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Unsteady Self-Cleaning Effect In The Lung Air Ways

Nadezhda Fedosenko [1], Anna Iatcenko [2]

1 St.Petersburg State Polytechnical University
Polytechnicheskaya, 29, 195251, St.Petersburg, Russia,
fedosenko_n@mail.ru

2 St.Petersburg State Polytechnical University
Polytechnicheskaya, 29, 195251, St.Petersburg, Russia,
anuta_sf_18@mail.ru

Abstract

The lung modeling is very intriguing subject to investigate. It may be useful for: investigation respiratory ventilation systems, predicting lung diseases, to developing an anesthesia simulator or other air drag delivery systems.

This work is focusing in the lung modeling with particle deposition. Main attention is paid to the behavior of particles in a periodical (breathing) flow in the extensive system of channels.

From the mechanical point of view lung appears as network in which every branching divides on the number of channels of smaller diameter.

Method of our study is numerical simulation of three – dimensional flow of incompressible air in few first branches of lung. Flow describes by 3D Navier – Stokes equations. Model of walls allows describing their deformation according some number of functions developed during the study. The task is formulated as solution of coupled problem of calculation of gas flow inside deformable boundaries.

During the time of monitoring, particular attention is paid to distribution of average axial velocity along arbitrarily taken sequence of cannels connected inlet and outlet of system. It appears that velocity increase in approaching of any brunch, decrease inside it and then increase again. Such qualitative feature realizes at any moment of time both on breath and outward breath. It's means that in any moment the flow can reach any point that it need. In the contrary with classical subsonic flow inside convergent – divergent channel, flow inside network of channels has an ability both accelerate and decelerate gas flow with changing in time of total area of inlet and outlet of channels involved into the control. In other words, such geometry is "alive" because it shows possibility to self – regulation.

Then particle deposition was simulated using the lagrangian approach. Particles enter the domain with zero velocity slip. The calculations identified areas in which particles of different masses are beginning to gather in the caustic, which can then lead to the blocking of channels of air ways. In technical systems this can lead to erosion in these areas of channels.

On the breathe in and breathe out, the particles move at different speeds and acceleration over the section of the channel. You can also see that the particles with greater mass, in contrast to the light particles pass through the entire computational domain.

Depending on the ratio of drag force and gravity acting on the particle, and its location along the cross section, the particles of different masses behave differently. Particles during breathing out could remain in place or move. The calculations found that the phase of breathing out can be used to clear the lungs. This calculation shows that this method would be more effective when used in combination with transverse vibrations of the channel walls.

Keywords: lungs, lagrangian approach, self-regulation, particle.

Introduction

Lung modeling is very intriguing subject to investigate. It may be useful for investigation of respiratory ventilation systems, predicting of lung diseases, in developing an anesthesia simulator or other air drag delivery systems. For that purpose we need correct model to adequately predict temporal properties and space properties in the respiratory systems. The goal of this work is to develop model that is easy enough for use everywhere we want and can correctly predict spatial and time distributed properties. For that purpose we considered several levels of the scales for full physical modeling. Numerical simulation based on three dimensional unsteady Navier –Stokes equations is used for it. The possibility of wall's deformation is used, too.

This work is focusing in the lung modeling with particle deposition. Main attention is paid to the behavior of particles in a periodical (breathing) flow in the extensive system of channels.

The common pumps in human physiology have a several distinguish features from their technical counterparts. One of the features is the presenting multiple scales in the problem. The over features is a needs to pump fluid there and back periodically in deformable domain.

There are several commonly using ways to modeling aforementioned complex problem: full physical modeling, lumped modeling, distributed parameter modeling. All of them have their advantages and disadvantages. From one point of view, to be reasonable for use it must be easy enough. From another point of view it must capture necessary physical properties. For example, the lumped modeling and distributed parameter modeling are easy enough and can correctly predict changing in time. But it can not correctly predict spatial and time distribution simultaneously.

