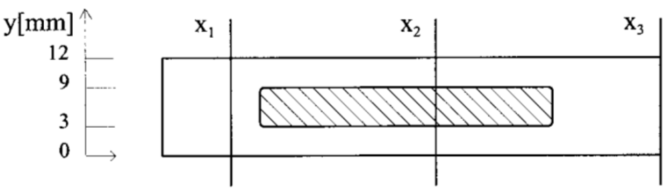

Figure 4 - Evaluation in three cross section location for temperature, velocity and relative humidity.

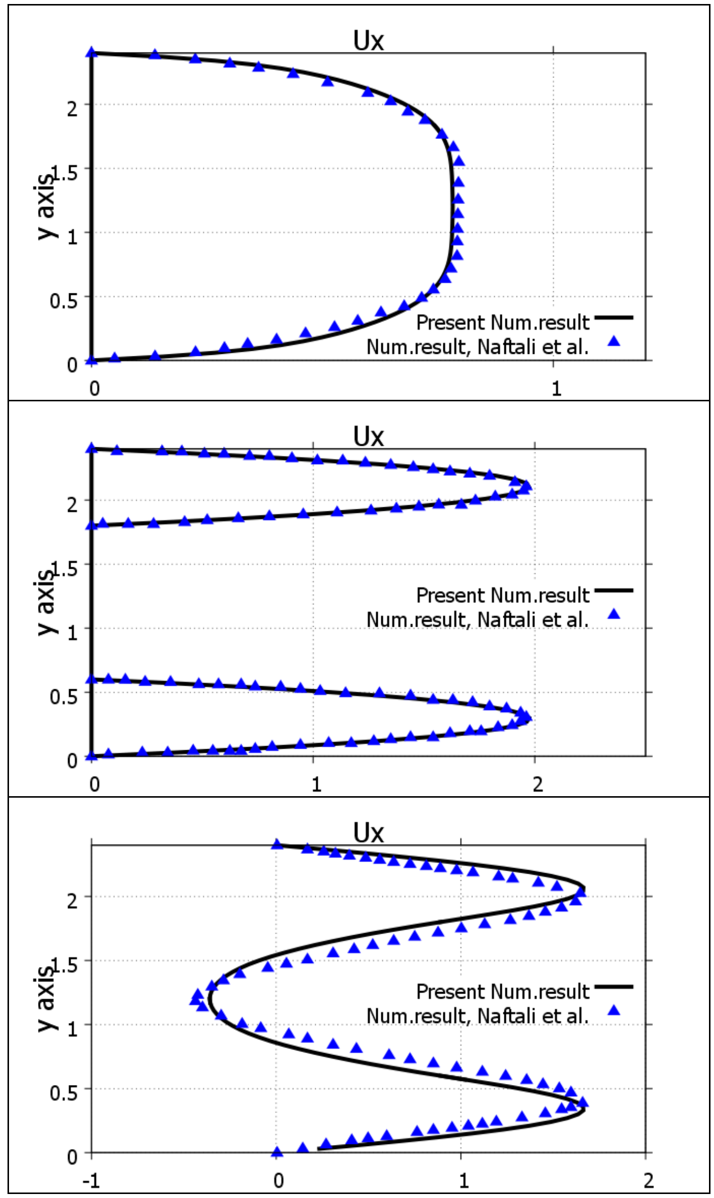

Figure 5 - Comparison of the velocity component profile for the cross sections x_1=17 mm, x_1=49 mm and x_1=80 mm with the calculations results from the paper [1].

