Experimental assessment of the laryngeal jet effect on the fluid flow pattern within the trachea

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University of Toledo

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A Dissertation

Entitled

Experimental Assessment of the Laryngeal Jet Effect on the Fluid Flow Pattern within the Trachea

by

Mehran Salehi

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Doctor of Philosophy Degree in Engineering Science

Dr. Terry Ng, Committee Chair

Dr. Dan Olson, Committee Member

Dr. Abdollah Afjeh, Committee Member

Dr. Sorin Cioc, Committee Member

Dr. Jeffrey Hammersley, Committee Member

Dr. Ronald C. Scherer, Committee Member

The University of Toledo

August 2016
Drug aerosol inhalation is a modern way to combat lung diseases. It is also becoming the preferred route for insulin delivery, pain management, cancer therapy and nanotherapeutics. The specific airflow characteristics within the central human airways, however, have a major influence on aerosol delivery and particle deposition.

In this study the association of human inspiratory laryngeal function on the unique transitional turbulence this creates in the central airways and its association to particle deposition were investigated. The true vocal cords expand with increasing inspiratory flow rates and independently, with enlarging lung volumes. This creates a specific constriction to the inspiratory airstream and subsequent vortex formation below each vocal cord. The study compares triangular vocal cord shapes (physiologic) to rectangular (symmetric) shapes over a range of inspiratory directed flows. Disturbances below the laryngeal obstruction were visualized and the turbulence intensities as a function of distance below the vocal cord constriction in scale models under similitude flow conditions for a human trachea was also measured using laser Doppler anemometry in both primary (axial) and secondary (tangential) directions in a simplified larynx-trachea model.
The turbulence length scale and energy spectrum were also calculated using hot-wire anemometer data to determine the size distribution of eddies and the rate of energy decay along the trachea for different larynx geometries and Reynolds numbers. Both visualizations and measurements were made at Reynolds numbers between 1000 and 4000 which represent mild to severe breathing conditions. The larynx geometry is modeled by a constriction inside a straight tube. The group of constrictions consists of 2 rectangular and triangular shapes at apex angles of 45°, 60° and 75° degrees. The base circular tube was 5 cm in diameter (D) and 30 cm in length (L) (to keep the relative ratio of L/D=6). The inlet area created by the larynx constriction is approximately 10% and 50% of the tube area. Forty eight different combinations of aperture, area ratio, angle of the glottis and flow rates were visualized. Arrays of 72 measurements were made respectively at downstream planes of 1D and 3D from the larynx within the trachea. Results show that both the average and rms velocities change rapidly with respect to distance down the trachea. High levels of turbulence intensity at the anterior part indicate the potential region for particle deposition. The two vortices below the laryngeal constriction appear to interact, creating a transitional turbulence which propagates down the trachea, developing a structure to the turbulence which enhances the lateral flow energies and in turn enhances particle movements toward the tracheal walls (especially the posterior membranous tracheal wall) and subsequent particle capture. It appears that the locations of particle capture on the tracheal walls are at sites optimal for subsequent expectoration with cough.
This dissertation is dedicated to all my family
Acknowledgments

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Table of Contents

Abstract ........................................................................................................................................... iii

Acknowledgment ............................................................................................................................. vi

Table of Contents ............................................................................................................................ vii

List of Figures ................................................................................................................................. x

List of Tables .................................................................................................................................. xv

List of Nomenclature ......................................................................................................................... xvi

List of Abbreviations ......................................................................................................................... xvii

1. Introduction ................................................................................................................................ 1

2. Literature Review ......................................................................................................................... 7

   2.1 Airway Models ......................................................................................................................... 8

   2.2 Experimental Studies ............................................................................................................. 14

   2.3 Numerical Studies .................................................................................................................. 18

3. Experimental Procedures ......................................................................................................... 25

   3.1 Experimental Model ............................................................................................................. 25

   3.2 Experimental Set Up ............................................................................................................. 28

   3.3 Background Theory ............................................................................................................. 31

      3.3.1 Principles of Flow Visualization .................................................................................. 31

      3.3.2 Principles of Laser Doppler Anemometry .................................................................. 31
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3.3</td>
<td>Principles of Hot-wire Anemometry</td>
<td>34</td>
</tr>
<tr>
<td>3.3.4</td>
<td>Relationship Between the Hot-wire and Fluid Velocity</td>
<td>36</td>
</tr>
<tr>
<td>3.3.5</td>
<td>Hot-wire Probes</td>
<td>37</td>
</tr>
<tr>
<td>3.3.6</td>
<td>Hot-wire Calibration</td>
<td>38</td>
</tr>
<tr>
<td>3.3.7</td>
<td>Principles of Particle Image Velocimetry</td>
<td>38</td>
</tr>
<tr>
<td>3.3.8</td>
<td>Principles of the Energy Cascade and Kolmogorov Hypotheses</td>
<td>40</td>
</tr>
<tr>
<td>3.3.9</td>
<td>Instability</td>
<td>44</td>
</tr>
<tr>
<td>3.4</td>
<td>Testing Procedures</td>
<td>46</td>
</tr>
<tr>
<td>3.4.1</td>
<td>Flow Visualization</td>
<td>46</td>
</tr>
<tr>
<td>3.4.2</td>
<td>Laser Doppler Anemometer</td>
<td>46</td>
</tr>
<tr>
<td>3.4.3</td>
<td>Particle Image Velocimetry</td>
<td>48</td>
</tr>
<tr>
<td>3.4.4</td>
<td>PIV Calibration</td>
<td>50</td>
</tr>
<tr>
<td>3.4.5</td>
<td>Hot-wire Anemometer</td>
<td>51</td>
</tr>
<tr>
<td>3.5</td>
<td>Error Analysis</td>
<td>52</td>
</tr>
<tr>
<td>4.1</td>
<td>Introduction</td>
<td>55</td>
</tr>
<tr>
<td>4.2</td>
<td>Flow Visualization in the Trachea with Glottis Aperture of 10%</td>
<td>56</td>
</tr>
<tr>
<td>4.3</td>
<td>Flow Visualization in the Trachea with Glottis Aperture of 50%</td>
<td>58</td>
</tr>
<tr>
<td>4.4</td>
<td>Flow Visualization in the Traverse Cross Section</td>
<td>60</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Traverse Flow Visualization at 0.5D Downstream of the Flow</td>
<td>60</td>
</tr>
</tbody>
</table>

4. Results and Discussion

4.1 Introduction

4.2 Flow Visualization in the Trachea with Glottis Aperture of 10%

4.3 Flow Visualization in the Trachea with Glottis Aperture of 50%

4.4 Flow Visualization in the Traverse Cross Section

4.4.1 Traverse Flow Visualization at 0.5D Downstream of the Flow
4.4.2 Traverse Flow Visualization at 1D Downstream of the Flow ........................................ 61

4.5 LDA Results .................................................................................................................. 75

4.5.1 Axial Velocity Contour ......................................................................................... 75

4.5.2 Tangential Velocity Contour .................................................................................. 77

4.5.3 Axial Velocity Fluctuation ..................................................................................... 78

4.6 PIV Results .................................................................................................................. 94

4.7 Spectral Analysis ........................................................................................................ 99

5. Conclusions and Recommendation ............................................................................. 106

6. Appendix ....................................................................................................................... 109

References ...................................................................................................................... 132
List of Figures

Figure 1-1: The human airways [4]

Figure 2-1: The upper respiratory tract for a human subject: top view of the mouth (A), inside oblique view of A cutting through A along the white line (B), front view of the CT-based human airway (C), oblique view of C (D) [19].

Figure 2-2: The idealized extra-thoracic airway (ETA) seen in a side view (left) and back view (right) [20].

Figure 2-3: Determination of the vocal fold geometry: (a) detailed frontal view of the plaster cast of the glottal channel, (b) the 3D computer model, (c) location of the mid-membranous coronal section, (d) the 2D geometry of that coronal section, (e) the right part of the coronal section corresponding to the shape of the right vocal fold, (f) the regression curve representing the best mathematical fit of the glottal channel shape (color online) [17].

Figure 2-4: Schematic of the design of the vocal fold pieces for model M5 with design equations. Values for Ro and T are human values rather than model values [18].

Figure 2-5: PIV results for flow-rate on coronal plane in pharynx, larynx, and trachea (UP) and average velocity distribution for expiration (DOWN LEFT) and inspiration (DOWN RIGHT)[46]

Figure 2-6: Contours of plane-normal velocity with in-plane velocity vectors on successive y–z slices [45].

Figure 2-7: Particle trajectories and cross-sectional profiles for 4-μm aerosols at a constant inhalation flow rate of 15 l/min in the TB models with the laryngeal approximation (A) and without the larynx (B) [65].

Figure 2-8: Velocity vectors (up right ) and mean velocity magnitude profiles(down) [52].

Figure 3-1: Rectangular and triangular inlet shapes at a) 10% opening area and b) 50% opening area.

Figure 3-2: Different attachment angles of glottal aperture-a) 45° b) 60° c) 75°.

Figure 3-3: Experimental apparatus

Figure 3-4: Different experiment components: 1) Round glass tube, 2) Pressure transducer, 3) Argon-ion laser, 4) Laser Doppler Anemometer, 5) Digital camera 6) Hot-wire probe, 7) Flow straightness, 8) Glottic aperture model
Figure 3-5: The basics of LDA[66]

Figure 3-6: Removing directional ambiguity with frequency shifting[66]

Figure 3-7: Constant temperature circuit

Figure 3-8: Schematic PIV experiment

Figure 3-9: Eddy sizes showing the various length scales and ranges[69]

Figure 3-10: Instability of an axisymmetric jet; A laminar stream of air flows from a circular tube at Reynolds number 10,000 and is made visible by a smoke wire. The edge of the jet develops axisymmetric oscillations, rolls up into vortex rings, and then abruptly becomes turbulent[70]

Figure 3-11: (A) 1D and 3D planes location (B and C) triangular and rectangular larynx.(D) distribution of measurement points at each axial position within the tube

Figure 3-12: PIV experiment set up

Figure 3-13: Hot wire measurement points

Figure 3-14: Mean and margin of error for axial and traverse velocities at 50% opening triangular model and Re 2000

Figure 4-1: Flow visualization for 10% opening area and Re 1000 at different attachment angles and inlet aperture shapes

Figure 4-2: Flow visualization for 10% opening area and Re 2000 at different attachment angles and inlet aperture shapes

Figure 4-3: Flow visualization for 10% opening area and Re 4000 at different attachment angles and inlet aperture shapes

Figure 4-4: Flow visualization for 50% opening area and Re 1000 at different attachment angles and inlet aperture shapes

Figure 4-5: Flow visualization for 50% opening area and Re 2000 at different attachment angles and inlet aperture shapes

Figure 4-6: Flow visualization for 50% opening area and Re 4000 at different attachment angles and inlet aperture shapes

Figure 4-7: Traverse flow visualization at 0.5D downstream for 50% opening area and Re 1000 at different attachment angles and inlet aperture shapes
Figure 4-8: Traverse flow visualization at 0.5D downstream for 50% opening area and Re 2000 at different attachment angles and inlet aperture shapes

Figure 4-9: Traverse flow visualization at 0.5D downstream for 50% opening area and Re 4000 at different attachment angles and inlet aperture shapes

Figure 4-10: Traverse flow visualization at 1D downstream for 50% opening area and Re 1000 at different attachment angles and inlet aperture shapes

Figure 4-11: Traverse flow visualization at 1D downstream for 50% opening area and Re 2000 at different attachment angles and inlet aperture shapes

Figure 4-12: Traverse flow visualization at 1D downstream for 50% opening area and Re 4000 at different attachment angles and inlet aperture shapes

Figure 4-13: LDA results for 50% opening triangular inlet model and Re 2000 at each point within 1D cross section

Figure 4-14: Contour of axial velocity (u) at Re 2000(45º Attachment angle)

Figure 4-15: Contour of axial velocity (u) at Re 4000(45º Attachment angle)

Figure 4-16: Contour of axial velocity (u) at Re 2000(50% Opening)

Figure 4-17: Contour of axial velocity (u) at Re 4000(50% Opening)

Figure 4-18: Contour of tangential velocity (v) at Re 2000(45º Attachment angle)

Figure 4-19: Contour of tangential velocity (v) at Re 4000(45º Attachment angle)

Figure 4-20: Contour of tangential velocity (v) at Re 2000(50% opening)

Figure 4-21: Contour of tangential velocity (v) at Re 4000(50% Opening)

Figure 4-22: Contour of axial velocity standard deviation at Re 2000 and 45º attachment angle

Figure 4-23: Contour of axial velocity standard deviation at Re 4000 and 45º attachment angle

Figure 4-24: Contour of axial velocity standard deviation at Re 2000 and 50% Opening

Figure 4-25: Contour of axial velocity standard deviation at Re 4000 and 50% Opening

