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Experimental and Numerical Study of Dysphagia

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Abstract

Dysphagia, meaning difficulty in swallowing, is a symptom of disease that occurs in young children and elderly people. It occurs particularly due to two reasons, weak neural network and/or deformities in oral section/s. The Helen DeVos Children's Hospital's Intensive Feeding Program takes care of children suffering from Dysphagia. In order to make the swallowing process easier and in some cases safer, thickener is added to the liquids. Depending on the requirement of thickness, the amount of thickener is varied. Although the directions to prepare the mixtures are given by the thickener product company, the required thickness is not achieved when the thickeners are added to different fluids, reason being each base fluid having its own viscosity. The hospital follows the viscosity scale given by National Dysphagia Diet (NDD) and volumetric measures for preparing Nectar thick and Honey thick liquids with various base liquids are to be determined through experimentation. The effect of time on the viscosity of the samples was studied after 24 hours of refrigeration.

A Computational Fluid Dynamics (CFD) study was carried out in order to study the flow of the fluid in the oropharyngeal track to identify the necessity of specific viscosity in typical geometry, geometry affected due to cleft palate and geometry with poor Velo-Pharyngeal Range of Motion (VPROM).

Using a viscometer, the viscosity values of Nectar and Honey thick samples were recorded and the necessary volumetric measures for Nectar and Honey thick scales were determined, followed by the viscosity analysis of the selected samples before and after 24 hours of refrigeration. The CFD study for the base case and two selected cases were carried out to study the flow patterns and the requirements of specific scale of viscosity for the specific oropharyngeal geometries were analysed.

After the experimental and numerical study on Dysphagia diet fluids regarding their viscosity, followed by the analysis of the results so obtained, the volumetric measures were provided to the clinic and time effect analysis was presented. The analysis of the flow patterns in the oropharyngeal track with different viscosities was carried out and the results were presented.

It was found that the thickener contents react with the base fluids differently. Therefore, the amount of thickener to be added to each of these base fluids varies, to get the desired consistency. The numerical study reveals that altering the viscosity of the samples helps for easy swallowing. People suffering from Dysphagia with deformities in their oropharyngeal track can swallow easily by altering the viscosity of the sample. With the poor VPROM case, it was also noted that increasing the viscosity of the sample does not always help for easier swallowing.

Keywords: Dysphagia, National Dysphagia Diet (NDD), Viscosity, Computational Fluid Dynamics (CFD)

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1 Introduction

The World Health Organization (WHO) describes dysphagia as “difficulty in swallowing”. Dysphagia can be characterized into 3 types, oral, pharyngeal, and esophageal. For the purpose of this study the focus will only be on oral and pharyngeal dysphagia which is referenced together as oropharyngeal dysphagia. Oropharyngeal dysphagia is difficulty in the transition of fluid and/or drink from the oral cavity through the pharynx and down to the upper esophageal sphincter. It is usually a sign of a problem with one’s throat or esophagus, the muscular tube that moves fluid and liquids from the back of the mouth to the stomach. Although dysphagia can happen to anyone, it is most common in older adults, babies, and people who have problems of the brain or nervous system. There are many different problems that can prevent the throat or esophagus from working properly. Some of these problems can be minor, and others are more severe. If one has a hard time swallowing once or twice, problems can be a medical problem. However, if a person has trouble swallowing on a regular basis, a more serious problem may be occurring and could require treatment. [1]

As fluid is chewed, the muscles of the tongue gathers the fluid and push it in to the pharynx. Now, the neural network closes the larynx (wind pipe) with the help of the epiglottis and nasal cavity is closed by the soft palate. Once the fluid is in the esophagus, these muscles reopen the nasal cavity and larynx.

If a person has neural problems, this process of closing and opening of the air pipe and nasal cavity does not take place appropriately and there is a risk of fluid entering into the air pipe, which is termed ‘Aspiration’. Also, if the neural network is weak, the tongue and the oral muscles may not appropriately manipulate and transfer fluid through the oral cavity and pharynx. This is one example of difficulty that would be called ‘Dysphagia’.

1.1 Causes of Dysphagia [1]

As discussed above, the chewed fluid or liquid is pushed in to the esophagus with the help of muscles in the throat and the esophagus squeezing. This happens in regular case, whereas, sometimes the fluid does not travel to the esophagus naturally. There are various reasons due to which it can happen. There are basically two types due to which Dysphagia can happen.

