IOP Conf. Series: Materials Science and Engineering **225** (2017) 012132 doi:10.1088/1757-899X/225/1/012132

Airflow and Particle Transport Through Human Airways: A Systematic Review

S. B. Kharat[a], A B Deoghare[b], K M Pandey[c]
a M.Tech, Dept. of Mech. Engg., N.I.T. Silchar, India
b Assistant Prof., Dept. of Mech. Engg., N.I.T. Silchar, India
c Head of Department, Dept. of Mech. Engg., N.I.T. Silchar, India

Abstract: This paper describes review of the relevant literature about two phase analysis of air and particle flow through human airways. An emphasis of the review is placed on elaborating the steps involved in two phase analysis, which are Geometric modelling methods and Mathematical models. The first two parts describes various approaches that are followed for constructing an Airway model upon which analysis are conducted. Broad two categories of geometric modelling viz. Simplified modelling and Accurate modelling using medical scans are discussed briefly. Ease and limitations of simplified models, then examples of CT based models are discussed. In later part of the review different mathematical models implemented by researchers for analysis are briefed. Mathematical models used for Air and Particle phases are elaborated separately.

Keywords: Aerosol Deposition, Airflow Behavior, Human Airways, Particle Transport

1. INTRODUCTION

Respiration is one of the vital processes executed by almost all living beings. On an average, a healthy human being breaths about 20 times in a minute. The respiration process starts from Nasal passages from where air is taken in and passing through nasal cavity it enters trachea. From trachea air enters primary bronchus then secondary bronchus followed by segmented bronchus and at the end air reaches at alveolus. Alveolus consists alveoli sacs and alveoli ducts through which oxygen enters blood capillaries and carbon di oxide is taken out from blood capillaries into alveolus.

While breathing along with air many small particles present in surroundings are also inhaled, which are deposited inside lungs as air is taken in through respiratory airways. Such external particles deposition may cause harmful effects on human health. Deposition of harmful particles leads to many respiratory health problems. But particle transport through airways also has beneficial application when inhaled in controlled conditions; This technique is called as Aerosol Drug Therapy [54]. For efficient Aerosol drug transmission, it is essential to understand Aerosol flow through the complex shapes of airways. Knowledge of governing parameters affecting Aerosol deposition is essential, such that varying these parameters optimum Aerosol deposition can be achieved. Also, it is essential to understand about harmful particle deposition like smoke and pollutants damaging human airways. It may also need to explore with the two-phase system to understand the behavior of deposition.

2. LITERATURE REVIEW

To analyze airflow and/or particle deposition inside human airway, researchers have implemented various methods. Classification of these methods can be done as numerical methods [1,2,3,4], experimental methods [5,10], and theoretical/analytical methods [11,12]. The available literature can be differentiate mainly based on types of Geometrical model constructed and mathematical method implemented. These models are discussed further according to literature.

***2.1** Geometrical Modelling*

According to explored literature, Geometric models of human airways can be categorized as Approximated models and Accurate models.

***2.1.1** Approximate Modelling*

In the early studies, most of the work utilizes simplified form of geometric model due to complexity of airway geometry. In simplified geometry (e.g. fig. 1.), dimensions and cross sections are approximated for reducing computational time and efforts [6,7]. This simplification eases the analysis but accuracy of results is compromised. Many of current research works [13,14] are based on such simplified models. These models are advantageous when global deposition values are to be determined but lacks in precision.

Bora Sul *et al.* [45] compares airflow characteristics in normal and obstructive airways with the help of simplified models. These models are developed in AutoCad12. To investigate human tidal breathing through airways Azarnoosh *et al.* [49] constructed a CAD model using SolidWorks modelling package. For studying Deposition Fraction of Aerosol Particles in a Human Oral Airway approximated oral airway model is used [46]. Airflow structures and Nano-particle deposition [47] and Comparison of micro- and Nano-size particle depositions [44] are also studied based on such approximated models. For analyzing flow structure and particle deposition in asthmatic human airway [48], asthmatic airway is constructed by simply decreasing diameters of normal airways. For further simplification, some researchers assumed airways to be symmetric [22, 26]. Whereas there some researchers considered asymmetric models [1, 9, 28, 29].

