Multiphase dynamics in a three dimensional branching network

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Abstract - The article aims at understanding the complex unsteady fluid dynamics in six generations of a human bronchial tree, which comprises of 63 straight sections and 31 bifurcation modules in a complete breathing cycle. The effects of 3-D arrangement on oscillatory flow is analyzed. Unsteady effects are maximum during the shift of expiration to inspiration and vice versa. It is also observed that the symmetry of the flow in cased of fully developed flow is destroyed due to unsteady effects. The flow division at the bifurcations causes a large asymmetry in the flow field during the inspiration than during the expiration process at the same cross-sections, thus displaying irreversibility of fluid dynamics. The second part of the study is aimed at analyzing the multiphase fluid dynamics inside a six generation bronchial tree for the case of an active smoker. Both the velocity magnitude contours and volume fractions of air and smoke is analyzed and it is observed that the general symmetry of the flow in the main two halves of the branching network is lost due to the interaction of smoke and air in the branches during inhalation and exhalation. It is also observed that higher mass of smoke is accumulated within the daughter branches which are at a lesser angular deviation with the trachea, whereas the branches at the extreme ends have little to no smoke deposit. This phenomenon can be attributed to the high smoke particulate density compared to that of air.

1. Introduction
The process of breathing is an unsteady flow phenomenon involving periodic reversal of the predominant flow direction. The total breathing cycle comprises of essentially two distinct phases viz. inhalation/aspiratory phase during which air is sucked inside the respiratory system and an exhalation/expiratory phase during which air is released out. The present study is aimed at analyzing the fluid dynamics at four specific positions namely peak inhalation, end of inhalation, peak exhalation and end of exhalation. It is important to realize that apparent symmetry in the geometric structure doesn’t automatically imply symmetry in flow field. The combined effects of flow path curvature, flow division at a bifurcation and inertia of flow result in skewed velocity profiles which are not symmetric. It should also be noted that viscous effects present try to establish a symmetric paraboloidal profile but the length of the branch is not sufficient for complete removal of asymmetry. A thorough explanation and discussion on this matter is done in [1]. Before indulging into the complexities of oscillatory flow in branching networks it is important to acknowledge the literature available for oscillating flow in a pipe. Womersely [2-3] showed that the interaction between inertial and viscous effects in oscillatory pipe flow would alter the velocity profile such that it would not remain parabolic. However it has been shown here that the flow field is developing and non-axisymmetric and is a function of all three space coordinates and time. Since the geometric complexity of branching networks renders an analytical solution practically impossible, so in such a case numerical and experimental results are the way forward. Fresconi and Prasad [4] experimentally investigated the unsteady flow field in 4 generation branching network. Nowak, Kakade and Annapragada[9] put forward computational fluid dynamics simulations for air flow and particle deposition in a human trachea upto 4th generation. Soni and Thompson[8] identified the crucial aspects of particle transport in the bronchial tubes due to unsteady flow. Martonen, Quan, Zhang and Musante[7] performed flow simulations in the upper respiratory
tract. Elcner, Lizal and Jicha[10] performed a numerical simulation of air flow inside an idealized geometry of tracheobronchial airways and verified it with experiments. Gorji and Pourmehran[12] studied the airflow behaviour and particle transport and deposition in different breathing conditions. Lieber and Zhao[13] experimentally studied the oscillatory flow inside a bifurcation model. Pradhan and Guha[14] studied the effects on oscillatory flow in a three dimensional branching network. Most authors in the above mentioned literatures have adhered to using the Weibel structure and have taken the branches to be rigid. So to keep the focus of the discussion the present article has also used the same. The present computational study has adopted tight spatial and temporal accuracy (with double precision Arithmetic) and convergence at each time step with 450000 nodes and time step size of 0.01s.

2. Numerical Model Development

A particular generation in the network is referred to here as ‘Gn’ where n takes values from 0 to 5. The six generation network considered here starts from G0 to G5. The dimensions of the branches are given in the Table 1 below which is in order according to Weibel [11]. The bifurcation angle between two daughter branches is set at 70°. All the branches are denoted by four characters ‘GnBk’ where ‘Gn’ represents the generation and ‘Bk’ denotes the branch number at a particular generation. The cross-sectional plane at the end of each straight section of a branch is denoted by “GnPk”. Fig 1 shows a three dimensional view of the symmetric model of the human bronchial network.