Type 1: The muscles that help the swallowing procedure and esophagus are not functioning correctly. There are several reasons due to which it can happen. This reasons are listed below:

- Brain injury
- Nervous system problems
- Immune system problems causing inflammation
- Esophageal spasm, meaning, the muscles of the esophagus suddenly squeeze
- Scleroderma, where the tissues of the esophagus become hard and narrow.

Type2: Throat or esophagus is blocked due to some reasons. The reasons causing this problem are listed below:

- Gastroesophageal reflux disease (GERD). When stomach acid backs up regularly into the esophagus which can cause ulcers in the esophagus. This can cause scars and these scars can make the esophagus narrower.
- Esophagitis, which means inflammation of the esophagus.
- Diverticula, which are small sacs in the walls of the esophagus or the throat.
- Esophageal tumours, which are growths in the esophagus may be cancerous or not cancerous.

2 Review of Literature

According to Rebecca J. Leonard Et. Al. [2], manipulation of the bolus is considered to be primary treatment strategy for managing the oral-pharyngeal dysphagia. This study was mainly focussed on investigating the effects of viscosity on aspiration. This study was carried out across three standardized and randomized conditions. These conditions were thin liquid barium, liquid barium thickened with starch based agent and liquid barium thickened with gum based agent. 23% of the patients experienced 56 episodes of aspiration. It was noted that the thin liquid causes more aspiration than that of other viscosities which are more viscous. Also, the study referred to National Dysphagia Diet's scale of viscosities for dysphagia diet.

According to Azizollaah Zargaraan Et. Al. [3], "Dysphagia is a symptom, commonly found in healthcare residents and the elderly, may lead to undernutrition and negative effects on quality of life. Providing special fluid products that cannot only be swallowed by patients but also meet nutritional requirements is a challenge for fluid rheologists and healthcare staff." The main purpose of this literature was to review the literature on rheological aspects of dysphagia oriented fluids. The viscosity ranges for the dysphagia diet were confirmed to be following the NDD scale from this literature.

Another publication [4] revealed that due to inconsistencies in the overall structure of the starch based products, the patients might not be getting the advised consistency fluid, which could then affect detrimentally on their swallowing ability. Also, the NDD scale for dysphagia diet was confirmed from this literature reference.

From the literature reviewed above and from the information obtained from other publications [6, 7, 8], it was understood that the National Dysphagia Diet (NDD) had categorised the dysphagia fluids as below:

- Thin (1 cP - 50 cP)
- Nectar (51 cP - 350 cP)
- Honey (351 cP - 1750 cP)
- Pudding (Greater than 1750 cP)

In the literature, it was found that a very few people had done the viscosity measurement experiments of the dysphagia fluids with the use of Viscometer and many of the others have used the Line Spread Test (LST). LST is the simplest test that can be done to find viscosity scale in which the tested specimen falls. The specimen is poured on to the LST board and depending upon how long the specimen spreads over the markings on the board, the viscosity and hence the scale of the specimen is determined. One significant limitation with this method of viscosity determination is not very accurate and viscometers must be used for the purpose. The findings of Viscosity-Time comparison study [11] are presented below. The study considered five different thickeners for comparison. The thickeners used were as follows:

- Thick and Easy
- Thick It
- Thicken Up
- Simply Thick
- Thik and Clear

Viscometer used: **Brookfield RVDV-II +**

Experimental results were as follows:

Table 1. Nectar-like Viscosity measurements [11]

Thickener	Viscosity (cP)
Thick and Easy	
Standard	48
10 minutes later	67
30 minutes later	77
Thick It	
Standard	62
10 minutes later	123
30 minutes later	130
Thicken Up	
Standard	136
10 minutes later	169
30 minutes later	210
Simply Thick	
Standard	54
10 minutes later	52
30 minutes later	53
Thik & Clear	
Standard	153
10 minutes later	144
30 minutes later	144

From the table above, it was noticed that the viscosity of the sample with Simply Thick as thickener was less than that of the rest of the thickeners in comparison except for Thick and Easy. The samples with Simply Thick as thickener barely had the consistency of Nectar according to NDD scale. From these results, it was noticed that Simply Thick does not add more thickness to the fluid as compared to other thickeners.