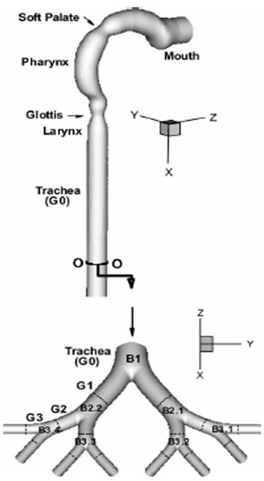

Fig. 1. oral airway model and bifurcation [44]

***2.1.2** Accurate Modelling*

For better analysis, it is essential to use more accurate models. Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) scans [8, 9, 16] are helpful for accurate airway modelling. CT, HRCT and MRI are medical scan images which are imported into image processing software such as Mimics, 3d Slice, 3-D Doctor etc. These software processes images based on their grey values to construct a model for visualization and/or analysis. Human airways have complicated cross sections which are accurately modelled with such medical images [18,19]. For studying flow analyses in lower airways Backer *et al.* [50] implements patient specific model and boundary conditions. CT scan data of 73-year-old female patient suffering from chronic obstructive pulmonary disease (COPD) is processed using Mimics 10.0 to construct a 3D model. Thoracic CT scans of a 60-year-old male patient are processed using Mimics to model bifurcating flow in a human lung airway [51]. CFD simulation of airflow behavior and particle transport and deposition through the realistic model of human airways in different breathing conditions is conducted on a cad model developed from DICOM images using 3-D Doctor Cad package [52].

These medical scan images also can be used for Rapid prototyping. This can be done by generating. STL file from medical images using Imaging software mentioned above. Kim et al. [17] uses such method to study the airflow with PIV method. Cheng et al. [5] produced a human airway cast till three generations of bronchi to study the particle deposition in the oral airways. Jayaraju *et al.* [8] built a geometrical model of human upper airway with the help of DICOM images to study turbulent modeling methods [36] and the airflow fields in airways with the tracheal stenosis [20].For determining effect of geometrical modelling on the airflow field and particle transport, four different geometrical modes of upper airway are adopted by Xi *et al.* [16].The W. H. Finlay et al[25] carried out different geometric models for Child and adult patients with asthma or other pulmonary diseases may have different features. Rapid prototyped model developed from CT scan is used for experimental study to of turbulent particle transport in human airways under steady and cyclic flows [53].

Literature also revels analysis of bronchial airways at various generation levels. Flow field in the first generation largely influence the subsequent flow in the subsequent bifurcations [40]. In general, secondary flow still exists in the generations from G10 - G13 [41]. Nowak et al. [30] and Cebral et al. [37] uses CT scans to model bronchial airway from generation 0 to generation 4 (G0 - G4). Van Ertbruggen et al. [31] created a geometry model for seven generations based on the morphometrical data cited in Horsfield et al. [37]. Seventeen generations of human respiratory tract are abstracted topological graphical data from anatomical model defined in Schmidt et al. [38], was adopted by Gemci et al. [32] to study the airflow in the human respiratory system. It includes seventeen generations of the total twenty-six generations of the human tracheobronchial airways with 1453 bronchi [32].

