CFD Heat Transfer Simulation of the Human upper Respiratory Tract for Oronasal Breathing Condition

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Abstract

Injuries due to inhalation of hot gas is commonly encountered when dealing with fire and combustible material posing a threat to the human life. Various studies have been carried out in the literature investigating the heat and mass transfer characteristics in the human respiratory tract. This study focuses on assessing the injury taking place in the upper human respiratory tract and identifying acute tissue damage based on level of exposure. A three dimensional heat transfer simulation is performed using a CFD software to study the temperature profile through the upper human respiratory tract consisting of nasal, oral, trachea and the first two generations of bronchi. The model developed is for the simultaneous oronasal breathing during the inspiration phase with high volumetric flow rate of 90 liters/minute and the inspired air temperature being 100 degrees Centigrade. The geometric model depicting the upper human respiratory tract is generated based on the data available and literature cited. The results of the simulation give the temperature distribution along the center and the surface tissue of the respiratory tract. This temperature distribution will help to assess the level of damage induced in the upper respiratory tract and appropriate treatment for the damage. A comparison of nasal breathing, oral breathing and oronasal breathing is performed. The temperature distribution can be utilized in the design of the respirator systems where the inlet temperature is regulated favoring the human body conditions.

Introduction

Various studies have investigated the heat and mass transfer in the human respiratory tract. The inspired air is heated to normal body temperatures and the expired air is cooled to regain the heat back in the body. These measurements of the heat and water transport were carried out by the use of thermocouples by Farahmand and Kaufman [1]. Mathematical models depicting the heat and water transport phase by McCutchan et al. [2], Tsai et al. [3] and Tsu et al. [4] were used for numerical simulation and to determine the heat transfer characteristics of the region. Recent trends include, generating the three dimensional model of the respiratory tract into CFD software. The model generation is based on the magnetic resonance imaging (MRI) or computed axial tomography (CAT) scan of the respiratory tract obtained from a healthy volunteer. Most models use the Navier-Stokes equation for the CFD simulation. The simulation performed in the above cases analyzed the heat transfer at room temperature. Lv et al. [5] performed a 2D simulation to analyze the injury taking place in the respiratory tract during inhalation of hot air. The study of the heat and mass transfer, aerosol deposition and flow characteritics in the upper human respiratory tract using computational fluid mechanics simulation requires access to a 2D or 3D model of the human respiratory tract. An exact model is a complex task to obtain since it involves use of imaging devices on the human body. Hence a simplied 3D geometry representing the upper human respiratory tract is developed here consisting of nasal cavity, oral cavity, nasopharynx, pharynx, oropharynx, trachea and the first two generations of the bronchi. The respiratory tract is modeled circular in cross-section and varying diameter for various portions as identified in this study. The dimensions are referenced from the literature herein. Based on the dimesions a simplified 3D model representing the upper human respiratory tract is generated. This model will be useful in studying the flow characteritics and could assist in treament of injuries of the human respiratory tract and to help determine a drug delivery mechanism and dosages.

A study of the heat transfer mechanism of the human respiratory tract helps asses any heat, smoke and fire related injury affecting the human respiratory tract. The design of respirator systems used by people working in extreme environments, like fire fighters exposed to forest fire, chemical and biological exposure or hazardous material exposure can be better improved by comprehensive study of the thermal profile. This can help in better occupational health and safety in the case of firefighters and emergency responders. These emergency responders are exposed to extreme temperatures and do have protection equipments like a respirator for oxygen supply, but still the inhaled air is heated because of the extreme temperature in the surrounding atmosphere. Lv et al. [5] evaluated the burn injury due to inhalation of hot gas. The evaluation was based on a two-dimensional model of heat transfer normal respiration characteristics were taken into account (nasal breathing, cycle duration 3 seconds and respiration frequency 20 breaths/minute). In emergency situations there is bound to be chaos and confusion in addition to the physical load, the increased heart rate and respiration rate dictate a high possibility of oronasal breathing (simultaneous breathing via oral and nasal cavity) taking place expectedly when under physical stress. A 3D heat transfer study is performed here to identify the temperature obtained at the surface of the tissue during the inspiration phase. Various works are available in literatures that study the temperature profile in the respiratory tract which includes the nasal and the oral respiratory tract separately.