Table 2. Honey-like Viscosity measurements [11]

Thickener	Viscosity (cP)
Thick and Easy	
Standard	344
10 minutes later	557
30 minutes later	637
Thick It	
Standard	584
10 minutes later	985
30 minutes later	1219
Thicken Up	
Standard	251
10 minutes later	328
30 minutes later	405
Simply Thick	
Standard	213
10 minutes later	211
30 minutes later	210
Thik & Clear	
Standard	224
10 minutes later	241
30 minutes later	221

From the table above, it was noted that the samples with Simply Thick thickener, did not even fall in the Honey thick category according to NDD scale. Also, it confirmed that Simply Thick does not add much consistency to the liquid. The viscosity of the sample with Simply Thick as thickener did not lower much even after 30 minutes. This means that Simply Thick does not add much consistency to the fluid but it does hold the viscosity over the period of time. This may be because of the material properties of the contents of Simply Thick thickener.

After reviewing similar studies, the working range of the fluid viscosities was determined. The information is presented in the tabular format (All the values are in cP), see appendix.

With regards to the later part of the study, a mathematical study [14] was found which had done similar studies of bolus transport through the pharynx. Although, the basic purpose of that study was different, some important parameters about the solid model and the bolus parameters were found useful, and are presented below:

- Velocity of bolus in the pharynx = 5 cm/s
- Velocity of the bolus while travelling through the esophagus = 2.5 – 5 cm/s
- Newton-Raphson's solution algorithm was used to simulate the bolus transport
- Finite element mesh was built using solid elements for all the organs
    - Oral Cavity
    - Pharynx
    - Esophagus
- Most of them were eight node hexahedron
- Total of 0.6 to 2.2 million of node

3 Methodology

The Helen DeVos Children's Hospital Intensive Feeding Program (HDVCH IFP) treats children with dysphagia. One treatment approach the HDVCH IFP considers to treat oral and/or pharyngeal dysphagia is altering liquid consistencies by making liquids thicker or thinner based on the need of the child. When liquids need to have increased thickness, commercial thickeners are often used to achieve a desired consistency. However, despite the specified directions of commercial thickeners, desired thicknesses are often not achieved due to the commercial thickeners being tested on water and/or juice and not on nutritional supplements. Nutritional supplements are thicker than water and juice initially, so when commercial thickeners are added to them the result is often a liquid that is thicker than desired.

For the same reason, there was a need of experimentation to find the volumetric measures of the thickener that was being used for five different fluids to get the mixture samples to fall into Nectar and Honey categories as decided by the National Dysphagia Diet (NDD). This study can be divided in to two different sections, which are, Experimental study and Numerical Study. The table below explains the experimental study cases that are to be carried out.

Table 3. Plan of action (Experimental Study)

Base Fluid	Consistency
Water	Nectar thick
Whole Milk	
Pediasure 1.0	
Pediasure 1.5	
Pediasure Peptide 1.0	
Water	Honey Thick
Whole Milk	
Pediasure 1.0	
Pediasure 1.5	
Pediasure Peptide 1.0	

Also, the table below explains the case studies to be carried out for numerical study part of this whole study.

Table 4. Plan of action (Numerical Study)

Case	Consistency
Regular	Thin thick
	Nectar thick
	Honey thick
Cleft Palate	Thin thick
	Nectar thick
	Honey thick
Poor VPROM	Thin thick
	Nectar thick
	Honey thick

3.a Experimental Study

Given that the thickener used does not give the expected results with regards to the consistency of the samples prepared, the necessary volumetric measures will be decided based on the results from the experiments.

Below are the five base fluids that were to be tested:

1. Water
2. Whole Milk (Meijer Vitamin D milk)
3. Pediasure 1.0
4. Pediasure 1.5
5. Pediasure Peptide 1.0

Experiments were carried out to determine the necessary volume of thickener to be added to these base fluids until they fall in Nectar and Honey categories. According to NDD, the viscosity of the fluid for Nectar consistency must be within 51 cP to 350 cP, Experiments were carried out to make sure that the selected fluids fall under the Nectar class and similarly for the Honey consistency where the range of viscosities is 351 cP to 1750 cP.

Also, the samples were refrigerated for 24 hours to study and analyse the time and temperature effect on the viscosity of the fluid samples.