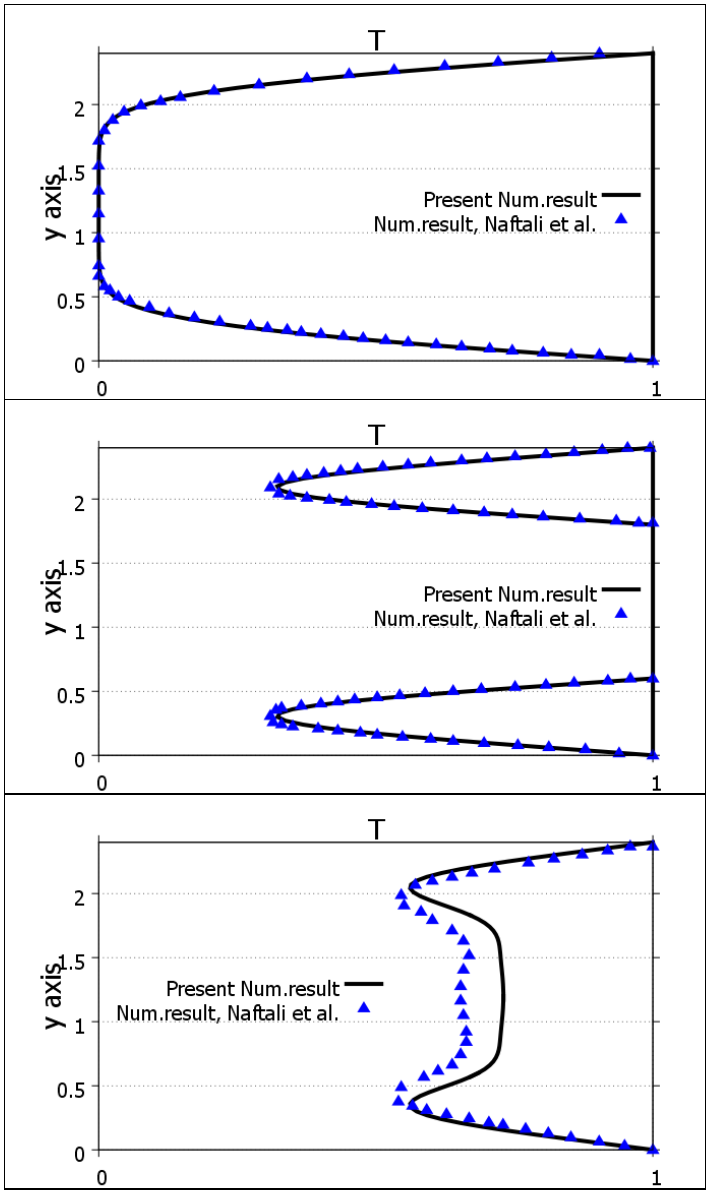

Figure 6 - Comparison of temperature profiles for cross sections x_1=17 mm, x_1=49 mm and x_1=80 mm with the calculations results from the paper [1].

From the figures can be seen that nasal cavity air is heated downstream, and relative humidity also increases when passing through narrow areas. And also from figure 6 you can see that behind the nasal septum the temperature increases and to the nasopharynx the air temperature is heated to the alveolar state. And at low ambient temperatures, relative humidity plays a very important role. Figure 8 shows the longitudinal velocity component in the cross section for different times ($t = 0.25\ s$, $t = 0.5\ s$, $t = 1\ s$). Figure 9 shows the transverse velocity component in the cross section for different times ($t = 0.25\ s$, $t = 0.5\ s$, $t = 1\ s$). From the figures can be seen those vortex currents appearing from the nasal conchas, which play an important role in the process of air heating. Figure 10 - 11 show the temperature components, and the relative humidity in the calculated area for different times ($t = 0.25\ s$, $t = 0.5\ s$, $t = 1\ s$).