From the mechanical point of view lung appears as extensive network in which every branching doubles number of channels of smaller diameter dn. Total number of channels N=223 [1]. The first channel – trachea has d1 =18mm, the last – about 10 microns. Lengthening of channel varies lies between 6 and 1. These purposes generates basic problem of correct description of hydromechanics of a lung as a whole.

Method of our study is numerical simulation of three – dimensional flow of incompressible air in few first branches of lung. Flow describes by 3D Navier – Stokes equations. Model of walls allows to describe their deformation according some number of functions developed during the study. The task is formulated as solution of coupled problem of calculation of gas flow inside deformable boundaries.

Quasi-Planar Model

Here the result of simulation of so-called “quasi-planar” model are described. In this model, first 4 levels of lung are modeled as 3D network but all axes of channels lay in one plane. Figure 1 depicts general and auxiliary coordinate systems used for correct description of wall’s deformation. Mentioned problem is solved in the following way. First, local coordinate systems are placed at cross section of any channel modeled. Than, are used for specifying of wall’s deformation of each channel. Figure 2 depicts screen of ANSYS-CFX with user’s expressions required for description of deformation. They are used at every time step. As example, the law of outlets displacement Zdis is placed on figure 3. Figure 4 depicts air velocity at the inlet of whole system (fig.1). Expression for outlet velocity is placed on screen’s image (fig. 2). During breath and outward breath these laws used in reverse order. Laws of velocity and deformation are correlated.

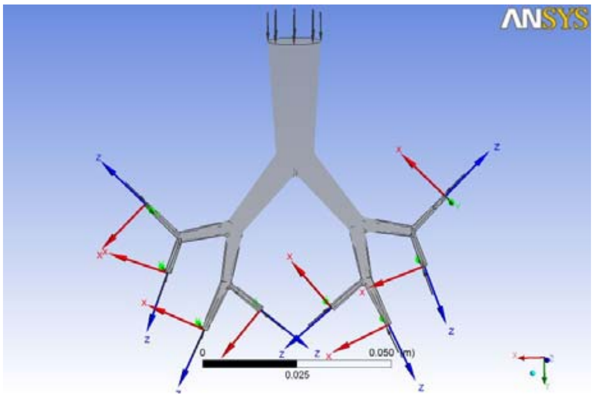
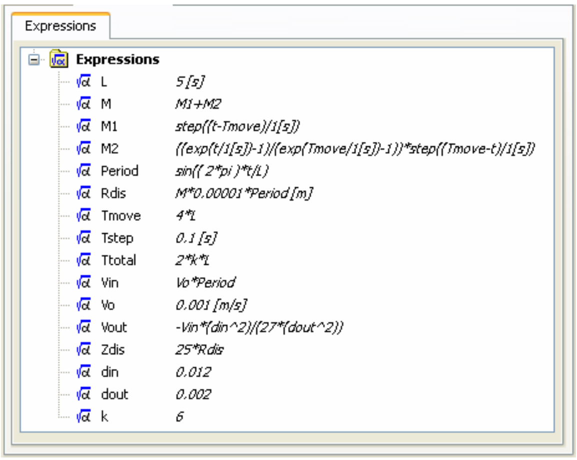


Fig. 1 Simple boundary domain for lung modeling



Expressions

Expressions	
L	5 [s]
M	M1+M2
M1	step((t-Tmove)/1[s])
M2	((exp(t/1[s])-1)/(exp(Tmove/1[s])-1))*step((Tmove-t)/1[s])
Period	sin((2*pi)*t/L)
Rdis	M*0.00001*Period [m]
Tmove	4*L
Tstep	0.1 [s]
Ttotal	2*k*L
Vin	Vo*Period
Vo	0.001 [m/s]
Vout	-Vin*(din^2)/(27*(dout^2))
Zdis	25*Rdis
din	0.012
dout	0.002
k	6