Table 1: Geometrical parameter details of the model

| Generation number | Diameter (mm) | Length (mm) |
|-------------------|--------------|-------------|
| G0                | 18           | 120         |
| G1                | 12.20        | 47.60       |
| G2                | 8.30         | 19.00       |
| G3                | 5.60         | 7.60        |
| G4                | 4.50         | 12.70       |
| G5                | 3.50         | 10.70       |

The governing equations for the multiphase flows are used in Eulerian-Eulerian platform and are detailed as follows:

**Continuity and momentum equations of gas phase:**

Continuity: \[
\frac{\partial (\alpha_g \rho_g u_g)}{\partial t} + \nabla \cdot (\alpha_g \rho_g \bar{u}_g) = 0
\]

Momentum: \[
\frac{\partial (\alpha_g \rho_g \bar{u}_g)}{\partial t} + \nabla \cdot (\alpha_g \rho_g \bar{u}_g \bar{u}_g) = -\alpha_g \nabla p + \nabla \left[ \alpha_g \mu_{eff} \left( \nabla \bar{u}_g + \nabla \bar{u}_g^T \right) \right] + \bar{F}_{g} + \alpha_g \rho_g \bar{g}
\]
Here $\alpha_g$ represent volume fraction of gas phase, $\mu_{\text{eff},g}$ is the effective viscosity of gas, $\tilde{F}_{G,g}$ is the interfacial source terms between the two phases.

The 3-D model of the branching network is built in SpaceClaim and Design Modeller in-built within ANSYS Workbench 18. All the meshing and simulations are performed on ANSYS Mesh Modeller and Fluent respectively on computer with i5 processor and 16GB RAM. A Viscous Laminar model is adopted. The scheme used for momentum is First order upwind and gradient being Least Square Cell Based.

A time varying velocity field given by $V = V_{\text{max}} \sin(2\pi ft)$ is prescribed at the cross sectional boundary of the first branch where $V_{\text{max}} = 1.235$ m/s, $f = $ frequency of breathing cycle = 12/minute.

For the multiphase simulation, following conditions are adopted: Puff Volume Rate, $Q = 100\sin\theta$ ml/s (From Ref [5]), Area of inlet = $A = 0.000254$ m$^2$.

For active smoker the volume fraction of smoke in mixture is taken to be 0.1 i.e. 10%. Volume flux of air = $1.235\sin\theta$ m/s, phase velocity of air = $1.235\sin\theta/0.9 = 1.372\sin\theta$ m/s, volume flux of smoke = $Q/A = 0.393\sin\theta$ m/s, phase velocity of smoke = $0.393\sin\theta/0.1 = 3.93\sin\theta$ m/s.

In the present case, the Womersley number turns out to be 2.64 which is greater than 1 thus depicting the dominance of unsteady effects in branching networks. The maximum Reynolds number attained is about 1550, which is safely below the critical value for the onset of turbulence, thus justifying the assumption of viscous laminar model in this article.
3. Results & Discussion

3.1 Normal Breathing Cycle

At T/4

Fig 3 shows the contour of velocity magnitude at specific locations like G0P1, G1P1, G2P1 and so on. The primary velocity distribution at G0P1 is somewhat similar to pipe flow with maximum velocity occurring at the centre. The velocity distribution for G1P1 is skewed with maximum velocity occurring at the inner edge of the bifurcation. Due to asymmetry the contours of G2P1 and G2P2 are different. Similar kinds of results are obtained for remaining cross-sections.

Figure 2: Oscillatory flow at inlet to branching network

Figure 3: Velocity contours at different locations.
At 3T/4
The contours are shown in Fig. 4. Two striking differences between flow structures at this instant is that it is characterized by more symmetrical flow as compared to the instant at t=T/4. This may be attributed to the difference in geometry of flow path during inhalation and exhalation. During inhalation, the flow at the centre of the flow path of the parent branch, is divided on reaching the bifurcation such that the maximum cross-sectional velocity is shifted toward the inner edge of the bifurcation module in the daughter branches, resulting in a skewed velocity distribution in the daughter branches which, in turn, leads to asymmetric mass-flow distribution among the downstream branches of the daughters. Whereas, during exhalation, as the flow reaches a bifurcation joining two daughter branches to a parent branch, the curvature of the flow path pushes the maximum velocity towards the centre of the cross section in the parent branch, leading to more symmetric velocity distribution in the parent branch and hence a reduction in the asymmetry in the mass flow distribution among the downstream branches.