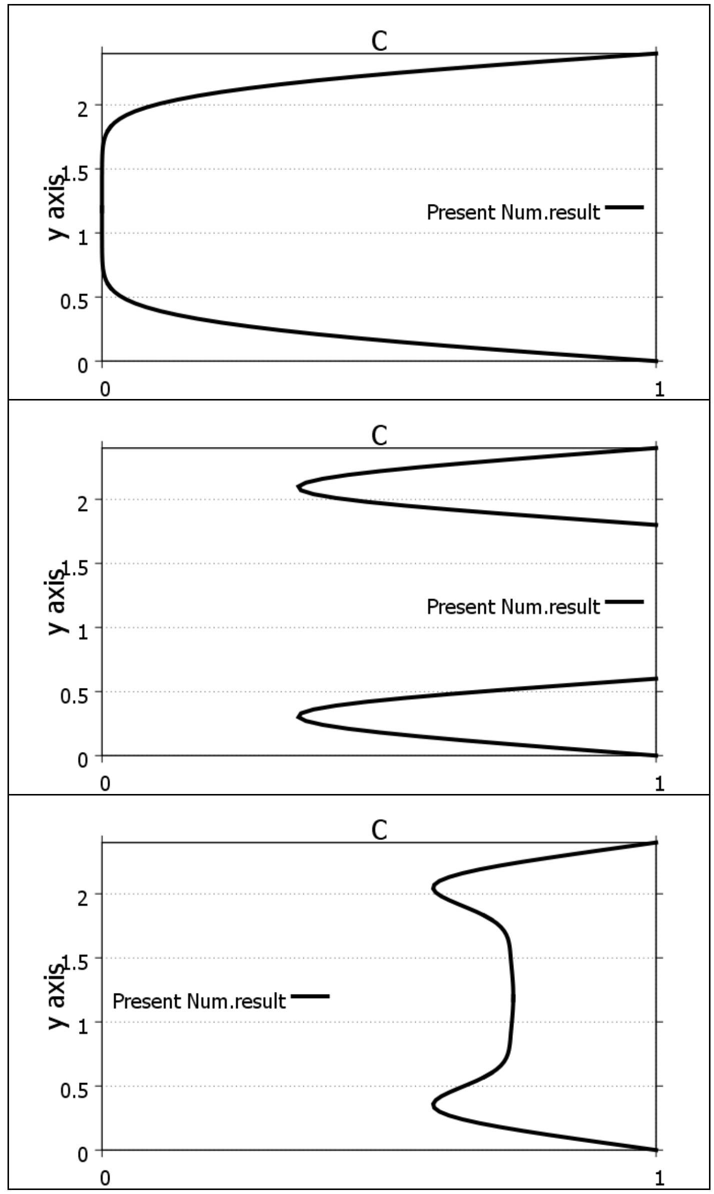

Figure 7 - Relative humidity profiles for sections x_1=17 mm, x_1=49 mm and x_1=80 mm.

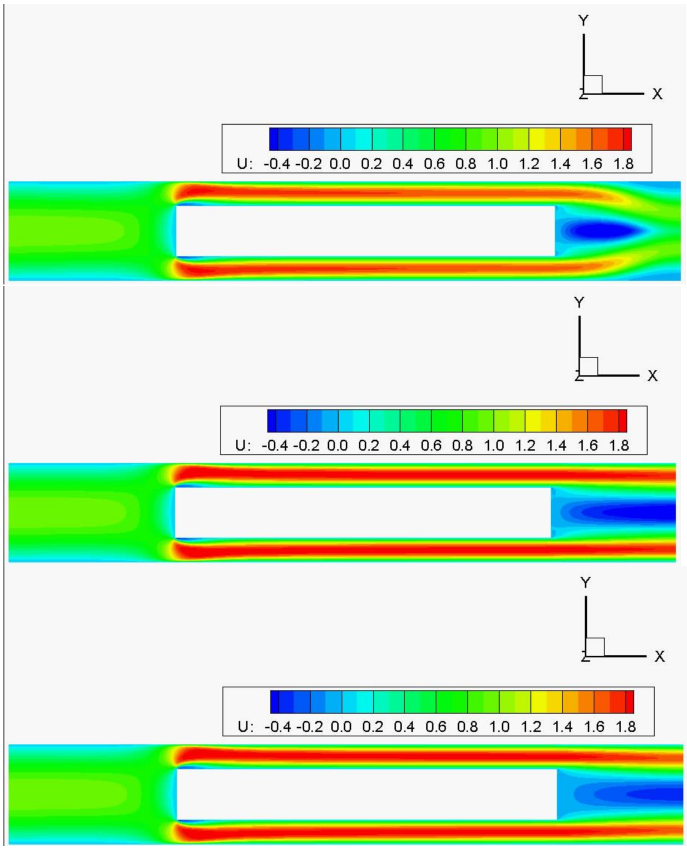

Figure 8 – Longitudinal velocity components in the cross section for different time.

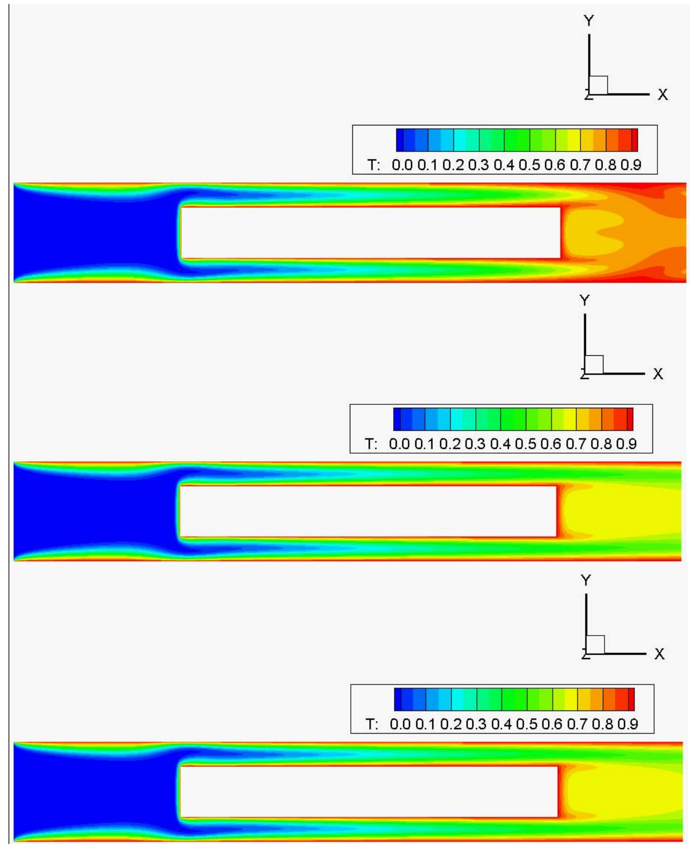

Figure 10 –Temperature component in the cross section for different time.