Figure 4-26: 50% opening, triangular inlet shape, Re 2000,45º attachment angle

Figure 4-27: 50% opening, triangular inlet shape, Re 4000,45º attachment angle

Figure 4-28: 50% opening, rectangular inlet shape, Re 2000, 45º attachment angle
Figure 4-29: 50% opening, rectangular inlet shape, Re 4000, 45° attachment angle
Figure 4-30: 50% opening, salt particle, Re 2000, 45° attachment, AP view
Figure 4-31: 50% opening, salt particle, Re 4000, 45° attachment, AP view
Figure 4-32: Power spectrum graphs for 10% opening triangular inlet model at Re 2000
Figure 4-33: Power spectrum graphs for 50% triangular inlet opening model at Re 4000
Figure 4-34: Power spectrum graphs for 10% rectangular inlet opening model at Re 2000
Figure 4-35: Power spectrum graphs for 50% rectangular inlet opening model at Re 4000
Figure 6-1: High speed camera used for visualization experiment (OLYMPUS)
Figure 6-2: Laser Doppler Anemometer
Figure 6-3: IFA 100 system intelligent flow analyzer used for hot-wires measurement
Figure 6-4: Pitot static probe and digital manometer used for hot-wire calibration
Figure 6-5: Hot-wire Calibration set up
Figure 6-6: Contour of tangential velocity standard deviation at Re 2000 and 45° attachment angle
Figure 6-7: Contour of tangential velocity standard deviation at Re 4000 and 45° attachment angle
Figure 6-8: Contour of tangential velocity standard deviation at Re 2000 (50% Opening)
Figure 6-9: Contour of tangential velocity standard deviation at Re 4000 (50% Opening)
Figure 6-10: 50% opening, salt particles, Re 2000, 60° attachment angle
Figure 6-11: 50% opening, salt particles, Re 4000, 60° attachment angle
Figure 6-12: 50% opening, salt particles, Re 2000, 75° attachment angle
Figure 6-13: 50% opening, salt particles, Re 4000, 75° attachment angle
Figure 6-14: 50% opening, olive oil particles, Re 2000, 60° attachment angle
Figure 6-15: 50% opening, olive oil particles, Re 4000, 60° attachment angle
Figure 6-16: 50% opening, olive oil particles, Re 2000, 75° attachment angle
Figure 6-17: 50% opening, olive oil particles, Re 4000, 75° attachment angle
Figure 6-18: Power spectrum graphs at point P0, Re 2000
Figure 6-19: Power spectrum graphs at point P1, Re 2000
Figure 6-20: Power spectrum graphs at point P2, Re 2000
Figure 6-21: Power spectrum graphs at point P3, Re 2000
Figure 6-22: Power spectrum graphs at point P4, Re 2000

Figure 6-23: Power spectrum comparison of different inlet shapes at 10% opening, Re 2000 and 45º attachment angle

Figure 6-24: Power spectrum comparison of different inlet shapes at 50% opening, Re 4000 and 45º attachment angle
List of Tables

Table 6-1: Different Combinations of shape, opening area, attachment angle and Reynolds numbers of the larynx trachea model used for visualizations.
Nomenclature

\begin{itemize}
  \item \( D \)  Diameter
  \item \( e \)  Voltage
  \item \( E \)  energy
  \item \( f \)  Frequency
  \item \( f_D \)  Doppler frequency
  \item \( k \)  Wave number
  \item \( k_a \)  Thermal conductivity
  \item \( l \)  Length
  \item \( R \)  resistance
  \item \( U \)  axial velocity
  \item \( Z \)  Axial direction
  \item \( v \)  Tangential velocity
  \item \( Re \)  Reynolds number
  \item \( Nu \)  Nusselt number
  \item \( \varepsilon \)  Energy dissipation
  \item \( \lambda \)  Wave length
  \item \( \eta \)  Kolmogorov length scale
  \item \( \mu \)  microns
\end{itemize}
### List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP</td>
<td>Anterior-Posterior</td>
</tr>
<tr>
<td>CCD</td>
<td>Charged-Coupled Device</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CT</td>
<td>Computed Tomography</td>
</tr>
<tr>
<td>cm</td>
<td>centimeter</td>
</tr>
<tr>
<td>ETA</td>
<td>Extra-Thoracic Airway</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transport</td>
</tr>
<tr>
<td>HUA</td>
<td>Human Upper Airway</td>
</tr>
<tr>
<td>HWA</td>
<td>Hot Wire Anemometer</td>
</tr>
<tr>
<td>LDA</td>
<td>Laser Doppler Anemometer</td>
</tr>
<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
</tr>
<tr>
<td>mm</td>
<td>Millimeter</td>
</tr>
<tr>
<td>PIV</td>
<td>Particle Image Velocimetry</td>
</tr>
<tr>
<td>RANS</td>
<td>Reynolds Average Navier Stokes</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>Rec</td>
<td>Rectangular</td>
</tr>
<tr>
<td>TIX</td>
<td>Axial Turbulence Intensity</td>
</tr>
<tr>
<td>TIY</td>
<td>Traverse Turbulence Intensity</td>
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<tr>
<td>Tri</td>
<td>Triangular</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

The human respiratory system consists of a set of organs and tissues that get oxygen from the air and send it into the lungs [1]. A schematic view of the human respiratory system with all the parts and functions is shown in Figure 1-1. The specific bronchial air flow characteristics of respiration must accommodate oxygen delivery to the blood from a relatively low environmental oxygen concentration. Evolution has created a bronchial branching system to uniformly deliver oxygen to a huge (100 m²) and thin (5 micron) alveolar membrane separating inspired air to blood [2]. In fact, this membrane was not fully recognized until 1950’s when electron microscopy was utilized. This exposure allows other components of inspirational air to potentially gain access to the body’s internal milieu [3].

Several organs of the respiratory system are responsible for the process of breathing. These organs are nose, pharynx, larynx, trachea, bronchi, and lungs which work together to allow gas exchange to occur at the cellular level. Air breathed in through the nose and mouth enters into the lungs at a continual pace to provide a new supply of oxygen the body needs to work properly. Upon passage through the upper (nasal, pharyngeal and laryngeal orifices) and central (trachea and large bronchi) airways, environmental air is conditioned to match the highly specific state of internal body. The inhaled air is warmed to body temperature (37°C) and humidified to 100% saturation, as not to cause dryness of the sensitive membranes that form the airways and alveoli in the lung. The inhaled air is also scrubbed of potentially harmful gases and filtered of particles,
which could chemically or biologically harm the membranes. These air modifying tasks are accomplished by the intricate convection currents within the airways repeatedly exposing the gas to the surface lining of the airways where warming, humidification, and chemical absorption (or modification) take place. The scrubbing is accomplished by convective impaction of particles along the mucus lining of the airways and by settling during repeated convective decelerations all this with minimal viscous energy expenditure.

The nose is the primary upper respiratory organ in which air enters into and exits from the body. Cilia and mucus line the nasal cavity and traps bacteria and foreign particles that enter in through the nose. In addition, air that passes through the nasal cavity is humidified and moistened. Air then passes through pharynx that is a cavity at the rear of the mouth. From the pharynx, air enters into the larynx. The larynx is part of the upper respiratory tract that has two main functions: making a constricted passageway for air to enter into the lungs through trachea (which is what we are going to study), and a source of vocalization. The larynx is made up of the hyoid bone and cartilage, which helps regulate the flow of air. The epiglottis is a flap-like cartilage structure contained in the larynx that protects the trachea against food aspiration. The trachea is made of c-shaped ringed cartilages that divides into the right and left bronchus at its downstream. The bronchuses also branch into lesser bronchioles. The branching process is continued to around, on average, thirteen times, increasing the number of tubes from four to about 45,000. The bronchioles finally end in air sacs called alveoli. The average adult has about 600 million alveoli, which are tiny grape-like sacs at the end of the respiratory tree.
Recently the inhalation of drug aerosols has become a modern pathway to combat lung diseases. This novel pathway leads to potentially rapid, nondestructive and noninvasive drug transfer into the systemic blood stream because of the large lung surface area involved.

The motivation for this study comes from the biological observations that the human airway is a highly efficient filter of inhaled particles plus scrubber of soluble gases. In addition, it has been repeatedly noted that the deposition and removal of inhaled particles are also highly coordinated in that the larger particles are predominantly removed from the inlet in the larger and more robust central airways and the smaller particles deposited and removed from the sequence of smaller (and delicate) airways as they sequence through sixteen branches. It further suggests that the soluble gases are predominantly scrubbed from the inlet along the liquid lining surfaces of the smaller airways.
The expectoration of these potential toxics also appears optimized via evolutionary changes of the detailed structure of both large and small airways.

The function of the larynx is obvious to clinicians when examining the airways (such as bronchoscopy). During inspiration, the aperture of the glottis expands with the inspiratory flow and also with expansion of lung volume. One presumes this function coupled to the important biological need of filtering toxic particles from the inlet even though the more constricted glottis adds to the effort to breathe. In addition, the structure of the glottis is complex being a “V” shapes structure (rather than parallel constricition). And the central airways are also complex in that the anterior structure of the trachea (and other central airways) is rigid with cartilages while the posterior structure, in line with the wide opening “V” of the glottis, is not rigid but a flat soft membrane. Thus presenting materials deposited in this specific location surface close to the exhaling tracheal air jet during cough or expectoration though the larynx pharynx and mouth. Although these observations may seem reasonable, these potential biological mechanisms have never been fully investigated.

Thus this biological filter (and scrubber) is assumed to be highly efficient due to the effects of evolution and the critical biological function. Such phenomenon may be a feature applicable to industry. A simple “larynx” in an industrial smoke stack may allow collection and disposal of particles and soluble gases (such as carbon dioxide) in the effluent. However, an understanding of this biological process would be necessary before applying such principles to industry. In addition, full understanding of this process may also allow use of the biological process for either focusing the deposition of therapeutic particles to specific parts of branchial airways or conveyance a therapeutic compound directly to the systemic blood.
As mentioned earlier, the deposition and transport of aerosol particles into the human lung is greatly influenced by the convective patterns of the inspired air in the upper and central airways. Therefore understanding the specific airflow characteristics within the central human airways is of fundamental importance. Physiological studies show that changes of glottal shape can greatly affect the overall deposition phenomenon [5, 6]. In the lung, if we consider the glottis as a nozzle, the flow behavior is strictly depending on the inlet shape and the angle of the nozzle [7]. From an aerodynamic viewpoint, the most significant passage is the one limited by the glottis aperture which is expected to produce a laryngeal jet, with the potential for associated phenomena like eddies and reverse flows [8-10]. Therefore in this study the effect of the throat and mouth to the flow is ignored and it is focused on the glottis and trachea region only.

The main objective of this study is to investigate effects of the larynx on the flow characteristics and therefore on the particle deposition process within the trachea. Different combinations of larynx shapes, opening and attachment angle to the trachea are studied at variety of Reynolds number. The flows are visualized and measured in both axial and tangential directions. As such the research effort not only attempts to observe and predict the airflow though the complex laryngeal and tracheal airway but attempts to understand the physics of this unique physiological phenomenon. We will study the flows through the characteristics biological structure and compare this to other geometrical orientations (non-biological) of the structures and flows. The protocol of this study consists of four chapters:

In chapter 2, a literature review on the effect of the larynx at the respiratory flow is presented. Velocity profiles at different human airway models and its association to particle deposition is discussed. The results reviewed include both previous experimental and numerical studies.
Chapter 3 provides a discussion on the experimental tools that are going to be used. Pressure sensors and calibration process, phase doppler anemometry and hot-wire anemometer which are employed in the experiments were be briefly explained.

Chapter 4 presents the results and discussion of the experiments. Each experiment results are explained in separate section.

Chapter 5 provides some possible recommendations for future research.
Chapter 2

Literature Review

As mentioned earlier, the human airway is a novel pathway for drug aerosol delivery. Such delivery directly to the systemic blood avoids adsorption alterations and potential alterations in the liver. As such drug compounds can be directly conveyed to the systemic organs. But several physical and anatomical factors can largely influence treatment efficiency. In particular, human upper airway (HUA) generally acts like a highly efficient natural filter. Although this phenomenon is very useful for purifying the breathing air stream before it reaches the lung, it limits the medical aerosol access to the body. More specifically, the larynx is the narrowest aperture within the airway and exerts a critical role regarding the motion of the inhaled aerosol because it creates a flow regime in the central airways which promotes particle deposition. This anatomical feature at the trachea entrance causes a jet like flow with cavitation and vortices within this region. Several studies focus to understand the behavior of particle transport within human airway. These studies can be divided into two types of numerical and experimental ones. Since studying flow characteristics is difficult within humans, most experiments are done in casts made from cadavers. Therefore the amount of the experimental studies in this area is very limited. For numerical studies, several airways models are suggested and Navier Stokes equations are employed to simulate the flow within these geometries. However, the flow instability which is the key feature of particle filtration within the airway is poorly described by numerical solutions.
2.1 Airway Models

As it was shown in figure 1-1, the human airway consists of many different areas with different cross sections and constrictions that each imparts influence on the flow and biological functions. Therefore the first step for studying this region is to define the geometry of the airway. Different models with different degrees of complexity and purpose of the study are proposed [11-13]. In 1963, Weibel [14] introduced two airway models based on measurements from several lung casts. These models have been used extensively in the literature, especially the symmetric model known as “Weibel’s symmetrical model A”. Weibel assumed a completely bifurcating system down to the terminal bronchiole. This assumption overestimated the number of structure at each order. Some studies have also been done on cadaver-based models [15]. But, recently CT-scans or MRI data are used for generating realistic lung models for either computational or experimental analysis [16]. Figure 2-1 shows the upper respiratory tract model obtained from CT-scan data. These models are then usually simplified to some extent depending on their study focus area. Figure 2-2 is the idealized extra-thoracic airway which is commonly used for computational and experimental studies.