Fig. 2 Expressions for description of the domain deformation

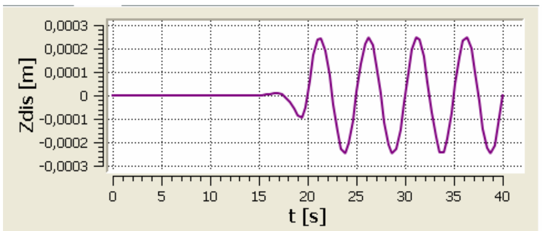


Fig. 3 Law of domain deformation

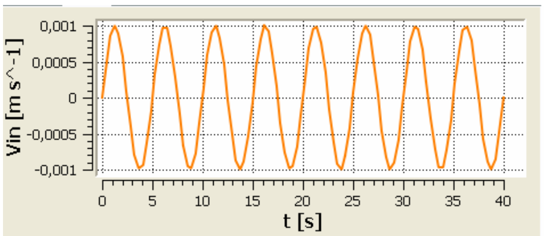


Fig. 4 Inlet velocity

At the beginning of monitoring, the symmetric flow of air originates inside network (fig. 5a). Than, at some moment three-dimensional vortex originates in some branching. It accelerates flow in this channel. (fig. 5b). Finally, all flow rate concentrates in this channel with suction from adjacent channels, velocity in which trends to zero. System does not work as a pump more (fig. 6). It have to be noted that simulation without of wall's deformation gives the same result. It seems reasonably to assume that enlarging of number of channels may help to avoid such blocking.

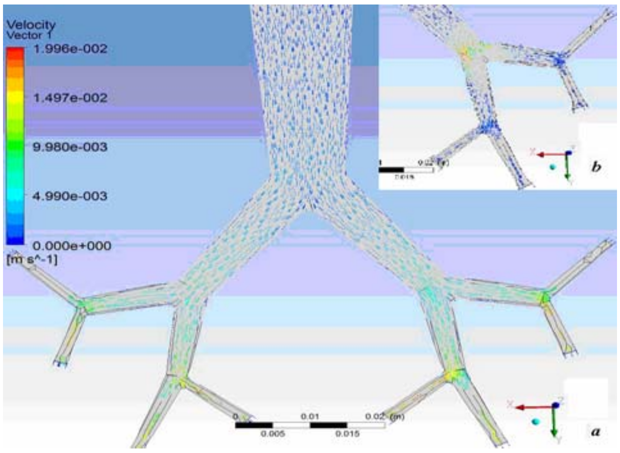


Fig. 5 **Vortex originates in some branching**

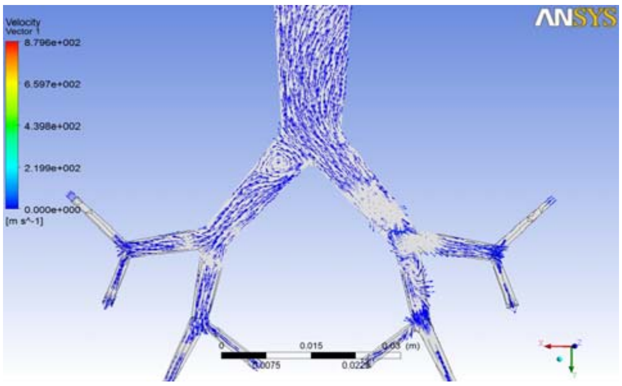


Fig. 6 System does not work us a pump more

Three – Dimensional Model

In accordance with above conclusion more complex model with 27 branches is studied. Axes of channels do not lay more in one plane but placed rather arbitrary in space (fig. 7). As first step, simulation without wall's deformation is realized. Distribution of velocity is shown on fig. 8. Inlet and outlet velocities are taken at the same manner as for quasy-planar case.