3.b Numerical Study

In numerical study, using STAR CCM+ software, the Computational Fluid Dynamics (CFD) study were carried out on three cases. Below are the brief objectives of the Numerical Study:

1. Developing the CFD model of swallowing process with unaffected oropharyngeal geometry. (Regular case)

2. Identifying the effect of viscosity of the fluid on the throat geometry with cleft palate and understanding the necessity of specific viscosity requirement for this specific Dysphagia case. (Cleft palate case)
3. Identifying the effect of viscosity of fluid through the oral and pharyngeal phases of the swallow and understanding the necessity of specific viscosity requirement for this unique Dysphagia case. (poor Velo Pharyngeal Range of Motion, (Poor VPROM))

3.b.1 Theoretical background

For the CFD study of the flow, it is of most importance to understand the governing equations of the flow. These equations were presented to the world by Navier and Stokes. These equations are called as Navier-Stokes equations. The Navier-Stokes equations consists of three main equations which are presented below.

1. Conservation of Mass equation
2. Conservation of Momentum equations
3. Conservation of Energy equation

The equation [15] below illustrates conservation of mass.

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

The equations [15] below illustrates conservation of momentum.

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho uu)}{\partial x}+\frac{\partial(\rho vu)}{\partial y}+\frac{\partial(\rho wu)}{\partial z}=\left(\frac{\partial(-p+\tau_{xx})}{\partial x}\right)+\left(\frac{\partial(\tau_{yx})}{\partial y}\right)+\left(\frac{\partial(\tau_{zx})}{\partial z}\right)+S_x$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho vv)}{\partial y}+\frac{\partial(\rho wv)}{\partial z}=\left(\frac{\partial(\tau_{xy})}{\partial x}\right)+\left(\frac{\partial(-p+\tau_{yy})}{\partial y}\right)+\left(\frac{\partial(\tau_{zy})}{\partial z}\right)+S_y$$

$$\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho uw)}{\partial x}+\frac{\partial(\rho vw)}{\partial y}+\frac{\partial(\rho ww)}{\partial z}=\left(\frac{\partial(\tau_{xz})}{\partial x}\right)+\left(\frac{\partial(\tau_{yz})}{\partial y}\right)+\left(\frac{\partial(-p+\tau_{zz})}{\partial z}\right)+S_z$$

The equation [15] below illustrates conservation of energy.

$$\rho\frac{DE}{Dt}=\left[\frac{\partial\left(u(-p+\tau_{xx})\right)}{\partial x}+\frac{\partial\left(u\tau_{yx}\right)}{\partial y}+\frac{\partial(u\tau_{zx})}{\partial z}\right]+\left[\frac{\partial\left(v\tau_{xy}\right)}{\partial x}+\frac{\partial\left(v(-p+\tau_{yy})\right)}{\partial y}+\frac{\partial\left(v\tau_{zy}\right)}{\partial z}\right]$$
$$+\left[\frac{\partial\left(w\tau_{xz}\right)}{\partial x}+\frac{\partial\left(w\tau_{yz}\right)}{\partial y}+\frac{\partial\left(w(-p+\tau_{zz})\right)}{\partial z}\right]-\left[\frac{\partial(q_x)}{\partial x}+\frac{\partial(q_y)}{\partial y}+\frac{\partial(q_z)}{\partial z}\right]+S_E$$

It was noted in the literature review that the flow velocity of the bolus is 5 cm/s. Therefore, for this study, the nature of flow was found out to be Laminar.

3.c Experimental Setup

The sole part of experiments is to record the viscosity of the liquid samples. Hence, the viscometer will be used to record the viscosity of the samples. Below are the details of the Viscometer:

- Model name: Viscolite d21 Portable Viscometer
- Units of measurement: Centipoise (cP)
- Range of measurement: Up to 10000 cP
- Accuracy of model: 1% of the full scale reading (100 cP)

The Viscolite is a “vibrational” viscometer. The sensor consists of a steel shaft with an end mass which is made to vibrate at its natural frequency. As the vibrating sensor shears through the fluid, its energy is lost due to viscous drag exerted by the fluid. The viscosity of the fluid is then determined by measuring the amount of energy lost.

In order to carry out the experiments, for consistency and repeatability, an experimental setup has been designed, as mentioned above. Figure 1 represents the experimental setup.