In this literature review, the main focus is on the laryngeal jet and its effect on the flow field and particle deposition downstream of the trachea. Therefore related studies on oral cavities or vocal fold functions during phonation are not discussed here.

Most of the proposed laryngeal models are designed for phonation experiments. Sidolf et al. [17] obtained detailed measurements on the geometry of the human vocal folds and the glottal channel in phonatory position (Figure 2-3). However, this model can be used for inhalation experiments with the assumption of constant laryngeal width.
Sherer et al. [18] also suggested a larynx model (M5) for measuring the pressure distribution along the surface of the vocal folds. His model was 7.5 times larger than the real geometry to permit the establishment of an array of pressure taps. Figure 2-4 shows M5 larynx model.
Figure 2-1: The upper respiratory tract for a human subject: top view of the mouth (A), inside oblique view of A cutting through A along the white line (B), front view of the CT-based human airway (C), oblique view of C (D) [19].
Figure 2-2: The idealized extra-thoracic airway (ETA) seen in a side view (left) and back view (right) [20].
Figure 2-3: Determination of the vocal fold geometry: (a) detailed frontal view of the plaster cast of the glottal channel, (b) the 3D computer model, (c) location of the mid-membranous coronal section, (d) the 2D geometry of that coronal section, (e) the right part of the coronal section corresponding to the shape of the right vocal fold, (f) the regression curve representing the best mathematical fit of the glottal channel shape (color online) [17].
Figure 2-4: Schematic of the design of the vocal fold pieces for model M5 with design equations. Values for $R_o$ and $T$ are human values rather than model values [18].
2.2 Experimental Studies

Recently most of the studies have been focused on computational modeling and the number of the experiments done on inhalation process is very limited in the literature. Early studies that dealt with the transport of air in the human lung were focused on the overall pressure drop between the mouth and pleura[21], overall resistance to the breathing [22], and the mechanics of regional ventilation [23]. However, very little attention had been focused on the flow characteristics in the trachea and its filtration effect. Some early experimental studies of deposition in the upper airway region did not include the larynx in their model [24-26]. Therefore, their findings are insufficient since larynx effects and its subsequent influence on the tracheal flows are very dominant. However, most recent studies have included laryngeal models and therefore have highlighted the resulting effects on central airway particle deposition [27-32]. The problem with all the published laryngeal models is that the detailed geometry of the larynx and (specifically) the true vocal folds have profound effects on the vortex development. The subsequent vertical interactions and large scale high energy turbulence development is uniquely related to the very detailed glottal geometries. These geometries are poorly depicted by radiological (CAT scan) measures. Casting of these airways can give a more detailed measure but the technique of casting such tissue lumens requires extensive incite and efforts; this has not been accomplished in previous studies. An equally important issue limiting the understanding of the laryngeal tracheal function is that the laryngeal glottal opening changes with both inspiratory flow rate and (independently) with lung volume. Although this laryngeal inspiratory function is likely a potential mechanism protecting the lung from toxic exposures (and thus has profound evolutionary influence) this function has been rarely studied.
Different ranges of ultrafine, fine and micrometer aerosols have been tested within laryngeal models [33, 34]. Few studies have also considered the effect of particle deposition with variable larynx at different flow rates [31, 35]. A majority of previous studies that have included a laryngeal model focused on propagation of flow features into the tracheobronchial geometry [15], as well as deposition within and downstream of the larynx [27].

Schlesinger and Lippmann [32] described the propagation of the larynx-induced disturbances. This work was later done in more detail by Martonen et al. [36] and Corcoran [15]. They used laser Doppler velocimetry to characterize the effects of the laryngeal jet on flow dynamics in the trachea and reported significant recirculation in the anterior portion of the trachea within one or more diameters downstream of the larynx. They also reported that the particle deposition decreases at higher Reynolds numbers.

Corcoran and Chigier [27] extended Martonen’s work by adding the main carina and the main bronchi to their airway model. As a result of this modification to their model, they reported that the observed region of reverse flow downstream of the larynx shifted from the anterior side of the trachea to the left side. Therefore, the laryngeal jet was strongly skewed to the right side of the trachea.

Chan et al. [37] and Martonen [30] showed that the deposition of fine and micrometer particles within the larynx is primarily controlled by inertial impaction and can be approximated using a Stokes number correlation that incorporates the minimum glottal diameter.

Schlesinger and Lippmann [32] added a laryngeal model upstream of a trachea replica. They compared the result with their previous study which was without any larynx and reported that the larynx created more asymmetric deposition along the walls.
Lippmann and Altshuler [29] examined the deposition of 9 µm particles in two casts, one with and the other without a laryngeal model. They found that the deposition increased by a factor of 10 for the model with the larynx included. Similarly, Martonen et al. [38] reported that the localized deposition of micro particles was greatest in the lobar-to-segmental bifurcation and lowest at the main carinal ridge at the model with the larynx.

Jayaraju et al. [39] investigated the axial dispersive effect of the upper airway structure on aerosols. They did aerosol bolus experiments on a hollow cast of a realistic upper airway. They also conducted CFD simulations to compare the results with the experiment. They showed that 50 ml boluses dispersed with a half width ranging from 80 to 90 ml at the model exit for different flow rates.

Martonen and Lowe [40] suggested that the larynx can influence the downstream deposition through direct impaction due to the laryngeal jet and the creation of more turbulence which may lead to more particle deposition. They proposed that if the turbulence level is high enough, the particles may have sufficient momentum to cross the near wall viscous sublayer and reach the wall where they can be absorbed or deposited.

Corcoran and Chigier [27] suggested that flow recirculation created by the larynx is possibly another mechanism that can cause more particle deposition. Particles trapped inside these regions would tangentially turn and go nearer to the walls and if they have enough momentum they might be able to reach the wall.

Johnstone et al. [41] studied the flow inside an idealized human upper airway using single and X-hot wire anemometry (HWA). They measured the mean and RMS axial velocity fields in the central plane of the model. Regions with high levels of turbulence intensity were spotted at different flow rates. However they did not change the larynx opening area for different flow rates.
Grosse et al. [42] tried to investigate the flow field that evolves during normal breathing. They focused on the study of steady and oscillatory flow in the first bifurcation of a three dimensional realistic lung model using the PIV technique. The results indicated that the flow within the upper airway is highly three dimensional due to the asymmetric geometry of the realistic lung model. However, the weakness of their study is that the larynx constriction is not included to their model.

Soodt et al. [43] used PIV to measure the flow field velocity. They investigated the spatial and temporal development of the flow in a realistic human lung model. Their focus was at lower branches of the airway path. The results showed a U-shaped high speed velocity profile inside the left primary bronchi. Both primary bronchi contained one vortex pair also.

Scheinher et al. [44] conducted an in vivo experiment on two healthy male and female volunteers. They recorded their breathing condition at two normal and forced breathing rates. Laryngo- fiberscopic investigations were made using a flexible nasofiberscope with a continuous cold light source and a color CCD camera. Laryngeal images were captured with a camera frame rate of 25 frames/s and an image resolution of 768x288 pixels. They reported the glottal area change with respect to different flow rates.

Banko et al. [45] investigated the steady inspiratory flow through an anatomically accurate model of the human upper airway. They used the magnetic resonance velocimetry technique to obtain the three components of mean velocity. They reported a strong single sided stream swirl in the trachea which continued until the first bifurcation. However, they ignored the effect of larynx opening area in their experiment.
2.3 Numerical Studies

In addition to experimental studies, many numerical investigations have also been done to highlight the effects of the larynx on respiratory flow fields and particle deposition. In numerical studies, the flow field is first calculated using CFD tools while a particle tracking method is used for determining deposition rate. Reynolds average Navier Stokes (RANS) approaches and eddy interaction models (EIM) are found to be the most widely used CFD and particle tracking tools, respectively.

Katz et al. [47, 48] simulated the movement of microscopic particles within a cast-base laryngeal model. They reported the turbulence caused by the larynx as the dominant mechanism for particle deposition.

Martonen et al. [49] extended Katz simulation to three dimensionals and evaluated the filtering capability of the larynx.

Florian et al. [20] studied the transport and deposition of quasi-monodisperse inside an ideal extrathoracic airway model by numerical simulation for particle sizes range between (14.5 nm<d_m<52 nm) at three different flow rates. They showed that decreasing flow rate and size particle increases the particle deposition.

Takano et al. [50] developed a realistic model of the human larynx and found good agreement between total micro particle deposition predictions and existing correlation data. Xi and Longest [51] designed a complete model based on CT images. Their results were in good agreement with the experiment done by Cheng et al. They could show the importance of the laryngeal shape on the velocity profile and particle deposition within the trachea.
Lin et al. [19] recently developed a highly realistic model of the mouth-throat and TB airways based on CT images of an adult human. They observed that the laryngeal jet was at the posterior side of the trachea.

Ball et al. [52] simulated the flow inside a modelled human extra-thoracic airway. They used this geometry to evaluate several turbulence model performances for predicting the flow patterns inside a complex geometry. They reported good agreement between their simulation data and some of the previous experimental ones including Heenan PIV experiment.

Srivastav et al. [53] focused their study on the effect of tumors present in the trachea on the airflow pattern and aerosol drug deposition. The inspiratory flow was numerically solved using k-ε turbulence model. They presented velocity contours, wall shear stress and deposition efficiency of aerosol.

In summary, most of the studies have reported the significant effects of the larynx on the downstream flow fields and particle deposition [19, 54-57]. However, there are still many studies that neglect the larynx in their simulation [58-62]. Neglecting the larynx may be a justified assumption if the purpose of the study is to isolate a specific variable of interest. For example, Longest et al [59] attempted to study the influence of bronchoconstriction on deposition by excluding laryngeal effects in his model. Some studies have assumed that laryngeal effects are largely dissipated when the third respiratory generation is reached [62-64]. However, the extent to which laryngeal-induced flow field effects penetrate into the upper TB airways is still not well understood. In addition, it is not known what effects these flow features have on particle deposition for aerosol sizes ranging from nanometer through micrometer scales.

Figures 2-5 through 2-8 show some of the experimental and numerical results selected from the discussed literature. Note that to the best of the author knowledge, there has been no
comprehensive experimental report that highlights the different effects of the larynx constriction shape, attachment angle to the larynx and its opening rate change according to the flow rate. Understanding this highly effective natural filtration process (created by evolution) may also help us to design particle removal nozzles that are able to passively clean the main stream from different micro size industrial pollutants.
Figure 2-5: PIV results for flow-rate on coronal plane in pharynx, larynx, and trachea (UP) and Average velocity distribution for expiration (DOWN LEFT) and inspiration (DOWN RIGHT)[46]
Figure 2-6: Contours of plane-normal velocity with in-plane velocity vectors on successive $y$–$z$ slices [45].
Figure 2-7: Particle trajectories and cross-sectional profiles for 4-μm aerosols at a constant inhalation flow rate of 15 l/min in the TB models with the laryngeal approximation (A) and without the larynx (B) [65].
Figure 2-8: Velocity vectors (up right) and mean velocity magnitude profiles (down) [52].
Chapter 3

Experimental Procedure

3.1 Experimental Model

In the present study several distinct features that may affect the characteristics of glottis induced turbulence were investigated. These features were emphasized by idealizing the geometry of the airway model discussed in previous chapters. The most consequential features were the distinct triangular (biological) shape of the glottal aperture versus rectangular (symmetric) one, its opening area relative to the flow rates, and its attachment angle to the trachea. The experiment geometry therefore consists of a straight optically clear round acrylic tube that represents the geometry of an idealized human trachea. Different inlets consisting of two rectangular and triangular shapes with apex angles of 45°, 60° and 75°, and opening cross section ratio of 10% and 50%. The inlets are designed according to the M5 model explained in chapter 2. Twelve different models were constructed for the experiments. All larynx inlet geometries were designed using ANSYS and printed using a 3D printer. The printed model surface is then sanded using a fine sand paper to create a smooth surface. Finally, the model surface was painted black to minimize light reflection during visualization. The airway model scaled upward to 2.5 that of a typical human adult airway to improve flow visualization and measurements accessibility. The pipe was therefore 5 cm in inner diameter and 30 cm long. Figures 3-1 and 3-2 show the larynx model.
Figure 3-1: Rectangular and triangular inlet shapes at a) 10% opening area and b) 50% opening area.
Figure 3-2: Different attachment angles of glottal aperture - a) 45° b) 60° c) 75°.
3.2 Experimental Set Up

Figure 3-3 shows the schematic view of the experiment set up. Each of the flow visualizations, LDA and Hot-wire measurements requires its own specific arrangements.