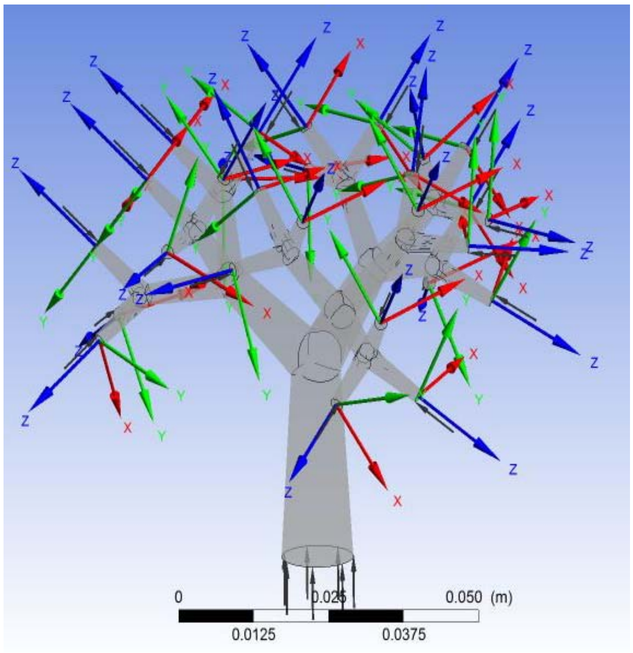


Fig. 7 Three-dimensional model

During the time of monitoring, particular attention is paid to distribution of average axial velocity V along arbitrarily taken sequence of cannels connected inlet and outlet of system. It appears that V increase in approaching of any brunch, decrease inside it and then increase again (fig. 8). Such qualitative feature realizes at any moment of time both on breath and outward breath.

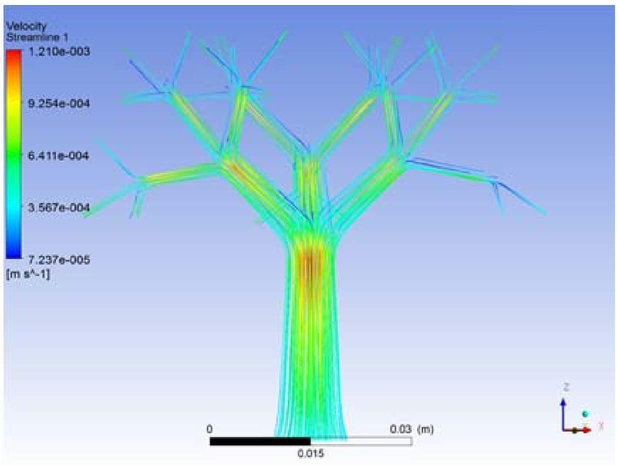


Fig. 8 Velocity distribution

In the contrary with classical subsonic flow inside convergent – divergent channel, flow inside network of channels has an ability both accelerate and decelerate gas flow with changing in time of total area of inlet and outlet of channels involved into control. In other words, such geometry is “alive” because it shows possibility to self – regulation.

Another problem of essential importance researched during simulation is coordination of breathing and deformation of walls of system of channels. In order to solve it, the following experiment was done. After stabilization in time of flow pattern inside system under the study, the deformation of walls is switched on. Four laws of switching of deformation are studied: step-wise, linear, sinusoidal and exponential. It appears that only the last method ensures absence of mismatch of breathing and deformation. On fig. 9 the difference between maximal and minimal value of pressure inside whole system is depicted. From the beginning till 20 sec. flow is realized due to regulation of inlet and outlet velocities. After 20 sec. wall’s deformation is switched on exponentially. It is seen that it does not stopped breathing. This result seems useful for regulation of artificial lung and similar devices for lung ventilation.