2.2 Mathematical Methods

2.2.1 Air Phase

The major difficulty in analysis of Gas phase is that due to geometrical complications and variations of Airways the flow changes from laminar to turbulent. Method should be efficient to formulate not only laminar flows, but also transitional and turbulent flow structures [19, 23, 36]. The complexity of the extra-thoracic airway includes the bends, sudden cross-sectional area change [18, 19], this creates turbulence in the flow. Currently, there are many methods available for analyzing the laminar-transitional-turbulent flow in the human respiratory system for example direct numerical simulation (DNS), large eddy simulation (LES) [9, 36], Reynolds-averaged equations [8, 7, 33], detached eddy simulation (DES) [36]. K-ε model is suitable for simulating the flow with small pressure gradient, while it cannot accurately predict the flow containing large adverse pressure gradient [37]. The K-ω model is another kind of the most commonly used two-equation turbulence models including the transport equations of kinetic turbulent energy and specific turbulent dissipation [38]. Some of the work [2, 7, 8, 19, 33] implements the RANS(Reynolds-averaged Navier–Stokes equation) method to simulate the flow field. Large eddy simulation (LES) predicts particle deposition. LES also predicts the large-scale flow structures by solving the filtered Navier-Stokes equations and modeling unresolved vortices with subgrid scale model. Jayaraju et al. [36] used RANS k - ω, detached eddy simulation (DES), and LES methods for comparing accuracy of these models corresponding to deposition inhaled aerosol medication. Until now, the governing equations have been solved with commercial software such as KIVA [39], FLUENT [52] and CFX [2]. Sometimes, it is accompanied with the user-defined program in C, Fortran or Openfoam.

2.2.2 Particle Phase

At present, there are basically two different approaches in the analysis of the phenomenon of particles dispersed in the airflow in the respiratory system such as Euler-Lagrange method [15] and Euler-Euler method [21]. In the Euler-Lagrange method, a particle trajectory is calculated by solving equations of the motion for each particle using Lagrangian approach [8, 14, 19, 21, 33]. On the other hand, in the Euler-Euler approach, a particle concentration distribution of the carrier fluid is calculated [34]. The parcel method assumes that there are more particles in one parcel with the same physical properties such as diameter and velocity [35]. If there are more particles, the volume fraction will become large, then it may be necessary to consider the influence of particle momentum on the airflow field, which means that two-way coupling should be adopted [35]. The inertial impaction of particle is decided by the air. Thus, the larger of IP means the larger of particle inertial impaction [15]. Gravitational settling is a function of particle size, particle density and time, with the rate of settling proportional to particle size and particle density micro-particle transport and deposition have been extensively studied by a lot of researchers in the oral airways [5, 4, 7, 12, 19,]. Other than total and regional particle deposition, local particle deposition pattern is another important parameter for the assessment of particle deposition influence on the health [4]. The different particle trajectories have been obtained and discussed to understand the effects of airflow and Stokes numbers [19]. Particle deposition in the Tracheobronchial airways has been found to be contributed to the occurrence of asthma attacks [42]. Aerosol drug deposition in the Tracheobronchial region can reduce drug delivered into pulmonary region [25]. In contrast, some aerosol drug is targeted to Tracheobronchial region, such as bronchodilator and corticosteroids, to treat Tuberculosis airway asthma [43]. A series of research has been developed to study the particle transport and deposition in the lung with experimental and numerical methods from one to several bifurcations [1, 2, 24, 30, 31, 34].

3. CONCLUSION

Literature revels development of accurate Airways model is feasible with CT data. For accurate analysis, deeper generations of bronchi are needed to be modelled. Two phase system intended to be analyzed for particle deposition inside airways. According to the flow conditions most applicable mathematical method is implemented in analysis.