The air coming from a pressure compressor passes through the TSI 6-jet atomizer and then enters a cylindrical stagnation chamber. The atomized olive oil was used as the seeding particles for the LDA measurements. The olive oil was reduced to particles of about 0.8 µm in diameter using a jet atomizer. It was assumed that the seeded particles would closely follow the air. The jet atomizer used in this experiment is Model 9306, produced by TSI. The flow then passes through a nickel based alloy honeycomb which is placed inside the pathway to remove large-scale disturbances before entering the test section. Finally a conical nozzle connects the stagnation chamber to the test section glass tube. All these measures are to make sure that the flow enters the test section with the minimum initial turbulence level so that any turbulence intensity that is going to be measured later on inside the model would only be from the larynx effect. A Pressure transducer is placed between the stagnation chamber and nozzle outlet to serve as a flow rate indicator. The flow rate of the air into the model was controlled using a pressure regulator. The flow rate was monitored using a mass flow meter and a LabView computer program. An argon-ion laser was used for both visualization and LDA experiments. The beam position and direction can be changed using optical mirrors and precision traverse. The precision traverse allowed the LDA to move in increments as small as 0.025 mm. The LDA output data were analyzed using FIND Data Acquisition software from TST, Inc. Figure 3-4 shows the positions of the laser, camera hotwire and test sections.
Figure 3-3: Experimental apparatus
Figure 3-4: Different experiment components: 1) Round glass tube, 2) Pressure transducer, 3) Argon-ion laser, 4) Laser Doppler Anemometer, 5) Digital camera 6) Hot-wire probe, 7) Flow straightness, 8) Glottic aperture model
3.3 Background Theory

3.3.1 Principles of Flow Visualization

Visual inspection is very helpful in understanding the pattern produced by a physical process. It can help to get an idea of the whole development of the flow. However, the motion of most fluids like air remains invisible to the human eye because of their transparency. Therefore in order to identify the motion of the fluid, a special technique is needed to make the flow visible. These methods are called flow visualization techniques and have had an important role in understanding fluid problems.

One of the earliest and yet the most powerful flow measurement technique is to visualize the flow by recording the path of marker particles introduced into a flow. This method can give an overall qualitative data to the experimenter. Such studies provide general information about the flow field and it is mostly used to detect the large scale structure of turbulence. Both hot-wire and LDA provides information at only one discrete point at a time while flow visualization can give the overall pattern of the flow along a whole plane at a time.

In this technique the flow field is first seeded with some particles. These particles should be small enough to follow the flow (i.e. be naturally buoyant). Then a laser is expanded through a cylindrical lens to produce a laser sheet that is directed to the test section. The whole process is then recorded with a high speed camera. The recorded frames can then be analyzed in slower motion to visually examine the flow behavior.

3.3.2 Principles of Laser Doppler Anemometry

The concept of a Doppler shift is familiar to us from the downshift in pitch that we hear as a siren moves towards and then away from us [66]. The faster the moving sources of sound, the
greater the shift in frequency. This effect is also observed with light. The reflected light from a moving object is shifted by an amount proportional to the speed of the object. Therefore the speed of the object can be measured by observing the frequency shift. This is the basics of how LDA works.

In LDA, a photomultiplier tube (PMT), which generates a current in proportion to absorbed photon energy, detects the scattered light and then amplifies that current. The difference between the scattered light and incident frequencies is called Doppler shift.

The Doppler Shift, $f_D$, depends on the speed, $V$, direction of the particle motion, the light wavelength, $\lambda$, and the orientation of the observer. The relation between these factors is as follows:

$$f_D = \frac{2V}{\lambda} \cos \beta \sin \frac{\alpha}{2}$$

(3.1)

Therefore, by measuring the Doppler shift, the velocity can be measured. To improve the estimate of $f_D$, a method with two beams has been developed. In this method, the incident beam is split into two beams with equal intensity. These beams are then directed to intersect to create the measurement volume. Particles that pass through the measurement volume scatter light from both sides.
beams. Since the orientation of the two beams relative to the photodetector and particles are different, each beam has its own frequency shift of the scattered light.

Assume $f_{D1}$ and $f_{D2}$ as the Doppler shifts of the two scattered beams. Therefore the scattered beams will have frequencies of $f + f_{D1}$ and $f + f_{D2}$. Since both $f_{D1}$ and $f_{D2}$ are much smaller than $f$, the scattered light waves have almost equal frequency. The superposition of such two waves creates beats. The beat frequency is one half of the difference between the two original frequencies. Thus, the resulting signal has a beat frequency, $|f_{D1} - f_{D2}|/2$. Therefore the beat frequency will be the Doppler frequency we seek. Using equation 3-3 we have:

$$\frac{|f_{D1} - f_{D2}|}{2} = \frac{2V}{\lambda} \cos\left(\frac{\theta}{4}\right) \sin\left(\frac{\theta}{4}\right) = \frac{2V}{\lambda} \sin\left(\frac{\theta}{2}\right) \quad (3.2)$$

Equation 3-2 shows that the Doppler shift depends only on the velocity magnitude and not its direction. Moreover, both positive and negative values of $V$ produce the same Doppler frequency. To solve this directional ambiguity, the frequency of one of the incoming beams is shifted by a known value, $f_s$. This causes the fringe pattern to move at speed $V_s=f_d$ toward the incoming unshifted beam. Therefore the frequency recorded by the photodetector is now as follows:

$$f_d = |f_s + \frac{2V}{\lambda} \sin\left(\frac{\theta}{2}\right)| \quad (3.3)$$

Therefore the velocity direction is reflected in $f_d$. That is, a particle moving through the fringes at speed $V$ shifts the detected frequency up (positive $V$) or down (negative $V$) from $f_s$. To avoid directional ambiguity, $f_s > |\frac{2V}{\lambda} \sin\left(\frac{\theta}{2}\right)|$. Therefore depending on the flow condition, different frequency shifts might be needed.
To measure two velocity components, two extra beams can be added to the optics in a plane perpendicular to the first beams.

The LDA system has several advantages. It does not disturb the flow being measured (like hotwire or pitot static tube does) and it can give accurate measurements in unsteady and turbulent flows where the velocity is fluctuating with time. Among its disadvantages however are expensive equipment, the need for a transparent flow through which the light beam can pass, and the fact that they do not give continuous velocity signal.

3.3.3 **Principles of Hot-wire Anemometry**

The hot wire anemometer has been widely used for many years as a research tool in fluid mechanics. Despite the many recent available non-intrusive velocity measurement systems, it is still widely applied since it is the only instrument that is delivering a truly analogue representation of the velocity up to high frequency fluctuations.
The hot wire anemometer consists of a sensor, a small electrically heated wire exposed to the fluid flow and of electrical equipment which transforms the sensor output into a useful electrical signal. The sensor dimension is very small. The typical dimensions of the heated wire are 5 µm in diameter and 1 to 3 mm in length and therefore it has an instantaneous response. The sensor is placed in a moving fluid and its heat transfer with the fluid is controlled and related to the velocity of the intercepted flow. The basic principle of operation of the system is the heat transfer from the heated wire to the cold surrounding fluid. Because heat transfer is a function of the fluid velocity, a relationship between the fluid velocity and the electrical output can be established. There are two modes for operating hot wires; constant current (CC) and constant temperature (CT). In the CC mode, the current passing through the wire is kept constant. Therefore the wire temperature (and thus the resistance) varies with fluid velocity. In CT method, the wire resistance is kept constant by using a Wheatstone bridge circuit. There are major advantages in using constant temperature method over constant current one. With the CT mode, the thermal inertia of the sensor element is automatically adjusted when the flow conditions vary. Also CT mode offers a much higher frequency response than the CC mode and that is why it is the best choice for turbulent flow measurements. Figure 3-7 shows the operation of a CT circuit. As the flow condition changes, the probe wire resistance varies corresponding to the flow condition. The voltage of the bridge is sent to an amplifier with a current output which is inversely proportional to the resistance change of the hot wire sensor. The sensor resistance is then restored to its original value by feeding back this current to the top of the bridge. Modern sensor fast response time makes it possible to maintain the sensor temperature constant except for very high frequency fluctuations. Assuming that temperature, pressure and composition of the fluid domain are constant, fluid
velocity will be the only variable affecting the heat transfer between the sensor and the flow. Therefore the excitation voltage of the wire can be directly related to the sensed velocity.

![Diagram of constant temperature circuit]

Figure 3-7: Constant temperature circuit

The main advantages of hot wire systems are their cheap price compared to LDA, having high frequency response up to 50 kHz and high sensitivity at low velocities.

3.3.4 Relationship Between the Hot-wire and Fluid Velocity

In hot wire heat transfer analysis, it is assumed that the wire acts as an infinitely long cylinder. Generally, there are three possible ways of heat transfer which are conduction, convection and radiation. Under normal operating condition in air, radiation losses are typically smaller than 0.1% of the electrical input and therefore it can be neglected. Assuming that there is no heat conduction to the wire supports and the surrounding fluid, the heat loss from the wire can
be directly related to the flow velocity. Corrsin [67] developed a dimensionless heat transfer equation from an infinitely long, straight cylinder as follows:

\[ Nu = \frac{h_t L}{k_a} = \frac{E^2}{R_s \pi l k_a (T_s - T_a)} \]  

(3.4)

Where \( R_s \) is the sensor resistance, \( E \) is the excitation voltage, \( k_a \) is the thermal conductivity of air, \( l \) and \( d \) are the length and diameter of the wire respectively. Neglecting the compressibility and buoyancy effects can greatly simplify this equation. The result is the classic calibration expression known as Kings law.

\[ Nu = A + B Re^n \]  

(3.5)

Where \( n=0.5 \) and \( A \) and \( B \) are calibration coefficients. The Kings law can be further simplified to incorporate the fluid properties into the calibration coefficients.

\[ E^2 = A + BU^n \]  

(3.6)

\( U \) is the velocity magnitude of the fluid flow passing through the wire. Therefore the probe calibration can be done by measuring the output voltage at a known velocity (measured by pitot static tube).

3.3.5 Hot-wire Probes

Single hot wires are the most widely used probes. They are typically oriented either perpendicular or at a 45° angle. Single hot wires can only measure one component of the flow which is perpendicular to its axis. Therefore to obtain maximum accuracy in obtaining a single velocity component, the probe should be aligned perpendicular to the mean flow direction. If the
probe is not perpendicular to the flow, the measured velocity will be its magnitude at the point of the probe.

3.3.6 Hot-wire Calibration

The hot wire calibration relates the output voltage to the velocity field. Therefore the King’s law equation is applied to the probe. A velocity magnitude calibration is performed by aligning the hot-wire probe with a known flow of low turbulence intensity. Typically, the core of a jet flow is used for the calibration. The main purpose is to obtain a set of calibration points that consist of a measured average velocity magnitude \(U\) and the resulting anemometer output voltage \(E\). These points are then plotted and linearized. The obtained trend line coefficients are the A and B constants at King’s law. Figure 3-13 shows the calibration set up.

3.3.7 Principles of Particle Image Velocimetry

Particle Image Velocimetry appeared 25 years ago and since then has become an essential measurement technique in fluid mechanics laboratories in both research institutes and industry[68].

The technique is based on measuring the displacement of fluid \(\Delta x\) over a given time interval \(\Delta t\) which is the definition of velocity. A laser sheet illuminates the liquid or solid particles that are floating within the flow. The scattered light from these particles determine the position of the fluid. In most applications however, the flow has to be seeded with tracer particles because such particles are not naturally present in the flow. These particles should be sufficiently small and light enough to move with local flow velocity.
A plane within the flow is illuminated twice by means of two superimposed laser light sheets. The scattered light by the particles is recorded on two separate frames on a special cross-correlation CCD (Charged-Coupled Device) camera sensor. For evaluation, the digital PIV recording is divided into small areas called “interrogation windows”. A spatially statistical cross correlation function is used to determine the displacement vector of the particle images between the two illuminations. Therefore the local velocity flow vector on the pane of the light sheet can be deduced using the image magnification obtained from camera calibration and the time interval between the laser pulses. Small overlapping between the neighboring integration windows is usually employed to reduce the spacing between two vectors in the resulting vector grid. In this study 50% overlapping is used which doubles the number of vectors in each direction and therefore the total number of vectors are increased four times.