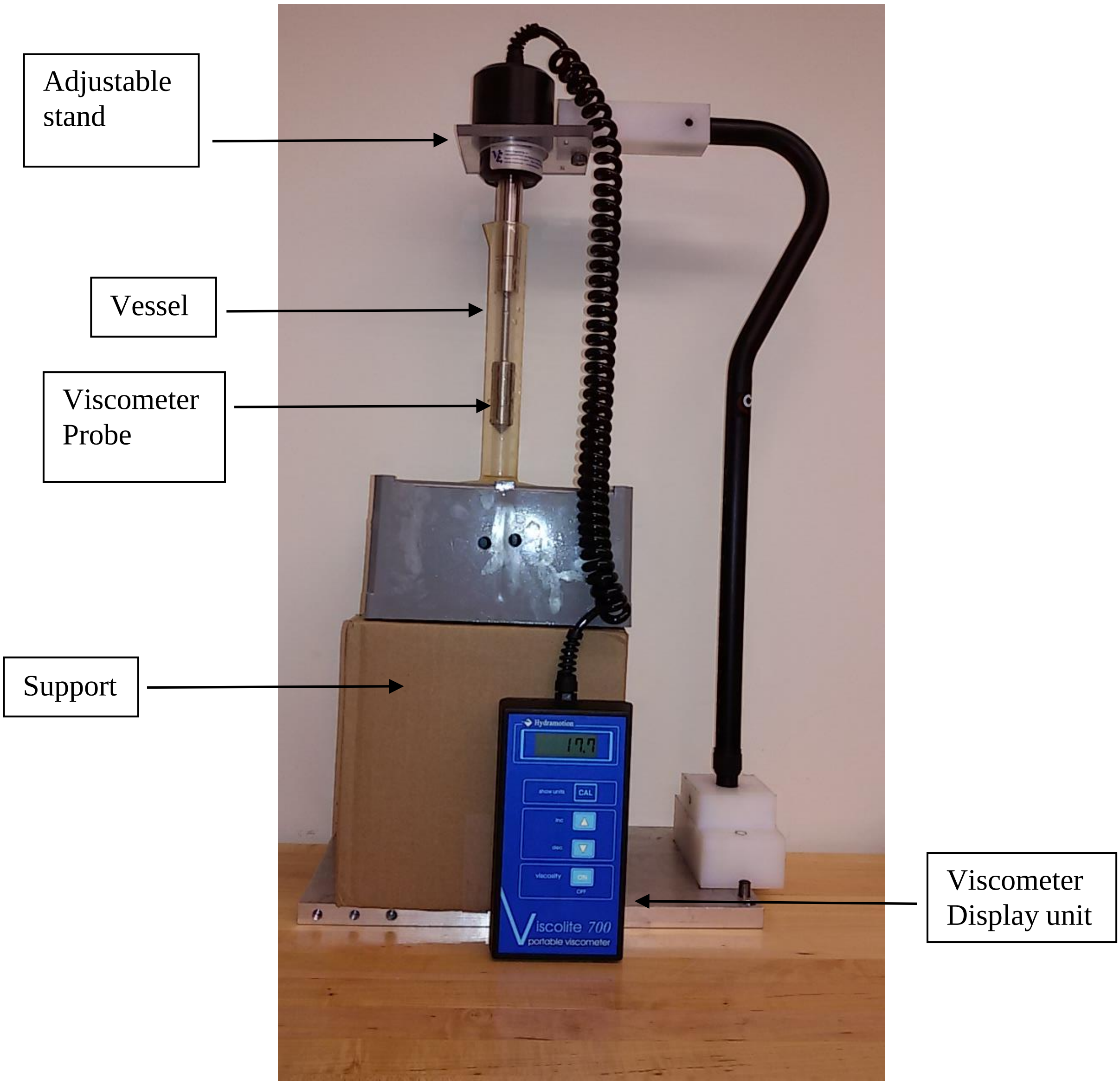


Figure 1. Experimental setup

Dimensions of the setup are as follows:

- Diameter of the probe = 21 mm
- Height of the entire probe = 145 mm

- Overall surface area of the setup = 1160 mm^2

3.c.1 Experimental procedure

1. An operation check has to be done each time at the beginning of the experimental process. (Can also be found in the user manual, section 2.2, page 10)
2. The display unit should read 0.0 while the probe is in air and not touching anything.
3. The display unit should read 1.0 while the probe is immersed in water at 20 ^oC.
4. Once the operation check is done, further procedure can be started. Assuming that the viscometer is placed as shown in figure 8, sample can be prepared.
5. Each sample is made by mixing the volumes of fluids and thickener.
    a. For Nectar thick consistency: Base fluid 120 ml + Simply thick thickener 1 stroke (15 ml)
    b. For Honey thick consistency: Base fluid 120 ml + Simply thick thickener 2 stroke (30 ml)
6. It is very important to shake each sample vigorously for 1 minute.
7. Once the sample is ready, it can be placed on the platform of the setup.
8. The probe is immersed in the sample with the help of adjustable device, by lowering it down.
9. Probe is kept immersed in the sample until the readings on the display unit are stable.
10. Once the stable reading is achieved, the reading is noted and the probe is removed from the sample by raising the device.
11. The probe is then wiped clean with the soft napkin and re-wiped with the help of alcoholic wipes in order to clean the probe totally.
12. The tested sample is then discarded, the vessel is cleaned again, and then is refilled with next sample for next reading.
13. Repeat procedures 4 to 13 for each sample testing.