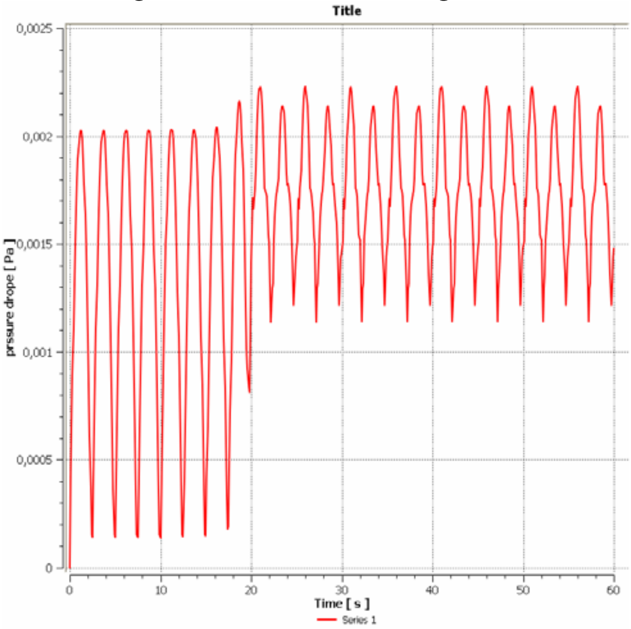


Fig. 9 Pressure drop in the domain

In next step particle deposition was simulated using the lagrangian approach. Particles enter the domain with zero velocity slip. The calculations identified areas in which particles of different masses are beginning to gather in the caustic (fig. 10), which can then lead to the blocking of channels of air ways. In technical systems this can lead to erosion in these areas of channels.

On the breathe in and breathe out, the particles move at different speeds and acceleration over the section of the channel. You can also see that the particles with greater mass, in contrast to the light particles pass through the entire computational domain.

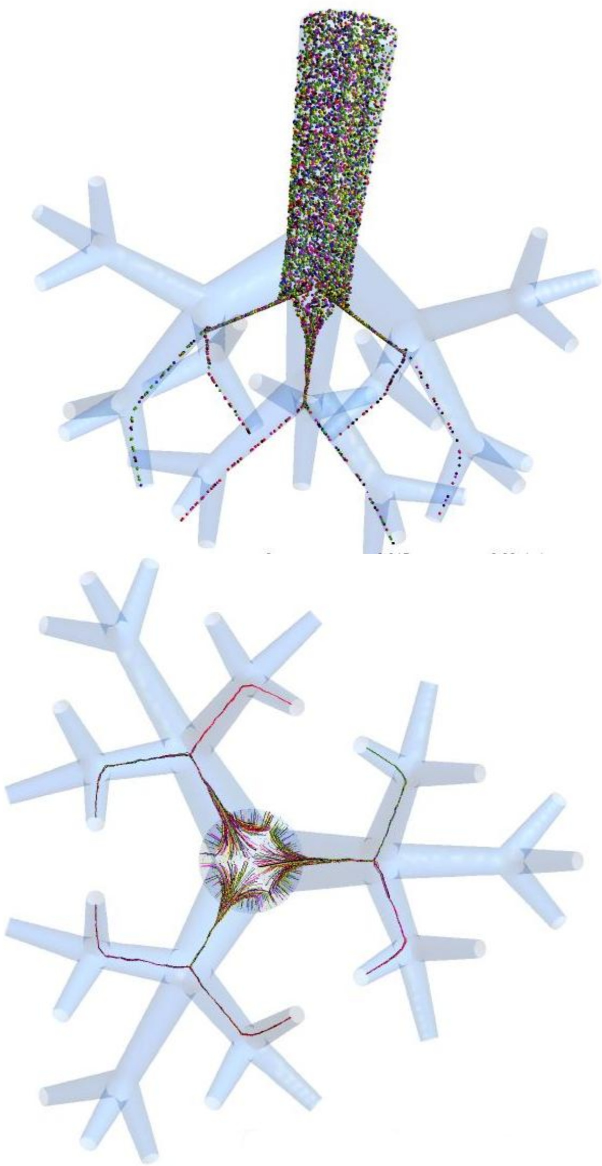


Fig. 10 Particles are gathered in the caustics

Depending on the ratio of drag force and gravity acting on the particle, and its location along the cross section, the particles of different masses behave differe ntly. Particles during breathing out could remain in place or move.