Methodology

To study the characteristics such as particle deposition, burn injury, and heat and mass transfer in the upper human respiratory tract (HRT) various models were developed. These models were based on the images obtained from computed tomography (CT) scans, MRI and or acoustic rhinomanometry (AR). This procedure is complex and access to these images is limited. The cost involved with the use of these data too is high. Hence simplified airway geometry of the HRT consisting of nasal airway, oral airway, pharynx, trachea and first two generations of the bronchi is developed based on the data available from the literature cited herein.

Simplified models which could be standardized for the purpose of CFD simulation were developed and used in this study. The geometry of the respiratory tract is complex and hugely differing for each individual. The model developed here is based on the data available in literature cited herein [6-21], as measurement of real time data is a complex process and costly. Based on the measurement in the literature, the simplified 3D geometry of the upper HRT is developed. The proposed method here is to build a simplified three dimensional model representing the upper HRT that serves as a simplified model to simulate and study various flow characteristics.

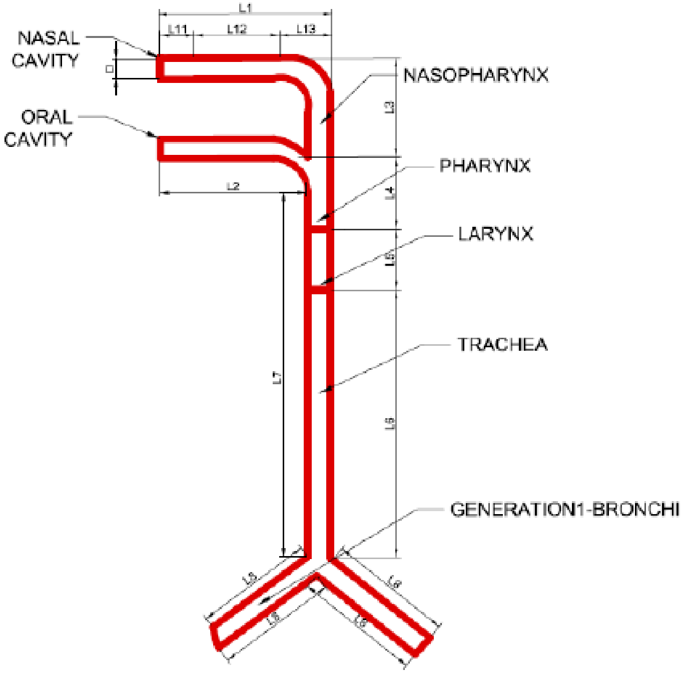

Figure 1. The Human Respiratory Tract

Figure 1 shows the structure of the HRT consisting of the nasal cavity, oral cavity, nasopharynx, pharynx, larynx, trachea and first two generations of the bronchi. The geometry here has varying diameter for nasal, oral, pharynx, larynx, tracheal and bronchi regions. The horizontal tract for simulation purpose is bent at an angle 90^{o}.

Variations in the diameter observed while joining the two portions having different diameters, and this is assumed to depict the irregularities in the human respiratory tract. Human tissue is highly flexible; it contracts and expands based on the amount of pressure applied on the human body. The pressure exerted by body posture also leads to the expansion or contraction of the internal organs including the HRT. For example when a person is lying backwards, there is expansion in the human body and while bending inwards or forward there is a contraction of the muscles. The above factors are complicated to address and contribute to the complexity in defining the geometry of the respiratory tract. The simple model created here represents an ideal HRT up to the first two generations of the Bronchi which are based on the dimensions cited. There is a difference between dimensions created in the geometry when drafted in 3D software and as in literature, but these variations were unavoidable and related to the complex shape of the HRT.

CFD Simulation

Computational Fluid Dynamics (CFD) software enables us to study the heat transfer characteristics (temperature profile), and performs calculations using the numerical formulas/equations based on the laws of physics. The CFD simulation is based on the Navier-Stokes equation for three dimensional incompressible flows. The CFD software used here for simulation Ansys CFX 12. The procedure to use the CFD software generally consists of four major steps; first the geometry is created using three dimensional modeling software, after development the model is imported into the CFD software that constitute the second step where parameters are defined followed by the third step of simulation run. The fourth step consists of the post-processing of the results.