![Figure 4: Velocity contours at different locations.](image)

### 3.2 Active Smoker
**At T/4**

Figure 5 show the mid plane section of the model at t=T/4, i.e. during peak inhalation. For an active smoker, the volume fraction of smoke is taken to be 0.1, or 10% of total volume of respiratory fluid. Figure 5 also depict the air velocity and smoke velocity contours which depict the maximum velocity around 6m/s and 4m/s, occurring at the daughter branches respectively. It can be seen that these two flows are complementary to each other. The characteristics observed here may be attributed to the physical properties of smoke and air. Smoke, having a high particulate density, acts as a heavier fluid, forcing most of the air towards the walls of the branches. The remaining mass of air in mixture with smoke flows in unison along the inner edges of the bifurcation modules. It is also noted that the volume fraction and thereby mass percentage of smoke decreases as the angular deviation from the root (trachea) increases. This effect can also be attributed to the density of smoke which
facilitates flow in the downstream region and impedes flow as the branches become increasingly steep. The volume fraction contours has also been in Fig 5.
The results of peak expiration have been shown above in Fig. 6. The initial cycle has been simulated and left out so as to remove any initial effects. It is observed that the air velocity remains nearly about 3m/s along the core of all the branches whereas it is about 2m/s as we approach the walls. Any cross-section in the branching network is therefore characterized by a centrally located peak thereby giving rise to a plateau like distribution. In case of smoke, velocity reaches a maximum of about 2.5m/s nearer to the walls which are at a less angular deviation from the trachea, and the velocity drops to 1-1.2m/s as we further move away from the center line. The volume fraction nearly remains constant in the entire expiration cycle (about 0.9 of air and 0.1 of smoke) at each cross-section. While majority of the smoke is exhaled out into the atmosphere, a certain amount of smoke remains as residue along the walls of the branches. This residue may be explained by the viscous and wall friction due to which smoke, in contact with the inner edges of the bifurcations, come to rest. The force exerted by the expiratory air is not sufficiently high enough to push out the smoke along the walls owing to its higher density and hence a residual layer of smoke remains in the branches.
4. Validation of Data

The results obtained in the present article have been validated through comparative study with the results obtained by Pradhan and Guha[14]. The contours of cross section of the branches at similar positions have been taken and compared. The results obtained in this study agree closely with those of the previous works. The contours show reasonably close profiles at all the critical flow times in the breathing cycle. The deviation in data is about 4%-10%. As an example, the maximum velocity magnitude obtained by Pradhan and Guha during exhalation (without smoke) is 2.1m/s, whereas it comes to 2.26m/s in our current study. This minimal difference can be attributed to the difference in mesh structure and complexity and time step size. The study with smoke is based on the same model, with the addition of multiple phases. As mentioned in Section 2, the flow is considered to be viscous laminar as the maximum Reynold’s number during peak inhalation or exhalation is about 1550, appreciably lower than the critical value for turbulence. The article, therefore, successfully tries to illustrate the distribution of smoke in the daughter branches of a six generation human bronchial tree as well as shows the phenomenon of accumulation of smoke over time through computational fluid dynamics.

5. Conclusions

With the present study it has been established that due to the unsteady effects of oscillatory flow in branching networks the flow is seen to be asymmetric during the inspiration phase (Fig 3) of the breathing cycle. Moreover, the flow tends to acquire a more symmetric structure in the expiration phase (Fig 4). This can be attributed to the differences between bifurcating flow and combinatory flow in a branching network which further yields us to a conclusion that fluid flow in such geometry is irreversible. In the second part of the study it can be seen that there is distinguishable volume fraction distribution in the entire geometry during the inspiration phase whereas the volume fraction is nearly same at all cross-sections during the expiratory phase. During the aspiratory phase the maximum amount of smoke concentration is found at the daughter branches nearer to the centre line which can be attributed to the smoke particulate density than air, whereas air concentration maximum in branches farthest from the centerline (Fig 5). As the slope gets steeper as we move further away from the center line, the velocity thus tends to decrease. The velocity is further decreased due to the high density of smoke. While majority of smoke particles get exhaled out during expiratory phase, a certain quantity, albeit low, remains deposited along the walls of the branches (Fig 6). This observation asserts that, in each breathing cycle, a certain amount of particulates remain deposited and accumulate over time in the respiratory organs, which may, in turn, lead to serious health complications.

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