The figure 11,12 are demonstrates the self-cleaning effects. We are looking to traveling one of the particles. In the phase of breathing out the particle vel ocity reduced by flow and between 13 -14 seconds bec ame negative. This is giving to us an opportunity to use these effects for force the particles to moving out of the domain.

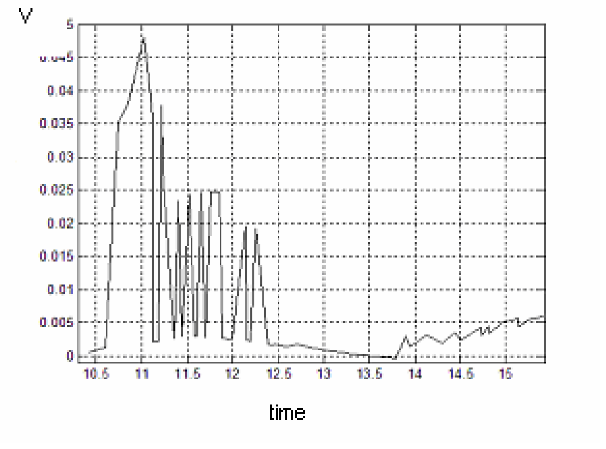


Fig. 11 Typical particle velocity along its tracking line

Figure 12 depicts the tracking line of considered particle.

The ball showing at the constant time intervals so we can see then and where particle reduce the velocit y and so in that point we can force the particle to mo ve out or change the traveling direction.

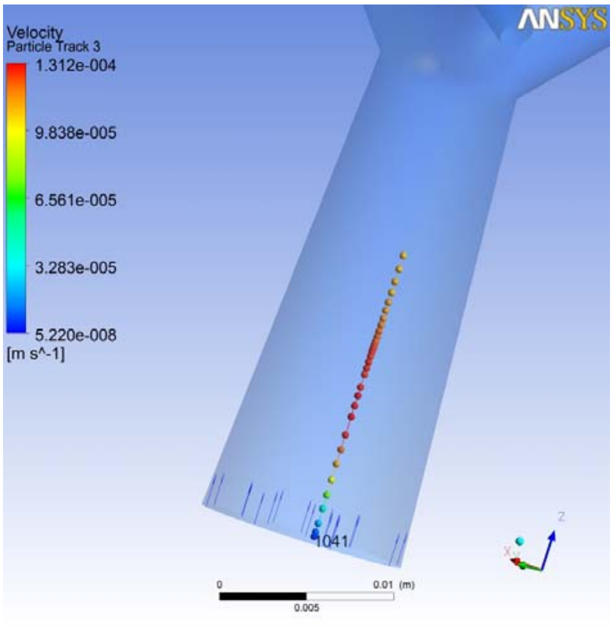


Fig. 11 Positions of the particle along its tracking line colored by velocity magnitude

The calculations found that the phase of breathin g out can be used to clear the lungs. This calculation s hows that this method would be more effective when u sed in combination with transverse vibrations of the ch annel walls.

Conclusions

In this work showing that such systems us a lung air ways have several features to the self-regulation. All of them are essentially unsteady effects. As a main result we can underline the influence of the character of breathing to self-regulation effects.

One of the effects studied was arising vortex in some branching. This leads to situation then the system does not work as a pump more. This effect will diminish when breathing out is longer than breathing in. Conversely, if the breathing in longer blocking effect will increase. Enlarging number of channels help to avoid such blocking too.

Another effect was self-cleaning effect in the lung air ways. In the work was showing the potential possibility to force the particles moving out of the domain.

As future directions to development we can introduce the finding such characters of the breathing that can help to stop or to start necessary effects. It can give a potential possibility to develop noninvasive influence to lung deceases.

Also unequal influence the characters of breathing to the different spatial positions inside the domain can help to develop noninvasive method of the diagnostic.

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