The volume of air intake in the respiratory tract will be in the case of an excited condition where oronasal breathing takes place in emergency situations. The volume of air intake in this case will be subject to oronasal breathing during heavy exercise. Wheatley et al. [22] have determined the airflow characteristics during heavy exercises and have stated that over 80% of normal subjects breathe oronasally. The minute ventilation (V_E) before the exercise was 10.7 +/- 1.01 l/min. The switch from nasal to oronasal breathing took place at a minute Ventilation of 22.3 +/- 3.5 l/min and the final value obtained was 75.7 +/- 5.01 l/min. Malarbet et al. [23] in their study observed that the switch from nasal to oronasal was made at the ventilation rate 35 l/min and the maximum observed value of ventilation rate was 90 l/min. The minute ventilation or total ventilation (V_E) is the product of tidal volume (V_T) and frequency of breathing (f). Mathematically expressed as $V_E = V_T . f$. Where V_T is the volume of air exhaled during one respiratory cycle.

The fluid breathed in during the inspiration phase consists of hot air having a temperature of 100 degrees Celsius and the density of air being 0.946 kg/m^3. The wall is maintained at a temperature of 37 degrees Celsius with the heat transfer option selected. The fluid flow is a turbulent flow having a high Reynolds number. Varene et al. [24] have conducted a study that the temperature during inspiration (T_I) and during expiration (T_E) differs for oral and nasal cavity, oral cavity having the higher temperature rate than the nasal cavity. But this was concluded by the fact that no large differences exists from an energetic point of view between nasal and oral cavity as the difference in heat exchange were found to be very less and the total power loss was only 7 % lower during the nasal breathing than during mouth breathing. Niinima et al. [25] also studied the effect of exercise over breathing. It was concluded that as the intensity of exercise increased, the flow rate increased. The Reynolds number calculated here is 4130 based on the diameter of the Trachea. The convergence criterion was set to 1E-6 and the due to time and computational limitations (computer configuration) the maximum number of iterations was set to 200. Two different mesh configurations were considered for the study.

Results

The results from the simulation are obtained for temperature distribution along the flow for the nasal cavity, oral cavity and the trachea. A cross-sectional view showing the temperature variation inside the respiratory tract up to the tracheal region is shown in Figure 2.

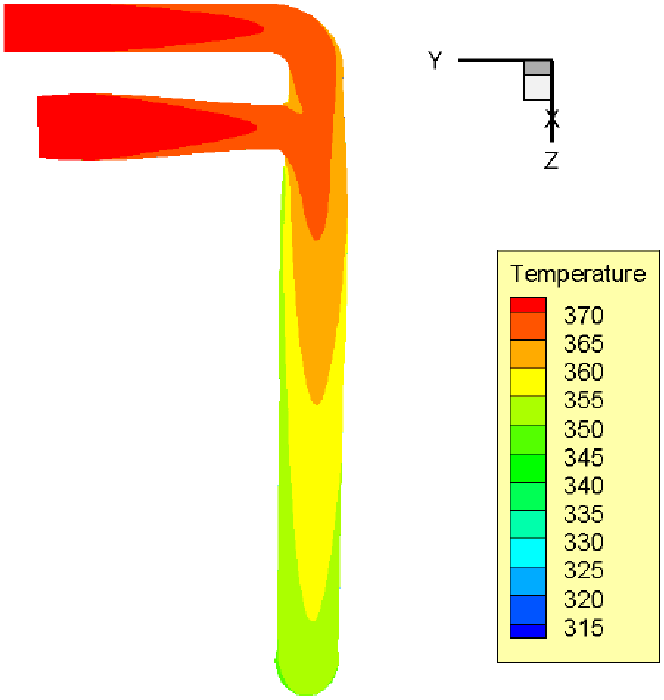

Figure 2. Temperature variation (A cross sectional view)

The temperature variations can be observed here, at the inlet the temperature is the air temperature (surrounding temperature) and the air temperature decreases as it flows through the tract. This is due to the heat exchange between the inlet air and the respiratory tract. Temperature profiles for the portion of nasal cavity, oral cavity and the tracheal region along the cente as the path along which temperature variation shown is identified as A for nasal cavity, B for oral cavity and C for tracheal region in Figure 3.