REFERENCES

[1] C. Kleinstreuer, Z. Li, and Z. Zhang, “Particle deposition in the human tracheobronchial airways due to transient inspiratory flow patterns,”. Jr. of Aerosol Sci., vol.38, pp. 625-644, 2007.
[2] C. Kleinstreuer and Z. Zhang, “Transient airflow structures and particle transport in a sequentially branching lung airway model,” Phys. Fluids, vol. 14, pp. 862-880, 2002.
[3] C. Kleinstreuer, Z. Li, and Z. Zhang, “Simulation of airflow fields and microparticle deposition in realistic human lung airway models. Part II: Particle transport and deposition,” European Jr. of Mech. B-Fluid., vol. 26, pp. 650-668, 2007.
[4] C. Kleinstreuer, Z. Zhang, J. F. Donohue, and C. S. Kim, “Comparison of micro- and Nano-size particle depositions in a human upper airway model,” Jr. of Aerosol Sci., vol. 36, pp. 211- 233, 2005.
[5] Y. S. Cheng, Y. Zhou, and B. T. Chen, “Particle deposition in a cast of human oral Airways,” Aerosol Sci. and Tech., vol. 31, pp. 286-300, 1999.
[6] W. I. Li, M. Perzl, J. Heyder, R. Langer, J. D. Brain, K. H. Englemeier, R. W. Niven, and D. A. Edwards, “Aerodynamics and aerosol particle deaggregation phenomena in model oral-pharyngeal cavities,” Jr. of Aerosol Sci., vol. 27, pp. 1269-1286, 1996.
[7] K. W. Stapleton, E. Guentsch, M. K. Hoskinson, and W. H. Finlay, “On the suitability of k-epsilon turbulence modeling for aerosol deposition in the mouth and throat: A comparison with experiment,” Jr. of Aerosol Sci., vol. 31, pp. 739-749, 2000.
[8] S. T. Jayaraju, M. Brouns, S. Verbanck, and C. Lacor, “Fluid flow and particle deposition analysis in a realistic extra thoracic airway model using unstructured grids,” Jr. of Aerosol Sci., vol. 38, pp. 494-508, 2007.
[9] Y. Liu and H. Y. Luo, “Modeling the bifurcating flow in a CT-scanned human lung Airway,” Jr. of Biomech., vol. 41, pp. 2681-2688, 2008.
[10] K. H. Cheng, Y. S. Cheng, H. C. Yeh, and D. L. Swift, “Deposition of ultrafine aerosols in the head airways during natural breathing and during simulated breath-holding using replicate human upper airway casts,” Aerosol Sci. and Tech., vol. 23, pp. 465-474, 1995.
[11] W. H. Finlay and A. R. Martin, “A general, algebraic equation for predicting total respiratory tract deposition of micrometer-sized aerosol particles in humans,” Jr. of Aerosol Sci., vol. 38, pp. 246-253, 2007.
[12] W. Stahlhofen, G. Rudolf, and A. C. James, “Inercomparison of experimental regional aerosol deposition data,” Jr. of Aerosol Medicine, vol. 2, pp. 285-308, 1989.