The CCD sensor converts photos to an electric charge based on the photoelectric effect. These sensors are used in most cameras to record the digital image. The CCD sensor consists of many individual sensors that are arranged in a rectangular array. The size of each pixel is about 10×10 μm. In PIV double frame mode, the repetition rate is on the order of 10 Hz. Although PIV
principals are relatively simple, its practical implementation should be carefully done to reduce uncertainties and obtain reliable measurements.

One of the major advantages of the PIV technique over other measurement tools like laser Doppler velocimetry is that it is capable of delivering a quantitative and instantaneous measurement of the velocity not only at one point but over a whole plane simultaneously. Therefore both visualization and quantification of the 2D flow structure become available using PIV. Within the last two decades, together with advances in electronic imaging and computing tools, PIV is becoming a very successful and popular measurement method. The heart of the most commercially available data processing software is the computation of the cross correlation function that is commonly based on Fast Fourier Transform (FFT) algorithm. Nowadays, most of the software use iterative methods and initial velocity evaluation using large integration windows. These velocity vectors and their gradients are then used in the next step to sufficiently shift and deform the integration windows in each of the two exposures to reduce in plane loss of correlated particle images. The interrogation window size is also progressively reduced to reach a final size of 32x32 or 16x16 pixels in practice, depending upon the density of the particle images.

3.3.8 Principles of the Energy Cascade and Kolmogorov Hypotheses

Kinetic energy enters the turbulence (by production mechanisms) at the largest scales of motion. This is the main idea of the energy cascade. This energy is then transferred, through an inviscid process, to smaller scales until viscosity dissipates it[69]. Kolmogorov expanded this idea and in particular identified the smallest scales of turbulence to those that now are known by his name.

Assume a fully turbulent flow at high Reynolds number with characteristic velocity $U$ and length scale $L$. Turbulence is composed of different size eddies with a characteristic velocity $u(l)$
and timescale $\tau = l/u(l)$. Therefore a turbulent motion localized within a region of size $l$, which is at least moderately coherent over the region, is called eddy. Smaller eddies can also be present where it is occupied by large eddy. Largest size range of eddies are characterized by the length scale $l_0$ which is comparable to the flow scale $L$, and their characteristic velocity $u_0 = u(l_0)$ is on the order of the rms turbulence intensity $u' = (\frac{2}{3} k)^{1/2}$ which is comparable to $U$. Therefore, because the Reynolds number of these eddies ($Re_0 = u_0 l_0 / \nu$) is large, (i.e., comparable to $Re$), the direct effects of viscosity are negligibly small. Large eddies are usually unstable and therefore transfer their energy to smaller eddies by a breaking up process. The newly formed smaller eddies also break up and transfer their energy to even smaller eddies. This cascade of energy, where is transferred to successively smaller and smaller eddies, continues until the Reynolds number is sufficiently small and the molecular viscosity dissipates the kinetic energy. Notice that in this process the dissipation is placed at the end of the sequence of processes. However, the dissipation rate, $\epsilon$, is determined by the first process in the sequence which is transfer of energy from the largest eddies.

These eddies have energy of order $u_0^2$ and timescale $\tau_0 = l_0/u_0$, so the rate of transfer of energy can be supposed to scale as $u_0^2/\tau_0 = u_0^3/l_0$. Consequently, at relatively high Reynolds numbers, $E$ scales as $u_0^3/l_0$ and is independent of $\nu$. Kolmogorov argued that as the energy passes down during the cascade process, all the information about the geometry of the large eddies which is determined by the mean flow field and boundary conditions are lost. Therefore the small scales motions of turbulence are universal which means they are similar in every high Reynolds number turbulent flow. Now the question is what are the parameters that this statistically universal state depends on? As mentioned earlier, during the energy cascade (for $l < l_{EI}$), transferring of energy to successively smaller eddies and viscous dissipation are the two dominant processes.
A plausible hypothesis, then, is that the rate at which the small scales receive energy from the large scales (which we denote by $\tau_{EI}$), and the kinematic viscosity $\nu$ are the important parameters.

The size range $l < l_{EI}$ is called the universal equilibrium range. In this range, the timescales $l/u(l)$ are small compared with $l_0/\nu_0$, so that the small eddies can adapt quickly to maintain a dynamic equilibrium with the energy-transfer rate $\tau_{EI}$ imposed by the large eddies. Given the two parameters $\varepsilon$ and $\nu$, there are (to within multiplicative constants) unique length, velocity, and time scales that can be formed. These are the Kolmogorov scales:

\begin{align}
\eta &= \left(\frac{\nu^3}{\varepsilon}\right)^{1/4} \\
\eta u &= (\varepsilon \nu)^{1/4} \\
\tau &= \left(\frac{\nu^2}{\varepsilon}\right)^{1/2}
\end{align}

These definitions clearly show that the Kolmogorov scales characterize the very smallest, dissipative eddies. First, the Reynolds number derived from the Kolmogorov scales is unity, i.e., $\eta u_\eta / \nu = 1$, which is consistent with the notion that the cascade proceeds to smaller and smaller scales until the Reynolds number $u(l)/l/\nu$ is small enough for dissipation to be effective. Second, the dissipation rate is given by

$$
E = \nu \left(\frac{U_\eta}{\eta}\right)^2 = \frac{\nu}{\tau_\eta^2}
$$

showing that $\left(\frac{U_\eta}{\eta}\right)^2 = \frac{1}{\tau_\eta}$, provides a consistent characterization of the velocity gradients of the dissipative eddies. Now that the Kolmogorov scales are identified, the sequence of the hypotheses that demonstrates its potency can be stated and phrases like “similarity hypotheses” and “universal form” can be clarified.
Consider a point \( x_0 \) in a high-Reynolds-number turbulent flow at a time \( t_0 \). In terms of the Kolmogorov scales at \((x_0, t_0)\), non-dimensional coordinates are defined by

\[
y \equiv (x - x_0)/\eta
\]

and the non-dimensional velocity-difference field is defined by

\[
w(y) \equiv [U(x, t_0) - U(x_0, t_0)]/u_\eta
\]

Because it is not possible to form a non-dimensional parameter using \( \varepsilon \) and \( \nu \), the “universal form” of the non-dimensional field, \( w(y) \), cannot depend (at least not only) on \( \varepsilon \) and \( \nu \). Consequently, as stated above, according to the Kolmogorov hypotheses, when the non-dimensional velocity field \( w(y) \) is examined on a moderate scale (specifically \( y(|y| < l_{EI}/\eta) \)), it is statistically isotropic and identical at all points. On the small scales also all high Reynolds number turbulent velocity jets are statistically similar which means they are statistically identical when they are scaled by the Kolmogorov scales.

The ratios of the smallest to largest scales are readily demonstrated from the definitions of the Kolmogorov scales and from the scaling \( \varepsilon \sim u_0^3/l_0 \). The results are

\[
\eta/l_0 \sim Re^{-3/4}
\]

\[
u_\eta/u_0 \sim Re^{-1/4}
\]

\[
\tau_\eta/\tau_0 \sim Re^{-1/2}
\]

At high Reynolds number, the velocity and time scales of the smallest eddies \((u, \text{ and } t,)\) are, as previously supposed, small compared with those of the largest eddies \((u_0 \text{ and } t_0)\). Inevitably, the ratio \( \eta/l_0 \) decreases with increasing \( Re \). As a consequence, at sufficiently high Reynolds number, there is a range of scales \( l \) that are very small compared with \( l_0 \), and yet very large compared with \( \eta \), i.e., \( l_0 \gg l \gg \eta \). Because this size range of eddies are much bigger than the
dissipative eddies, it may be supposed that their Reynolds number $u(l)l/\nu$ is large, and consequently that their motion is little affected by viscosity. Therefore in every turbulent flow at sufficiently high Reynolds number, the scale of $l$ in the range of $l_0 \gg l \gg \eta$ has a universal form that is uniquely identified by $E$ and independent of $v$. This turbulence dissipation range is called the inertial subrange.

![Figure 3-9: Eddy sizes l showing the various length scales and ranges[69]](image)

### 3.3.9 Instability

As we will see later on, the air flow enters the trachea in the form of a jet called the laryngeal jet. Therefore it is important to have some basic insight about the jet formation and its mixing effect before presenting the results.

Jet formation can be found in various engineering systems and as such constitute a canonical set of flow fields. Jet flows are usually used to promote mixing or dispersal of the injected fluid with the fluid into which the jet is introduced. Jets can also be applied for controlling thrust or force because they can introduce a localized force into the flow field. Velocity shear is the result of entering a moving fluid into a quiescent body of the same fluid which can cause turbulence and mixing. As mentioned earlier, large scales of turbulence greatly depends on the geometry of the flow and the type of the forces acting on the fluid. Therefore each situation is a separate problem requiring specific investigation. In this section, the scope is limited to the basic
case where a jet penetrates in a quiescent fluid. This case of jet penetration is also very similar to what happens at the flow inside human trachea.

Round jet is made of three main regions of initial (flow development) region, transitional region and fully developed turbulent mixing layer (self-similar region). Depending on the inlet type of the jet, the centerline stream wise velocity remains constant or sharply increases in the first two regions. The flow near the exit of the nozzle is uniform at the jet centerline and shear flows appear near the wall. This shear region near the wall is unstable where small disturbances are amplified and eventually roll-up into organized and quasi-periodic sets of vortices. Further downstream of the jet, the dynamics of these vortices that are described as events such as vortex pairing grow the shear layer. This vortex growth continues along the jet towards the end of the potential core until the dominant jet instability mode becomes that of the preferred mode. As the flow reaches the end of the potential core and beyond, complex nonlinear motions of the vortex destroy the organized motion of the vortices in the flow and results in the transition to turbulence. After that transition to turbulence, the jet flow behavior can be described as fully developed turbulent flow.

Figure 3-10: Instability of an axisymmetric jet: A laminar stream of air flows from a circular tube at Reynolds number 10,000 and is made visible by a smoke wire. The edge of the jet develops axisymmetric oscillations, rolls up into vortex rings, and then abruptly becomes turbulent[70]
3.4 Testing Procedures

3.4.1 Flow Visualization

The flow is visualized using a smoke technique. The smoke is generated using a commercial smoke generator and is released upstream of the flow. Images of the smoke streak lines were captured using a high speed camera at framing rates ranging from 60 to 500 Hz depending on the flow rate. Each recording is then analyzed frame by frame. Forty eight different combinations of aperture shapes, the area ratio, the angle of the glottis, and the flow rates were visualized at the mid lateral plane in the axial direction. The flow is also visualized in planes perpendicular to the flow at 0.5D, 1D, and 3D downstream of the larynx. The visualizations are performed at Reynolds numbers of 1000, 2000, 4000 and 8000 that represent mild to severe breathing conditions. Table 3-1 shows the different measurements combinations.

3.4.2 Laser Doppler Anemometer

The Laser Doppler anemometer technique was used to measure axial and tangential flow velocity at an array of points within the cylinder. The distribution of points at each downstream location is shown in Figure 3-11. The LDA employed in this experiment used an argon-ison laser that was split into four separate beams that later refocused at one focal point. In order for the LDA to read velocity, the air flowing through the model was seeded with small particles. As the particles pass through the focal point, they scatter the light from the laser beams. The scattered light is Doppler shifted, and the information is used to determine the particle velocity as described in the previous section. The data were converted from light signal to a velocity using a digital burst correlator. The one used in this experiment is IFA 655 produced by TSI, Inc.
The glass tube should be clean and transparent so that the laser beam will not be disrupted. A six-jet atomizer was used to create small droplets for the LDA measurement. The droplets created by the atomizer are small enough to ensure that droplet velocity accurately represents the air velocity. Excessive droplet deposition on the tube walls may happen if the experiment is run for long period. During LDA measurements it was made sure that there was no significant accumulation on the walls. Also, the laser beams were positioned vertically to the circular tube axis at all time to avoid lens effect from altering the beam intersection angle. The position of the LDA probe volume could be changed from point to point using a precision traverse.
The LDA measures the velocity of a successive number of droplets at each location, and the mean and root mean square of those measurements are then calculated. For the present study, 25,000 velocity measurements were obtained at each position to determine the mean and rms velocities. The turbulent intensity was calculated using equation 3.16.

\[ \sigma = \frac{V_{\text{rms}}}{V_{\text{mean}}} \]  

(3.16)

Where \( V_{\text{rms}} \) is the standard deviation of the measured droplet velocities and \( V_{\text{mean}} \) is the average velocity the flow. Turbulent intensities were calculated for both axial and traverse directions.

3.4.3 Particle Image Velocimetry

PIV experiment was performed to study the movement of two sets of particles within each model. In this study, the PIV system used in all measurements consists of a single cavity Nd:YAG laser with a nominal power of 25 mJ per pulse, a CCD camera with a resolution of 2048 * 2048 px. The camera lens is one of the most important parts for the experiment. A SIGMA EX DG Macro lens is used for this study. Macro lenses are suitable for images of very small sizes as in the case of particle tracers we have in this experiment. It is a variable zoom and exposure lens with a 105 millimeter focal length. Using this lens with CCD TSI camera allows for very small droplets to be captured precisely.