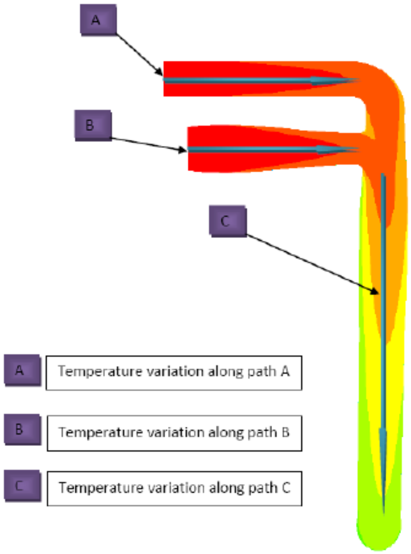

Figure 3. Temperature profile along the nasal, oral, and trachea

Figure 4 depicts the variation in the temperature along the center path of the nasal cavity up to a distance of 100 mm in horizontal direction i.e. part A in Figure 3. The variations in the temperature can be seen for the two different mesh configurations. A decrease in the flow of the temperature is observed.

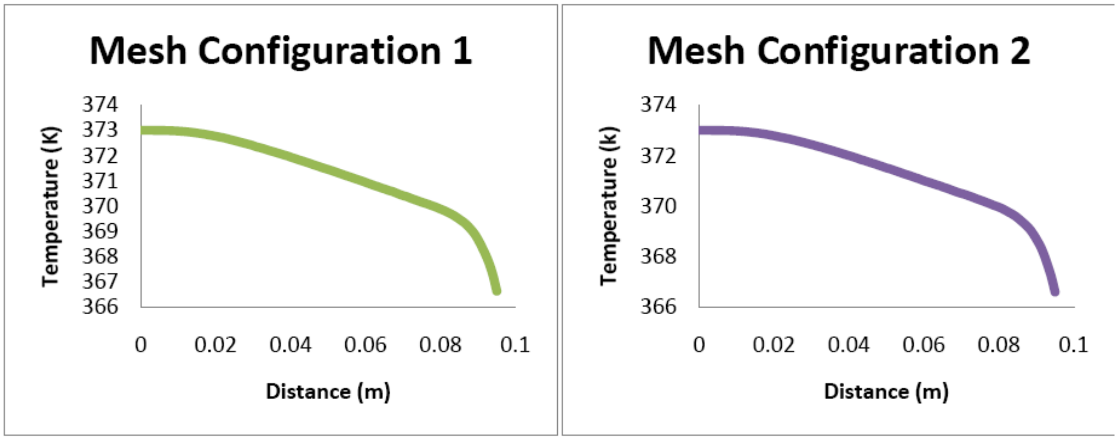

Figure 4. Nasal temperature profile for two mesh configurations

Figure 5 shows the variation in the temperature along the center path of the oral cavity in horizontal direction i.e. part B in Figure 3. The variations in the temperature can be seen for the two different mesh configurations. A decrease in the flow of the temperature is observed.