[13] C. Kleinstreuer, Z. Zhang, and C. S. Kim, “Comparison of analytical and CFD models with regard to micron particle deposition in a human 16-generation tracheobronchial airway model,” Jr. of Aerosol Sci., vol. 40, pp. 16-28, 2009.
[14] E. A. Matida, M. Ilie, and W. H. Finlay, “Asymmetrical aerosol deposition in an idealized mouth with a DPI mouthpiece inlet,” Aerosol Sci. and Technology, vol. 42, pp. 10-17, 2008.
[15] C. Kleinstreuer, Z. Zhang, and J. F. Donohue, “Targeted drug-aerosol delivery in the human respiratory system,” Annual Review of Biomedical Engineering, vol. 10, pp. 195-220, 2008.
[16] J. Xi and P. W. Longest, “Transport and deposition of micro-aerosols in realistic and simplified models of the oral airway Annual Review of Biomedical Engineering, vol. 35, pp. 560-81, 2007.
[17] S. K. Kim and S. K. Chung, “Investigation on the respiratory airflow in human airway by PIV,” Jr. of Visual Communication and Image Representation, vol. 12, pp. 259-266, 2009.
[18] S. T. Jayaraju, “Study of the air flow and aerosol transport in human upper airway using LES and DES methodologies,” Phd diss., Vrije Universiteit Brussel, Brussels, Belgium, 2009.
[19] Z. Zhang, C. Kleinstreuer, and C. S. Kim, “Micro-particle transport and deposition in a human oral airway model,” Jr. of Aerosol Sci., vol. 33, pp. 1635-1652, 2002.
20] M. Brouns, S. T. Jayaraju, C. Lacor, J. De Mey, M. Noppen, W. Vincken, and S. Verbanck, “Tracheal stenosis: airflow dynamics study,” Jr. of Applied Physiology, vol. 102, pp. 1178-1184, 2007.
[21] H. Takano, N. Nishida, M. Itoh, N. Hyo, and Y. Majima, “Inhaled particle deposition in unsteady-state respiratory flow at a numerically constructed model of the human larynx,” Jr. of Aerosol Medicine, vol. 19, pp. 324-28, 2006.
[22] R. C. Schroter and M. F. Sudlow, “Flow patterns in models of the human bronchial Airways,” Respiratory Physiology & Neurobiology, vol. 7, pp. 341-55, 1969.
[23] C. Kleinstreuer and Z. Zhang, “Airflow and particle transport in the human respiratory system, annual review of fluid mechanics, vol. 42, pp. 301-334, 2010.
[24] C. Kleinstreuer, Z. Li, and Z. Zhang, “Particle deposition in the human tracheobronchial airways due to transient inspiratory flow patterns,” Jr. of Aerosol Sci., vol. 38, pp. 625-644, 2007.
[25] W. H. Finlay. The Mechanics of Inhaled Pharmaceutical Aerosols: An Introduction. London, Academic press, 2001.
[26] A. Farkas and I. Balashazy, “Simulation of the effect of local obstructions and blockage on airflow and aerosol deposition in central human airways,” Jr. of Aerosol Sci., vol. 38, pp. 865-884, 2007.
[27] C. Kleinstreuer, Z. Zhang, and Z. Li, “Modeling airflow and particle transport/deposition in pulmonary airways,” Respiratory Physiology & Neurobiology, vol. 163, pp. 128-38, 2008.
[28] C.S. Kim and A. J. Iglesias, “Deposition of inhaled particles in bifurcating airway Models I. inspiratory deposition,” Jr. of Aerosol Medicine, vol. 2, pp. 1-14, 1989.
[29] H. Y. Luo, Y. Liu, and X. L. Yang, “Particle deposition in obstructed airways” JR. of Biomechanics, vol. 40, pp. 3096-104, 2007.
[30] N. Nowak, P. P. Kakade, and A. V. Annapragada, “Computational fluid dynamics simulation of airflow and aerosol deposition in human lungs,” Ann. Biomed. Eng., vol. 31, pp. 374-90, 2003.
[31] C. van Ertbruggen, C. Hirsch, and M. Paiva, “Anatomically based three-dimensional model of airways to simulate flow and particle transport using computational fluid dynamics,” JR. of Appl. Physiol., vol. 98, pp. 970-980, 2005.
[32] T. Gemci, V. Ponyavin, Y. Chen, H. Chen, and R. Collins, “Computational model of airflow in upper 17 generations of human respiratory tract,” JR. of Biomechanics, vol. 41, pp. 2047-54, 2008.
[33] C. Kleinstreuer, P. W. Longest, and R. Buchanan, “Efficient computation of microparticle dynamics including wall effects,” Computational Fluids, vol. 33, pp. 577-601, 2004.
[34] G. Ahmadi, P. Zamankhan, Z. C. Wang, P. K. Hopke, Y. S. Cheng, W. C. Su, and D. Leonard, “Airflow and deposition of nano-particles in a human nasal cavity,” Aerosol Sci. Technol., vol. 40, pp. 463-476, 2006.
[35] H.-W. Ge, “Probability density function modeling of turbulent non-reactive and reactive spray flows,” Phd diss., University of Heidelberg, Heidelberg, 2007.