Experiments were done at Reynolds numbers of 2000 and 4000 using two different particle sources: olive oil (with the particle diameter of around 0.6 \( \mu \)m) and salt (with the particle diameter of around 2\( \mu \)m). The olive oil particles are the ones that are also used during the LDA experiment and since they are small enough, it is assumed that they are able to follow the flow. However, the salt particles are around more than three times bigger than olive oil droplets. Therefore the behavior
of the relatively large particles inside the human airway can be observed. The camera is zoomed to the lateral central plane between 1D to 2D downstream of the model.

Each measurement was repeated 15 times at a frequency of 5 Hz. The field of view for these measurements was approximately 45 * 45 mm. The time interval between two consecutive images was about 150 µs depending on the flow rate. Data sampling for phase averaging is controlled by the image acquisition system. The synchronizer unit activates the Nd:Yag laser and CCD camera simultaneously. Figure 3-12 shows the experimental set up. Average velocity and root mean square values were calculated from 15 vector fields in each experiment. Since results became consistent when the number is higher than 15, it is assumed that 15 is a sufficiently large statistical sample. The data was processed using the commercial INSIGHT 3G software. An FFT correlator was applied starting with a 63 *63 px integration size with 25% overlap followed by an adaptive cross correlation with a final 32*32 px integration window size. The dynamic range in the PIV images was up to 4096 grayscales and 5-8 particles per integration area led to a high accuracy of the adaptive correlation routines.
3.4.4 PIV Calibration

Before running any experiment, the PIV system needed to undergo a spatial calibration process. This process involved converting a known dimension in the image field of view to an amount of pixels in the image. This calibration allowed for converting the pixels to physical dimensions during the image processing phase.

In this study the TSI calibration grid was used to accurately calibrate the system. The grid points are spaced 2.5 mm away from each other in both directions. After setting the desired field of view and magnification, an image was taken of the grid. Since the distance between two adjacent points is known on the calibration grid, the software measures the amount of image pixels in that distance and correlates it to the actual length. The conversion factor was then used for all image processing features. The calibration had to be done each time that the zoom setting on the camera is changed.
3.4.5 Hot-wire Anemometer

After measuring the mean and rms velocities, the next step was to obtain time resolved velocity and decompose it to its frequency components. Since LDA cannot effectively provide a continuous measurement of velocity, hot-wire anemometer was used for this purpose. The main advantages of hot wire systems in analyzing turbulent flows are their high frequency response, small size and lower noise to signal ratio\[71]\.

Eight points at each 1D and 3D downstream planes were chosen for spectral analysis. The points were selected at regions of high turbulence intensity. The main purpose was to detect regions with high energy and their frequency content to estimate the size of the flow eddies. Power spectrum of the signal was obtained using an FFT function. These data can give insight into the turbulence decay process and eddy sizes within the flow at each location. Figure 3-13 shows the location of points used for hot wire experiments at both 1D and 3D downstream of the flow.

![Figure 3-13: Hot wire measurement points](image)

Figure 3-13: Hot wire measurement points
3.5 Error Analysis

Errors can occur due to one of the following sources:

1. Positioning error that includes misalignment of the model to the plane of the laser beams, the inaccuracy of moving the focal point to a specified point in the flow and the inaccuracy in determining the wall location.

2. Flow rate errors that include miss adjusting the flow rate to the same value at the beginning of each experiment and the fluctuation of the flow rate during each experiment (±1%).

3. LDA related errors that include the finite measuring probe volume and the deflection of the laser light especially near the wall.

4. PIV related errors that include light reflection from the curved glass tube especially near the wall.

The individual determination of each error mentioned above is very difficult. Thus an integral approach was used. The overall error was determined based on two factors. The first was the error between the calculated flow rate based on the measured velocities in the model and the flow going into the model as measured by the mass flow meter. The second was the deviation in the axial velocity component at each crossing point between the vertical and horizontal arrays. At each crossing point two measurements of the same axial velocity component are available. The uncertainty in measuring the flow rate is 3.85% and the uncertainty in measuring the axial velocity is 4% on average. The uncertainty in measuring the flow rate and axial velocity can be considered as measures of spatial error and the accumulative error (or time error) respectively. The spatial error can be improved by using a finer measurement mesh. The accumulative error is tremendously improved by including a traverse mechanism to be able to place the model more accurately and efficiently. Figure 3-14 show non dimensional velocity and margin of error at each point along the
AP and side view lines. Since the error doesn’t show any strong correlation with the factors considered above, the error could be considered random. Furthermore, it indicates that the major source of error is the accuracy of adjusting the flow rate to the same value at the beginning of each experiment. However, the values of the errors are in the expected limit in such a three-dimensional flow with high swirling motion. However, some errors do exist in any LDV measurements due to the finite volume of the focal point. This error is important in regions with high velocity gradients. However, the error does not show a high correlation with the velocity gradient. This error can be reduced significantly by requiring a high number of fringe crossings to have a valid sample.
Figure 3-14: Mean and margin of error for axial and traverse velocities at 50% opening triangular model and Re 2000
Chapter 4

Results and Discussion

4.1 Introduction

Insight into a physical process is always improved if a pattern produced by or related to this process can be observed by visual inspection. In this chapter flow visualization results in all models with different inlet shapes, attachment angles and opening area ratios are presented. Important features of the flow pattern for each case were obtained using laser-sheet photography technique.

The flow in the airway is essentially a collection of basic flows such as those in curved ducts and jets flows. The main focus of the visual study is on the flow downstream of the glottis (up to 2D downstream). Both streamwise and cross-stream views are obtained due to three dimensionality of the flow pattern. Note that when analyzing flow visualizations snapshots, lines of smoke particles are described as streamlines (lines that are tangent to the velocity field). These lines, to be more accurate, are in fact streaklines (smoke particles that previously passed through a common point).

After examining the flow visually, LDA measurements were performed on selected cases. In this set of experiments, as will be explained in detailed in section 4-5, axial mean velocity, traverse mean velocity as well as their fluctuations were measured.

With the PIV results, the movement of larger particles (generated by atomizing salt solution) inside the domain were compared with the olive oil particles which are smaller. PIV
results can give insights, both visually and quantitatively, into the movement of particles along the trachea.

Finally in section 4-7, spectral analysis of the 4 points near the side walls and one point at the center of the tube is presented. These results show the formation of eddies at different frequency. Measurements are taken at 1D and 3D downstream of the inlet. Comparison is made between different angles and different inlet shapes.

4.2 Flow Visualization in the Trachea with Glottis Aperture of 10%

This section presents flow visualizations of the model with 10% glottis aperture of rectangular or triangular inlet shape. Attachment angles of 45°, 60° and 75° degrees were studied at Reynolds numbers of 1000, 2000 and 4000.

The initial jet cross section is dictated by the inlet geometry. Once it enters the domain, the flow expands and eventually reaches its final width which is the tube diameter. This process is similar for any of the models. However the speed of this evolution is influenced by the Reynolds number, inlet shape and attachment angle of the model.

Large velocity differences between the entering laryngeal jet and the initial flow inside the trachea, creates a thin shear layer which is very unstable. The shear layer is the origin of the initial flow instabilities that eventually lead to the generation of turbulent fluctuations. The lower velocity ambient fluid is dragged into the jet flow by this highly turbulent shear layer which enhances the mixing process. Consequently, both shear layer and jet spread laterally and the jet velocity decreases as it goes through the downstream duct. Near the tracheal inlet, and along the central open portion of the glottis, there is a region with an almost uniform mean velocity which is called the potential core. Because of the shear layer growth, the potential core eventually disappears when
shear layers from the sides of the tube merge together. The mixing process between the jet and the ambient fluid continues beyond the potential core such that the velocity distribution eventually becomes more like a fully turbulent flow within a pipe.

Figures 4-1 to 4-3 show that the flow enters the trachea in the form of a jet, with flow disturbances growing downstream at various rates. All flows can be seen to skew to one side of the tube. This phenomenon is associated with the coanda effect where a jet tends to attach to a convex surface. The side of the tube where the jet attaches to is dependent on the disturbances in the flow. Often, when repeating an experiment the flow would attach to one or the other side in a somewhat random fashion. In practice however imperfections in a model often introduce a bias in the jet skew.

The deposition probabilities of inhaled particles will be affected by the nature of the fluid motion which they are entrained. For instance, the interaction between secondary and axial motions generates more complicated flows (e.g. six distinct vortices[72]) that can create strong traverse motion that pushes the particles to the sidewall where they can be deposited. The visualization results show that the laryngeal jet skews to the side wall sooner as Reynolds number and attachment angle increase.

The approximate location of the first visible vortex from the inlet is measured using pixel analysis. This measurement is only a rough estimate of the location of the first visible vortices since their location can change frame by frame depending on when the image is captured. However, this measurement is useful for understanding the overall location of the flow downstream of the glottis. In Figure 4-1, the initial vortex rollup of the triangular jet changes from 27 mm to 14 mm as the attachment angle changes from 45º to 75º. This indicates that changing attachment angle from 45º to 75º causes the flow to separate increasingly sooner from the curved
side wall. This pattern also can be seen in Figure 4-2. In Figure 4-3 where the Reynolds number is 4000, the flow becomes fully turbulent soon after the entrance which makes it difficult to visually locate the initial vortex formation.

As can be seen in Figure 4-1, at 45° and 60° attachment angles the vortex rollup inside the triangular inlet model occurs sooner than the rectangular inlet model. This indicates that transition starts sooner in the model with the triangular inlet. At 75°, however, vortex rollup starts at about the same downstream distance for both triangular and rectangular inlet models. This suggests that 75° is sufficiently steep that the flow, regardless of the inlet geometry, separates almost immediately upon entering the tube. As such, the inlet shape has a minimal effect on the flow at this angle.

In comparison to Figure 4-1, Figures 4-2 and 4-3 show that transition starts sooner as the Reynolds number increases. The inlet geometry however still has a similar effect on the transition process at lower Reynolds numbers. This is evident by the presence of a wider range of the vortex scale in Figures 4-2 and 4-3 for the triangular inlet case.

4.3 Flow Visualization in the Trachea with Glottis Aperture of 50%

Results for the models with 50% aperture are shown in Figures 4-4 to 4-6.

In Figure 4-4, two vortices can be seen to form symmetrically for the rectangular inlet model with a 45° attachment angle. Increasing the angle to 75°, creates two more vortices within the same downstream distance. This suggests that increasing attachment angle is creating earlier, more upstream mixing. In the triangular model, two vortices are formed near the walls. These vortices are closer to the wall compared with those in the rectangular model.
In 10% opening area models, it was noted that the flows for both rectangular and triangular inlet models are the same for the 75° attachment angle. However, for the 50% opening cross section area and 75° attachment angle, flows are different between the rectangular and triangular models. This suggests that for wider inlet openings, the inlet shape affects the flow inside the tube even for steep attachment angles like 75°.

Increasing the Reynolds number to 2000, Figure 4-5, creates larger circulation regions near the potential core boundaries at both rectangular and triangular models which can help the overall mixing process. Flows inside the rectangular inlet model is symmetric for both the 45° and 60° attachment angles but becomes asymmetric at 75°.

Overall results for the 50% opening area and Reynolds number of 2000 show the central symmetric jet at the larynx downstream (except for the 75° attachment angle). The attachment angle effect is same as previous cases and vortices are created sooner at higher attachment angles.

At a Reynolds number of 4000, Figure 4-6, the jet is divergent toward the right side in the triangular inlet model. Comparison between the rectangular and triangular models shows that more vortices are separating from the core flow in the triangular model which increases the mixing near the walls.

Regarding the particle deposition and particle removal capability, the 50% opening area has better vortex formation at Reynolds 4000 compared to Reynolds 2000. At this Reynolds number, the jet potential core width becomes narrower due to shear layer expansion and is skewed to the side wall with large vortex structures near the walls that can take the particles from the main stream and transfer them to the locations near the walls where the chance of deposition is more. This phenomenon is not seen at lower Reynolds numbers of 1000 and 2000 because of having
fewer vortex structures and relatively wider jet potential core flows (smaller shear layer). Notice that the final size of all jets is the same (equal to the tube diameter), However higher Reynolds numbers flows have narrower potential cores due to early transition of the shear layer and formation of vortexes near the walls.

4.4 Flow Visualization in the Traverse Cross Section

4.4.1 Traverse Flow Visualization at 0.5D Downstream of the Flow

Figures 4-7 to 4-9 show traverse visualization at 0.5D downstream of the flow for the models with rectangular and triangular inlet shapes. Both inlets have a 50% opening. In each figure the flows for different attachment angles and a specific Reynolds number are compared.

At Reynolds of 1000, Figure 4-7 shows the formation of counter axial vortex pairs for the model with the rectangular inlet. The flow is nearly symmetric with the potential core at the center of the tube and the counter-rotating vortex pair at each side. The pattern is consistent for all three attachment angles.