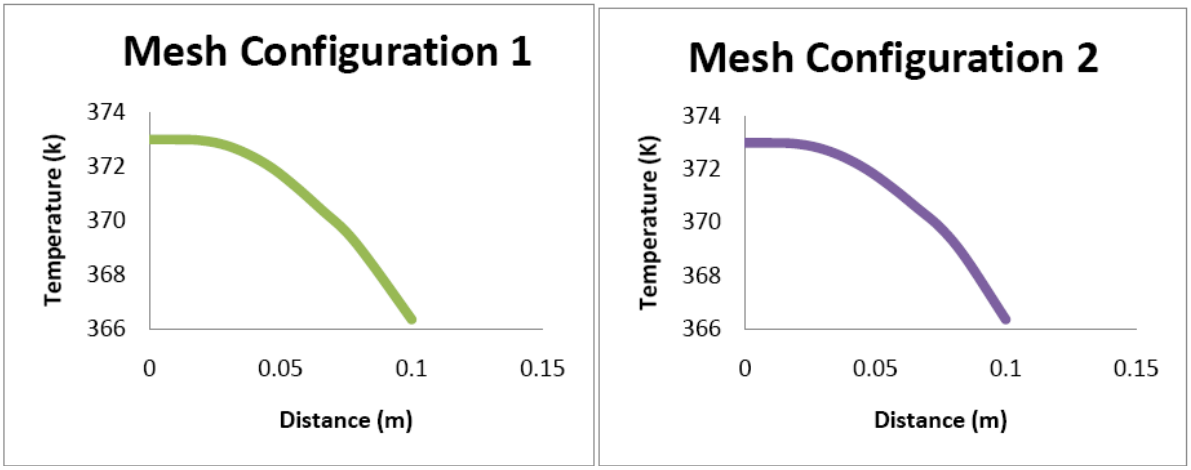

Figure 5. Oral temperature profile

Figure 6 depicts the variation in the temperature along the center path of the trachea up to a distance of 200 mm in vertical direction i.e. part C in Figure 3. The variations in the temperature can be seen for the two different mesh configurations. A decrease in the flow of the temperature is observed as the flow reaches close to the bronchial region.

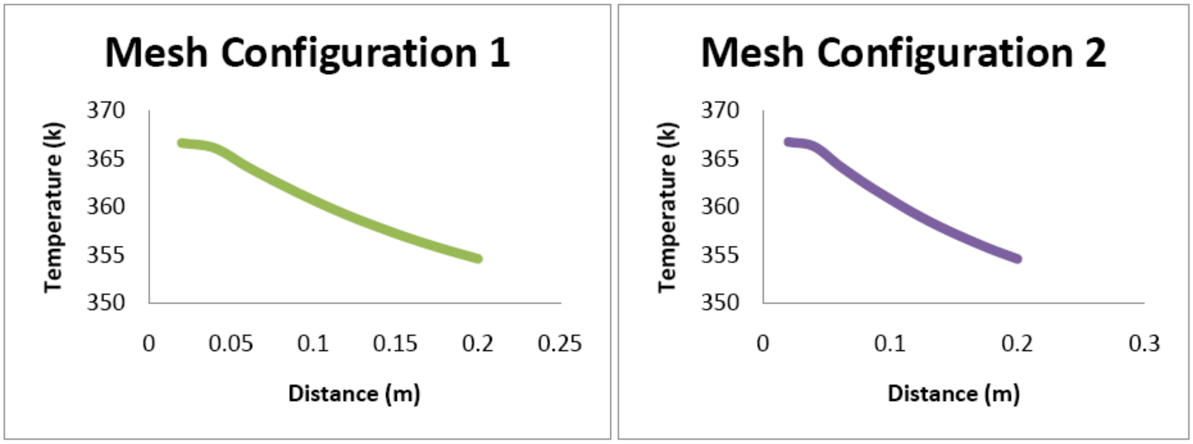

Figure 6. Tracheal temperature profile

The inlet air temperature decreases gradually as it passes through the bronchi and to the lungs. This phenomenon is observed due to the fact that body absorbs much of the heat from the inlet air if the inlet air temperature is higher body temperature. As it is assumed that the body temperature is constant throughout and less than the inlet air temperature, it is expected that there will be a decrease in the air temperature as it reaches the bronchi.

The temperature due to the flow along the wall surface being in range of 315 K for the two meshes. At the center along the centerline the temperature is high, which is the inlet atmospheric air at 373 K as in Figure 7. The temperature profile along the center of the respiratory tract is observed for the specified path in Figures 2, 3, 4,5 and 6.