[36] S. T. Jayaraju, M. Brouns, C. Lacor, B. Belkassem, and S. Verbanck, "Large eddy and detached eddy simulations of fluid flow and particle deposition in a human mouth throat," Jr. of Aerosol Sci., vol. 39, pp. 862-875, 2008.
[37] D. C. Wilcox, "Turbulence Modeling for CFD (Third Edition)," DCW Industries Inc., La Canada, CA, 2006.
[38] D. C. Wilcox, "Reassessment of the scale-determining equation for advanced turbulence Models," AIAA JR., vol. 26, pp. 1299-1310, 1988.
[39] A. A. Amsden, P. J. O'Rourke, and T. D. Butler, "Kiva-ii: A computer program for chemically reactive flows with sprays," Technical Report UC-96, Los Alamos National Laboratory, May 1989.
[40] C. Kleinstreuer, Z. Zhang, and C. S. Kim, "Flow structure and particle transport in a triple bifurcation airway model," Jr. of Fluids Engineering-Transactions of the Asme, vol. 123, pp. 320-330, 2001.
[41] Z. Zhang, C. Kleinstreuer, and C. S. Kim, "Airflow and nanoparticle deposition in a 16-generation tracheobronchial airway model," Ann. Biomed. Eng., vol. 36, pp. 2095-110, 2008.
[42] R. J. Pandya, G. Solomon, A. Kinner, and J. R. Balmes, Diesel exhaust and asthma, pp. hypotheses and molecular mechanisms of action. Environ". Health Perspect., vol. 110, pp. 103-12, 2002.
[43] T. Martonen, J. Fleming, J. Schroeter, J. Conway, and D. Hwang, "In silico modeling of asthma," Advanced Drug Delivery Reviews., vol. 55, pp. 829-49, 2003.
[44] Z. Zhanga, C. Kleinstreuer, J.F. Donohue, and C.S. Kim, "Comparison of micro- and nano-size particle depositions in a human upper airway model," Aerosol Sci., vol. 36, pp. 211-233, 2005.
[45] B. Sul, A. Wallqvist, M. J. Morris, J. Reifman, and V. Rakesh, "A computational study of the respiratory airflow characteristics in normal and obstructed human airways," Computers in Biology and Medicine, vol. 52, pp. 130–143, 2014.
[46] L. Zhang, Ho. Cheng, C. Zhang, Z. Xu, and J. Ye, "Deposition Fraction of Aerosol Particles in a Human Oral Airway Model on Stable Condition," Aerosol and Air Quality Research, Vol. 6, pp. 259-267, 2006
[47] Z. Zhang and C. Kleinstreuer, "Airflow structures and nano-particle deposition in a human upper airway model," Jr. of Computational Physics, vol. 198, pp. 178–210, 2014.
[48] H. Zhang, and G. Papadakis, "Computation analysis of flow structure and particle deposition in a single asthmatic human airway bifurcation," Jr. of Biomechanics, vol. 43, pp. 2453–2459, 2010.
[49] J. Azarnoosh, "CFD investigation of human tidal breathing through human airway geometry," The International Conference on Computational Sci., vol. 80, 956-976, 2016.
[50] J.W. De Backer, W.G. Vos, C.D. Gorl´, P. Germonpr´e, B. Partoens, F.L.Wuyts , P.M. Parizel and W. De Backer, "Flow analyses in the lower airways: Patient-specific model and boundary conditions," Medical Engineering & Physics, vol. 30, pp. 872–879, 2008.
[51] H. Luo & Y. Liu, "Modeling the bifurcating flow in a CT-scanned human lung airway," Jr. of Biomechanics, vol. 41, pp. 2681– 2688, 2008.
[52] M. Rahimi-Gorji, O. Pourmehran, M. Gorji-Bandpy, and T.B. Gorji, "CFD simulation of airflow behavior and particle transport and deposition in different breathing conditions through the realistic model of human airways," Jr. of Molecular Liquids, vol. 209, pp. 121–133, 2015.
[53] J. Jedelsky, F. Lizal and M. Jicha, "Characteristics of turbulent particle transport in human airways under steady and cyclic flows," International Jr. of Heat and Fluid Flow, vol. 35, pp. 84–92, 2012.
[54] C. Kleinstreuer, Z. Zhang, and J. F. Donohue, "Targeted drug-aerosol delivery in the human respiratory system," Annual Revision Biomedical Engineering, vol. 10, pp. 195–220, 2008.

a Mr. S. B. Kharat

IOP Conf. Series: Materials Science and Engineering **225** (2017) 012132 doi:10.1088/1757-899X/225/1/012132

M. Tech Scholar
Dept. of Mech. Engg.
NIT SILCHAR
Phone: 07086831330 Email: 15-22-303@student.nits.ac.in

b Dr. A.B. Deoghare
Assistant Professor
Dept. of Mech. Engg.
NIT SILCHAR
Phone: 08134977072
Email: abdeoghare@mech.nits.ac.in

c Dr. K.M. Pandey
Professor and Head of Department
Dept. of Mech. Engg.
NIT Silchar
Phone: 9435173130
Email: kmpandey@mech.nits.ac.in