Traverse flow visualization for the triangular inlet model show that the flow is roughly symmetric along the anterior posterior line. Vortex pairs are created between the side wall and the jet. While this is similar to the rectangular case, the vortexes are less symmetric and organized.

When the Reynolds number is increased to 2000 and 4000, Figures 4-8 and 4-9 show similar flow patterns as at Reynolds 1000. However the main differences are increased vortex motions, flow randomness, and range of vortex scale at the higher Reynolds numbers due to the more advanced state of transition.
Figures 4-7 to 4-9 show that at the same axial location there is an increase in the size of the vortex region and a decrease of the size of the potential core. This behavior is expected because the jet flow transition process happens sooner in models with higher attachment angles.

Increasing the Reynolds to 2000 at Figure 4-8 creates the same pattern with four and two circulation regions for rectangular and triangular inlet models respectively. However the potential core flow becomes narrower for both models at this Reynolds number. This is because of the shear layer transition that is happening more upstream at this flow rate. Therefore, more of the cross sectional area is occupied by the vortexes. However, the potential core flow is still apparent in both models.

Results show that changing attachment angle from 45° to 75° degrees increases the size of the vortex region and narrows the potential core. This observation is expected because the jet flow transition process happens more upstream in the models with higher attachment angles.

Figure 4-15 shows the results for Reynolds 4000. The visualization shows that the vortex region expands to around half of the cross section and the core jet becomes smaller. Some vortex can also be observed within the jet core region which indicates that the core jet flow is about to disappear at 0.5D downstream of the flow. These strong vortex structures are able to pick the particles from the middle of the stream and carry them to the regions near the wall which can increase the chance of deposition.

4.4.2 Traverse Flow Visualization at 1D Downstream of the Flow

Figures 4-10 to 4-12 show traverse visualizations at 1.0D downstream of the flow for the models with rectangular and triangular inlet shapes. Both inlets have a 50% opening. In each Figure the flows for different attachment angles and a specific Reynolds number are compared.
Overall the results are similar to those at 0.5D. At Reynolds of 1000, Figure 4-10 shows the formation of counter axial vortex pairs for the model with a rectangular inlet. The flow is nearly symmetric with the potential core at the center of the tube and counter rotating vortex-pairs at each side. The pattern is consistent for all three attachment angles. Traverse flow visualization of triangular inlet model shows that the flow is roughly symmetric along anterior-posterior line. Vortex pairs are created between the side wall and the jet. While this is similar to the rectangular case, the vortices are less symmetric and less organized.

When the Reynolds number is increased to 2000 and 4000, Figures 4-11 and 4-12 show similar flow patterns as at Reynolds 1000. The main differences are increased vortex motions, flow randomness, and the range of the vortex scale at the higher Reynolds number due to the more advanced state of transition. Figures 4-10 to 4-12 show that at the same axial location there is an increase in the size of the vortex region and a decrease of the size of the potential core. This behavior is expected because the jet flow transition process happens more upstream in the models with higher attachment angle.
Figure 4-1: Flow visualization for 10% opening area and Re 1000 at different attachment angles and inlet aperture shapes
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<tr>
<th>Attachment Angle</th>
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Figure 4-2: Flow visualization for 10% opening area and Re 2000 at different attachment angles and inlet aperture shapes.
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Figure 4-3: Flow visualization for 10% opening area and Re 4000 at different attachment angles and inlet aperture shapes
Figure 4-4: Flow visualization for 50% opening area and Re 1000 at different attachment angles and inlet aperture shapes
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Figure 4-5: Flow visualization for 50% opening area and Re 2000 at different attachment angles and inlet aperture shapes
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Figure 4-6: Flow visualization for 50% opening area and Re 4000 at different attachment angles and inlet aperture shapes
Figure 4-7: Traverse flow visualization at 0.5D downstream for 50% opening area and Re 1000 at different attachment angles and inlet aperture shapes
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Figure 4-8: Traverse flow visualization at 0.5D downstream for 50% opening area and Re 2000 at different attachment angles and inlet aperture shapes
Figure 4-9: Traverse flow visualization at 0.5D downstream for 50% opening area and Re 4000 at different attachment angles and inlet aperture shapes.
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Figure 4-10: Traverse flow visualization at 1D downstream for 50% opening area and Re 1000 at different attachment angles and inlet aperture shapes
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Figure 4-11: Traverse flow visualization at 1D downstream for 50% opening area and Re 2000 at different attachment angles and inlet aperture shapes
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Figure 4-12: Traverse flow visualization at 1D downstream for 50% opening area and Re 4000 at different attachment angles and inlet aperture shapes.
4.5 LDA Results

In this section, LDA measurement results for both axial and tangential mean velocities along with their fluctuations are presented for two Reynolds numbers of 2000 and 4000. Each section will discuss one of the parameters: axial velocity, tangential velocity and axial velocity standard deviation. Measurements are obtained at 1D and 3D cross sections. Figure 4-13 shows the results for the triangular model with 50% open area. For better comparison, results are arranged in contour form for all the cases. Comparison will be made between rectangular inlet models and triangular ones. Positions of the contours to be presented are shown in Figure 3-11.

4.5.1 Axial Velocity Contour

Figures 4-14 through 4-17 show axial velocity contours measured at the cross sections at 1D and 3D downstream of the inlet for rectangular and triangular larynx shapes with 10% and 50% opening areas. The magnitudes of the velocities listed on the contours are non-dimensionalized using the mean velocity. The mean velocity is 0.6 m/s for Reynolds number of 2000 and 1.2 m/s for Reynolds number of 4000.

Figures 4-14 and 4-15 compare the results for the 45° attachment angle. The results are consistent with the flow visualization presented in Figure 4-10. Figure 4-14 shows the existence of the core jet flow in both models with the 50% inlet opening. Reversal flows are at the anterior section of the triangular model. For the rectangular case, recirculation regions are located at the two sides. In both cases, the magnitude of the maximum velocity is about 20% of the mean velocity. The results at 3D indicates the existence of a higher speed region along the posterior part of the tube in the model with the triangular inlet. The maximum velocity in this region is approximately 1.3 times that of the rectangular model. In comparison, the jet flow inside
rectangular model at 3D downstream is more developed with the potential core no longer observable.

As expected, Figure 4-14 shows that for the 10% opening case the area occupied by the jet is small compared to the 50% case. For the rectangular case the potential core is nearly dissipated at 1D. For the triangular inlet case the core has separated into two regions, with the maximum velocity being higher than the 50% case due to the original flow being confined to a smaller opening. At 3D, the flow within the triangular model still has a “twin” potential core near the posterior, while the jet core has completely vanished for the rectangular case.

Figure 4-15 shows that the velocity fields at Reynolds 4000 are qualitatively similar to those at lower Reynolds numbers.

Figure 4-16 shows the velocity fields for the attachment angles 60° and 75° and Reynolds number of 2000. The results are similar to those for the attachment angle of 45°. Other than for the triangular inlet there is a moderate shift in the position of the reversal flow region as the attachment angle changes.

In summary, for cases with a 50% opening area, reversal flows are apparent for both inlet shapes at 1D downstream. This region is on the anterior side of the trachea for triangular larynx, while for the rectangular case it is located symmetrically at side walls. Since particles tend to gather in recirculation zones, these reversal flow regions can potentially play an important role in particle deposition. In comparison to the rectangular case, the triangular inlet produces a jet that retains its potential core farther downstream.
4.5.2 Tangential Velocity Contour

The combination of cross-stream circulatory flows and axial flows produce swirling motions that can be an effective transporter of particles. Regions of such flow exist in many of the flow conditions in both models. Figures 4-18 through 4-21 show tangential velocity contours measured at two cross section areas of 1D and 3D downstream of the inlet for rectangular and triangular larynx shapes with 10% and 50% opening area.

Figure 4-18 shows the results for the 45° attachment angle at Reynolds number of 2000. For model with a triangular inlet appreciable tangential velocities exist only near the anterior wall where circulatory flows are located. At 3D downstream the location of maximum tangential velocity changes from the anterior towards the posterior region. This suggests tilting or twisting of the jet as the flow moves downstream. For the rectangular case the tangential velocities are distributed through most of the cross section at 1D downstream. At 3D downstream the regions of tangential flow reduce. For both inlets the maximum velocity is about 10% of the reference velocity.

Results for the 10% opening area, shown in Figure 4-18 for both inlets, indicate significantly higher tangential velocities than for the 50% case. The regions of tangential flow also occupy a large portion of the tube. These behaviors are possibly a result of the tilting of the 10% opening jet as seen in the visualization results in Figure 4-2. At 3D downstream, the triangular model maintains higher tangential velocity values than rectangular one.

Figure 4-19 shows the results for the 45° attachment angle at Reynolds number 4000. The results are qualitatively similar to those at Reynolds of 2000.
Figure 4-19 shows the tangential velocity results for attachment angles of 60° and 75°. The results show that attachment angle has only a moderate effect on the tangential velocity distribution with the magnitude and the maximum tangential velocity remaining at about 10%.

Figure 4-21 shows the results at Reynolds 4000. As the Reynolds number increases from 2000 to 4000, the maximum tangential velocity increases from 10% to 20%.

In summary, at 50% opening area and Reynolds 2000, a circumferential secondary flow near the anterior walls can be seen for the triangular shape at 1D downstream of the tube symmetrically around constriction centerline. This secondary flow moves in the anterior direction. For the rectangular case, the secondary flows are located at the side walls same as their axial velocity reverse flows. The tangential velocity is larger in the trachea with the triangular shape inlet compared to the rectangular one. For the triangular case, a stagnation point near the anterior side is apparent at 1D downstream. Changing the opening area from 50% to 10% causes the secondary flows to expand towards the center of the plane. This relatively large rotating flow can possibly be responsible for a deposition process in this region. Maximum tangential velocity is 10% and 30% of the maximum axial velocity at Reynolds 2000 and 4000 respectively.

4.5.3 Axial Velocity Fluctuation

Axial flow fluctuation distributions for different flow conditions are illustrated by the standard deviation plots in Figures 4-22 through 4-25.

Figure 4-22 shows the results for Re of 2000 and attachment angle of 45°. With a 50% opening, the overall flow fluctuation level for the triangular inlet is noticeably higher than for the rectangular one. The maximum level is above 20% for the triangular case, with high levels of fluctuation concentrated near the anterior at 1D and spread over a large area at 3D. For the
rectangular inlet the fluctuation level at 1D is mostly below 10%, and at 3D there is only a small area where the level is above 15%. With a 10% opening, however, the overall flow fluctuation level is noticeably higher for the rectangular inlet than the triangular. While the maximum level is above 24% for both cases at 1D, the area with high fluctuation is much larger in the rectangular case. Also for both cases the fluctuation level decreases significantly from 1D to 3D.

Figure 4-23 shows the results for Re of 4000 and attachment angle of 45°. With a 50% opening, the overall flow fluctuation level for the triangular inlet is noticeably higher than the rectangular one. The maximum level is above 39% for both cases, with high levels of fluctuation concentrated near the anterior for the triangular case at 1D. For the rectangular inlet at 1D there is only a small area where the fluctuation level is above 39%. In both cases, the overall fluctuation decreases from 1D to 3D. With a 10% opening, the maximum level is above 35% for both cases at 1D. The fluctuation level for the rectangular inlet however decreases at a much faster rate than the triangular inlet as the flow moves from 1D to 3D.

Figure 4-24 shows the effect of increasing the attachment angle at Re of 2000. For both the 60° and 75° attachment, the overall fluctuation level for the rectangular inlet is much higher than for the triangular case regardless of axial location and opening size. Figure 4-25 shows that when the Re is increased to 4000 the fluctuation level increases for both, and the two cases become relatively similar.