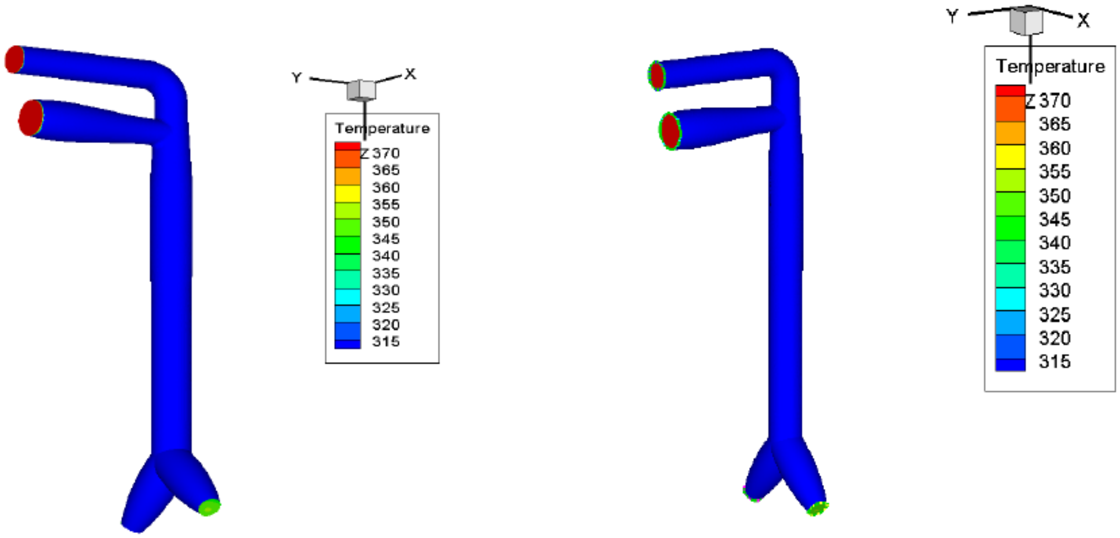

Figure 7. Surface temperatures obtained

Figure 8 compares the temperature profile along the three different types identified as oronasal breathing, nasal breathing and oral breathing conditions. The profile for the nasal cavity during the oronasal breathing and nasal breathing follow a similar trend. The inlet temperature here is 373 K and at a distance of 100 mm it drops to 366 K. For oral breathing the temperature profile has an upward trend. The profile for the oral cavity during oronasal and oral breathing follow a similar pattern where the inlet temperature is 373 K and the temperature obtained at a distance of 100 mm is about 364 K. The tracheal temperature profile for the three different breathing conditions has a similar trend. The temperature at the inlet point of the path being about 365 K – 368 K and decreasing to 350 – 355 K for a distance of 200 mm as defined in the model.