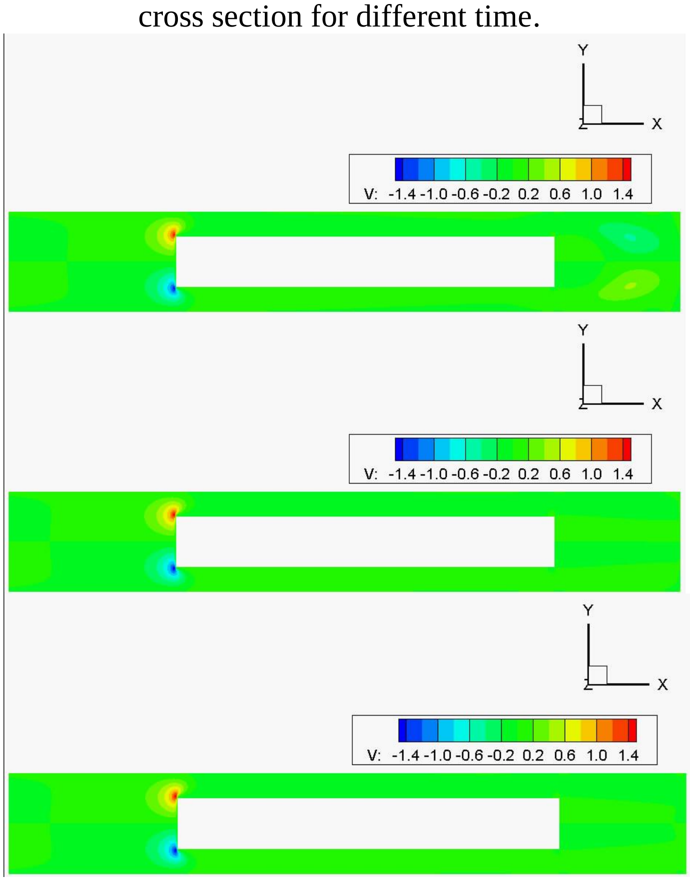

Figure 9 – Transverse velocity components in the cross section for different time.

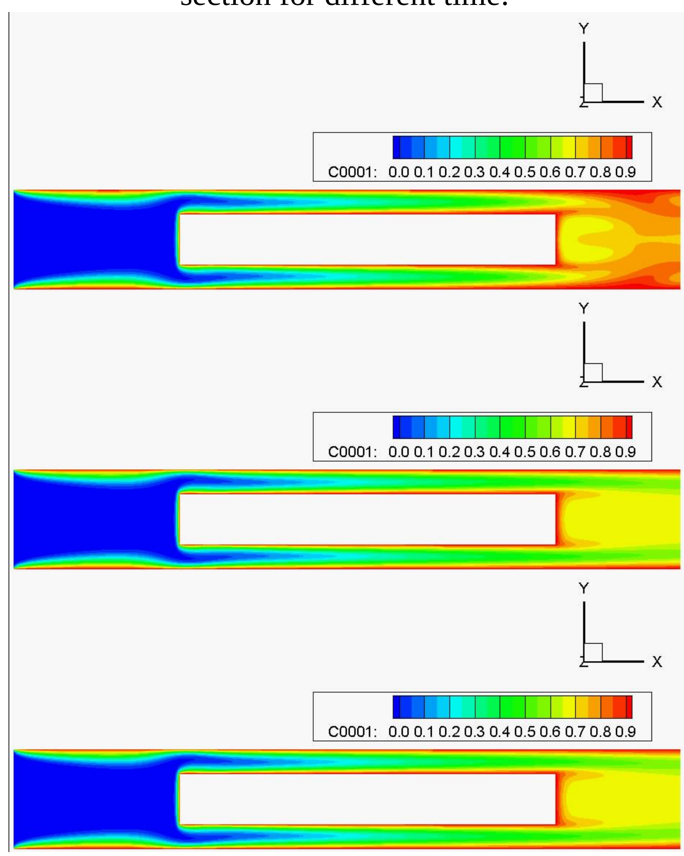

Figure 11 – Relative humidity component in the cross section for different time.

V. CONCLUSION

During the numerical examination of the nasal cavity, the following conclusions can be drawn that the nasal cavity walls contribute to the air heating and the appearance of vortices, which are of no small importance for the air transition to the alveolar state, before entering the nasopharynx. And also important is the relative humidity in the nasal cavity, since at low ambient temperatures, due to moisture, the incoming air is heated. Studies of air movement in the nasal cavity are important, as at present, for various reasons, the number of people with nasal breathing problems is increasing. This problem is solved by surgery, where it is important to optimally operate the nose structure, so that the nasal cavity correctly functions since normal breathing should be done with the nose.

VI. ACKNOWLEDGMENT

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