In summary, high velocity fluctuation regions are noted near the anterior side of the trachea for the triangular shape. It is proposed that these regions can have high potential for tracheal deposition. Schlensinger and Lippman[32] have also reported large numbers of particle deposition within this region and they proposed turbulence as the dominant mechanism for this deposition. These regions extend out symmetrically beyond the anterior-posterior midpoint of the tube.
Regions of high velocity standard deviation are more posteriorly in the 3D downstream plane because of the tilting of the jet. This high turbulence region can be identified near lateral side walls for the trachea with a rectangular aperture. Changing Reynolds number from 2000 to 4000 for the triangular constriction moves the high turbulence region from the posterior side towards the anterior side while for the rectangular one this area moves laterally.
Figure 4-13: LDA results for 50% opening triangular inlet model and Re 2000 at each point within 1D cross section
Figure 4-14: Contour of axial velocity (\(u\)) at Re 2000(45\(^\circ\) Attachment angle)
Figure 4-15: Contour of axial velocity (u) at Re 4000(45º Attachment angle)
Figure 4-16: Contour of axial velocity (u) at Re 2000 (50% Opening)
Figure 4-17: Contour of axial velocity (u) at Re 4000(50% Opening)
Figure 4-18: Contour of tangential velocity (v) at Re 2000(45° Attachment angle)
Figure 4-19: Contour of tangential velocity (v) at Re 4000(45° Attachment angle)
<table>
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<td>75°</td>
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Figure 4-20: Contour of tangential velocity \((v)\) at \(Re\ 2000\) (50% opening)
Figure 4-21: Contour of tangential velocity (v) at Re 4000(50% Opening)
Figure 4-22: Contour of axial velocity standard deviation at Re 2000 and 45° attachment angle
Figure 4-23: Contour of axial velocity standard deviation at Re 4000 and 45° attachment angle
Figure 4-24: Contour of axial velocity standard deviation at Re 2000 and 50% Opening
Figure 4-25: Contour of axial velocity standard deviation at Re 4000 and 50% Opening
4.6 PIV Results

Olive oil and salt water solutions were used as atomizer liquids for creating two particle size ranges. Olive oil particle size is around 0.6 µm and salt solution particle size is around 2 µm. The main purpose was to compare behaviors of particles of two different sizes and density within the flow domain.

The motion of any object is dictated by the balance between forces and inertia. In the present case, the particles are small and so viscous drag is the dominant flow force at the test speeds. The other important force is gravity, which is consistent for a given particle. Velocity lags between the flow and the particle will first develop in regions of low flow speed or sharp turns or both.

Each PIV result to be presented is the time-average of 15 instantaneous measurements. The images are taken with 0.2 seconds time interval. Thus the overall averaging time is three seconds. The camera is focused at 1D to 2D downstream region at the central lateral plane. For brevity only results for the 45° attachment angles are presented in this section. PIV results for other attachment angles and inlet model shapes are available in the Appendix.

The PIV results of olive oil and salt particles are compared in Figures 4-26 through 4-29 for different combinations of inlet and Reynolds number. The results show that the salt particles slow down and spread out as the flow moves vertically upward. Since the air flow fields are the same for both cases, the results indicate that significant velocity lags may have developed for the salt particles between 1D and 2D.

Figures 4-30 and 4-31 compare the salt particle velocity field at the mid-plane of the rectangular inlet case with that at the anterior-posterior plane of the triangular case. It can be seen
that as the flow moves from 1D to 3D the salt particles maintain a higher velocity in the triangular case than the rectangular. This is likely a result of the ability of the former to maintain a high speed region farther downstream as shown in the LDA results.
Figure 4-26: 50% opening, triangular inlet shape, Re 2000, 45° attachment angle

Figure 4-27: 50% opening, triangular inlet shape, Re 4000, 45° attachment angle
Figure 4-28: 50% opening, rectangular inlet shape, Re 2000, 45° attachment angle

Figure 4-29: 50% opening, rectangular inlet shape, Re 4000, 45° attachment angle
Figure 4-30: 50% opening, salt particle, Re 2000, 45º attachment, AP view

Figure 4-31: 50% opening, salt particle, Re 4000, 45º attachment, AP view
4.7 Spectral Analysis

Spectral analysis can give insight into the formation of the vortices and the cascade of the energy within the flow. Velocity signals were obtained using hot wire anemometry at various points and transformed to its frequency components using an FFT algorithm. Reynolds numbers of 2000 and 4000 are selected for both 10% and 50% opening inlets. In this section the results for both 10% and 50% opening at Reynolds 2000 and 4000 are presented. Other results are available at Appendix.

While the transition of a jet takes place at the shear layer, the process influences the entire flow. The potential core of the jet is affected mostly by the large scale vortices, developed in the shear layer, that induce a small fluctuation in the velocity across the core. The spectra in the central region will therefore be dominated by the large vortices and, as such, a distinct peak can be expected (if large vortices are present in the shear layer). The spectra at the shear layer on the outer part of the jet, on the other hand, will contain vortices and fluctuations of all the scales developed during transition. The shear layer flow therefore will have a broader spectrum compared to the potential core. Since the flow being study is three-dimensional and can involve a significant tilting of the jet axis, it is not known prior where the jet center is located. The spectra at five points (see Fig. 3.13) are therefore obtained at each cross-section to provide a more reliable representation of the spectral behavior than just a single point.

In the results to be shown, the Kolmogorov length scale, \( \lambda_K = \left( \frac{\nu^3}{\varepsilon} \right)^{\frac{1}{4}} \), and velocity scale, \( u_\lambda = (\varepsilon \nu)^{1/4} \), are used to normalize the spectra. A straight solid black line that appear in the graphs corresponds to \( K^{-5/3} \). In a fully developed turbulent flow \( K^{-5/3} \) is associated with the range of frequencies in which the inertial forces dominate the energy cascade process. After that
the slope is -3 which reflects the two dimensional turbulence. At higher frequencies the slope increases to around -7, which characterizes the dissipation range where viscous forces dominate the cascade of energy.

Figure 4-32 compares the spectra for the 10% opening triangular inlet model at five points. The Reynolds number is 2000. At 1D, a distinct peak can be seen only at P4 with 75° and 45° attachments. At all other locations the distribution is more broad-banded. Note also that for P4, save for the peak, the magnitude of the spectrum is significantly lower than at other points. This is one of the typical behaviors of a potential core during the early stage of transition. A peak can also be seen for the 60° attachment, but it is less distinct than other attachment angles and also at lower wavenumbers. The behavior is somewhat akin to that of a turbulent jet, for which there is at present no explanation.

As the flow reaches 3D downstream, the peak disappears and the energy distribution resembles that of a fully developed turbulent flow with identifiable inertial (-5/3 slope) and viscous dissipation (-3 slope) ranges. Having no peak at 3D downstream indicates that large vortex structures have dissipated before 3D downstream of the inlet and the energy cascade process is becoming universal afterward. Therefore the development of the spectra indicates that the flow is dominated by the shear layer vortex roll up at 1D downstream which eventually evolves to a broad frequency distribution with no discernable frequency peaks at 3D downstream.

Figure 4-33 shows the results for the 50% opening triangular at Re of 4000. Points P4, P0 and P1 show the behavior of potential core described previously. At points P2 and P3, the peaks are less distinct due to a higher base energy. Together the results indicate a tilting of the jet toward the direction of P1 and P4. All spectral peaks disappear as the flow reaches 3D except for point P4 where a small peak persists. This confirms the existence of large scale vortices at 3D downstream.
of the flow inside this triangular inlet model. This is consistent with the observation of a potential core (based on the LDA data) at this location.

The peak energy levels are higher in the triangular model compared to the rectangular one. Also the triangular inlet shape is creates a strong vortex near the posterior wall (an ideal place of deposition within human airway) while the rectangular one does not. Large vortex existence near the posterior wall can greatly influence the particle deposition by trapping the particles and turning them to the posterior side near the wall where they can be deposited. However this mechanism cannot be achieved with the rectangular inlet.

Figure 4-35 shows the spectra for the 50% rectangular opening area at Re of 4000. Overall behaviors are similar to the other cases discussed above. Results at P0, P2 and P4 are similar and exhibits potential core behavior at 1D. This indicates there is little to no tilting of the jet. At 3D all large vortices cascade to the smaller ones and therefore wide ranges of vortices can be seen at 3D. Comparing these results with the 50% triangular inlet models, it shows that there are still large scale vortices available at 3D downstream for the triangular model while all large vortices expand to create a wide frequency range for the rectangular model. This again shows the capability of the unique larynx model in preserving turbulence to further distances (up to 3D).
Figure 4-32: Power spectrum graphs for 10% opening triangular inlet model at Re 2000
Figure 4-33: Power spectrum graphs for 50% triangular inlet opening model at Re 4000
Figure 4-34: Power spectrum graphs for 10% rectangular inlet opening model at Re 2000
Figure 4-35: Power spectrum graphs for 50% rectangular inlet opening model at Re 4000
Chapter 5

Conclusions and Recommendation

The present study attempted to address the effects of the glottal constriction on the generation, convection and subsequent decay of the turbulence in the trachea. An attempt was made to provide full visualization and measurement of the flow within the trachea which can illustrate the crucial effects of glottic aperture on the flow. This is the dominant part of the lung system in filtering inhaled particles and gas scrubbing. In fact without this filtration pattern, human life would not be possible.

Three different geometrical features of opening ratio, shape and angle of the glottis are studied at different flow rates. Results confirm the existence of the glottal jet and recirculation regions within the trachea which can have significant effects on mixing and particle deposition. Such results can also be helpful in designing high performance, relatively simple and inexpensive natural industrial filtrations that can have wide ranges of applications.

Different experimental tools such as Laser Doppler Anemometer, hot-wire anemometer and PIV were applied to measure different features and three dimensionality of the flow. Such data can also be a great source for numerical analysis as a reference.

The results show the formation of a laryngeal jet and near wall vortex structures, in qualitative and quantitative manners, in both rectangular and triangular inlet models typical to inlet human trachea. The basic features of the flow show that the triangular inlet shape creates asymmetric vortex structures at anterior, posterior and lateral regions while the rectangular inlet causes symmetric vortex regions along the lateral region. These regions coordinate with the
geometric features of the human airway. The posterior wall of the trachea does not have a fixed cartilage structure, which allows us to decrease the trachea diameter during coughing. Therefore it is supposed that the larynx is evolved in a way to localize the deposition along this posterior region which the measurements also confirm this statement.

Attachment angle studies show that the 45º attachment angle at 50% opening area creates more turbulence intensities near the wall which can potentially increase the particle deposition.

PIV studies confirm the effectiveness of the triangular inlet in pushing the particles towards their nearest side wall. This effect was not very organized in the rectangular inlet model.

Power spectra studies show the existence of larger vortices even at 3D downstream of the inlet for the triangular model, which suggests the effectiveness of the triangular larynx in preserving the turbulence at high levels. The skewed laryngeal jet towards the posterior wall for the triangular inlet model also can potentially enhance the deposition.

However there are other ways to perform the study of examining the flow within the human trachea in more depth. One suggestion is to use a wider particle size range which needs particle atomizer equipment and measure the movement of larger particles within the domain. It seems that the olive oil and salt particle size range are close and therefore it is currently hard to get distinct difference between their movement within the models.

In this study the effect of the trachea downstream branching is neglected. Another suggestion can be doing the experiments in a model including the tracheal downstream branches which might have some effect at the flow inside the trachea.

Recently various numerical models have been developed that are able to simulate complicated turbulent flows. Developing such CFD models for predicting flow behavior inside the
human trachea at different Reynolds numbers and opening area can be another topic for the extension of this study.
### Appendix

Table 6-1: Different Combinations of shape, opening area, attachment angle and Reynolds numbers of the larynx trachea model used for visualizations.

<table>
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<th>Attachment Angle</th>
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Figure 6-1: High speed camera used for visualization experiment (OLYMPUS)
Figure 6-2: Laser Doppler Anemometer
Figure 6-3: IFA 100 system intelligent flow analyzer used for hot-wires measurement
Figure 6-4: Pitot static probe and digital manometer used for hot-wire calibration
Figure 6-5: Hot-wire Calibration set up
Figure 6-6: Contour of tangential velocity standard deviation at Re 2000 and 45° attachment angle
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Figure 6-7: Contour of tangential velocity standard deviation at Re 4000 and 45° attachment angle
Figure 6-8: Contour of tangential velocity standard deviation at Re 2000(50% Opening)
Figure 6-9: Contour of tangential velocity standard deviation at Re 4000(50% Opening)
Figure 6-10: 50% opening, salt particles, Re 2000, 60° attachment angle
Figure 6-11: 50% opening, salt particles, Re 4000, 60° attachment angle
Figure 6-12: 50% opening, salt particles, Re 2000, 75° attachment angle
Figure 6-13: 50% opening, salt particles, Re 4000, 75° attachment angle
Figure 6-14: 50% opening, olive oil particles, $Re = 2000$, $60^\circ$ attachment angle
Figure 6-15: 50% opening, olive oil particles, Re 4000, 60° attachment angle
Figure 6-16: 50% opening, olive oil particles, Re 2000, 75° attachment angle
Figure 6-17: 50% opening, olive oil particles, Re 4000, 75° attachment angle
Figure 6-18: Power spectrum graphs at point P₀, Re 2000

Figure 6-19: Power spectrum graphs at point P₁, Re 2000
Figure 6-20: Power spectrum graphs at point P₂, Re 2000

Figure 6-21: Power spectrum graphs at point P₃, Re 2000
Figure 6-22: Power spectrum graphs at point P₄, Re 2000
Figure 6-23: Power spectrum comparison of different inlet shapes at 10% opening, Re 2000 and 45° attachment angle
Figure 6-24: Power spectrum comparison of different inlet shapes at 50% opening, Re 4000 and 45° attachment angle
References


43. Soodt, T., et al., *Analysis of basic flow regimes in a human airway model by stereo-scanning PIV.* Experiments in Fluids, 2013. 54(6).