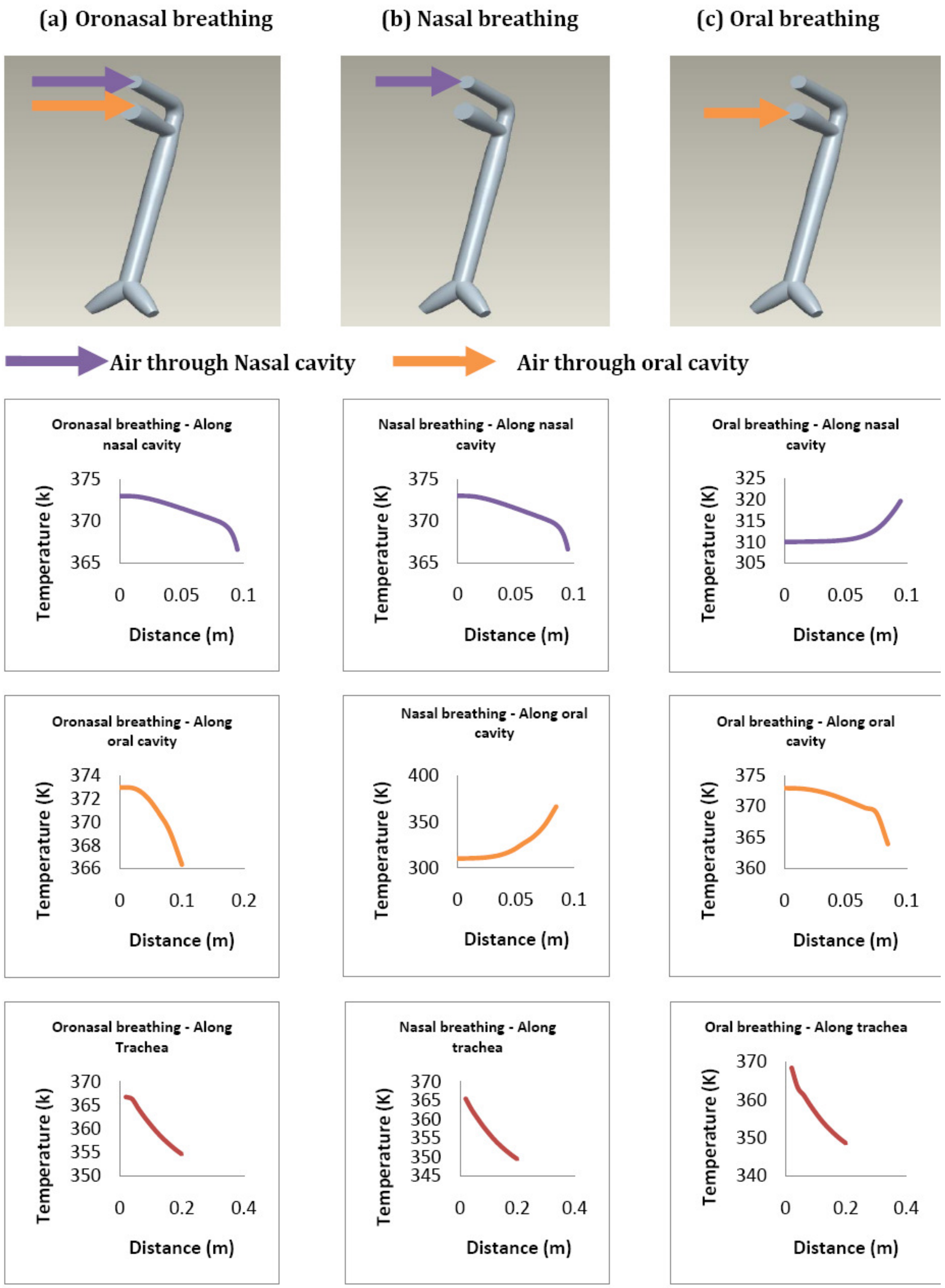

Figure 8. Comparison of nasal breathing, oral breathing and oronasal breathing

Discussion

The temperature plots shown in Figures 4, 5 and 6 give the temperature variations along the nasal cavity, oral cavity and the tracheal region. For the nasal and oral cavity the temperature variation shown starts from the inlet portion up to a distance of 100 mm inside the cavity. The temperature variation for the tracheal cavity is from the start of the oropharynx region up to a distance of 200 mm close to the bronchi. This temperature change is represented by the points along the centre of the cavity. The temperature of the walls for the two mesh configurations in Figure 7 shows a temperature of 315 K. Thus it can be inferred that the inhaled air causes the wall temperature of the respiratory tract to attain a temperature of 315 K when oronasal breathing takes place in the conditions specified. For the mesh validation two different mesh configurations were simulated. The two mesh sizes give similar results hence we can conclude that the results are independent of the grid size. This wall temperature will be the temperature obtained at the surface of the tissue leading to a possible injury to the respiratory tract.

Conclusion

A heat transfer study along the Human Respiratory Tract (HRT) gives the temperature distribution and variation along the surface of the respiratory tract for the given length during oronasal breathing conditions. The temperatures obtained along the tissue walls help in assessing the internal burn injury caused. This study will assist in developing safe and effective preventive measures and treatments to the injuries caused in the respiratory tract. Design of respirator devices and safety features for the occupations that involve exposure to extreme and unfavorable conditions hazardous to the human health can be well implemented by knowing the level of injury caused in the HRT. A comparison of the differences in the temperature profile in the HRT considering variations in breathing pattern and the implementation of respiratory devices to cool the inhaling air temperature to normal range will be quite effective in preventing any injury. Future studies could include the use of hazardous particle deposition along the respiratory tract during oronasal breathing while simulating various adverse conditions.

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Biography

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