3.c.2 Viscometer Calibration

From the manufacturers of the viscometer, it was noted that the viscometer was designed based on high shear rate and the reference values of the viscosity were based on low shear rate. Hence there was a need of calibrating the viscometer as per the experimental requirements. As per the user's manual provided by the viscometer manufacturers, in troubleshooting section (page 33), it is said to refer to section 4.9 (page 25) in user's manual for troubleshooting if the value read is less than expected.

Following directions were followed:

1. Note the reading obtained with the viscolite and call it VL.
2. Call the reference viscometer's read value for same fluid under same measurement conditions, as VR.
3. Calculate the ratio VR/VL.
4. Navigate to SPAn in the FCAL submenu and enter the calculated ratio.
5. The viscometer should read the values as expected.
6. A 120 ml Nectar sample was prepared with water as base fluid.
7. The value was read as 8 cP. This was called as VL.
8. From the literature, the value for same sample for same volume was noted, which was found to be 54 cP. [12] This was called as VR.
9. The ratio VR/VL was found to be 6.75.
10. This value was then entered in the SPAn submenu as per the directions in the user's manual. (Refer to section 4.3, page 21 for navigation directions in the user's manual)

The value so obtained after entering the correction factor, was found out to be 66. Now, given that the accuracy of the viscometer to be $\pm$100 cP, the new corrected value was accepted and the viscometer was said to be calibrated as per the experimental requirements.

3.c.3 Viscometer Validation

It is also important to make sure that the viscometer is validated. The validation of the viscometer was done using the Stokes falling sphere experiment. According to the Stokes falling sphere experiment, the viscosity of the fluid can be determined by the formula [16] given below:

$$\mu = \frac{gD^2(\rho s - \rho)}{18V\zeta}$$

Where,

μ = Viscosity of the fluid in centipoise (cP)

g = Acceleration due to gravity (m/s^2)

D = Diameter of the sphere (m)

ρ_s = Sphere density (gms/m^3)

ρ = Liquid density (gms/m^3)

V = Velocity of the falling ball (m/s)

ζ = Wall correction factor

Here, for validation of the viscometer and hence for the stokes falling ball experiment, the sphere that was selected was made of Nylon and the fluid selected whose viscosity was previously know was chosen to be Valvoline motor racing oil 10W-30.

Below is the figure that represents the experimental setup for the stokes falling sphere experiment.

Figure 2. Experimental setup for Stokes falling sphere experiment

Below are the details of Nylon sphere, the experiment vessel and Fluid that was selected.

Nylon sphere:

Mass = 1.2 gms

Diameter = 0.0127 m

Volume = 1.073E-06 m^3

Density = 1118398.8 gms/m^3

Experiment Vessel:

Diameter = 0.048 m

Fluid details:

Viscosity = 77 cP [17]

Mass of the fluid for the experiment = 428 gms

Volume = 0.0005 m^3

Density = 856000 gms/m^3

The velocity was calculated to be 0.123529 m/s.

According the graph from the referenced page [16],

$\zeta = 2.4$

Hence, by substituting the values so obtained, the viscosity of the fluid was found out to be 77.80082 cP. Hence, it was proven that the formula is correct. Furthermore, the fluid was tested using the viscometer and the reading from the viscometer was noted as 68 cP. Now given that the accuracy of the viscometer to be $\pm$100 cP, it was considered that the viscometer was validated.

It is very important to mention that the samples are prepared by considering their volumes. Table 5 has the comparative results that confirm that the mass and volume of the liquids and thickener are equal in magnitude.

Table 5. Mass-Volume readings

Fluid	**ml**	**gms**
Water	15	15
Pediasure 1.5	120	124
Pediasure 1.0	120	117
Pediasure Peptide 1.0	120	118
Simply thick	15	15

Also, table 6 represents the values of the viscosity of Simply thick. This experiment was carried out to confirm that the viscosity of the thickener is constant at room temperature.

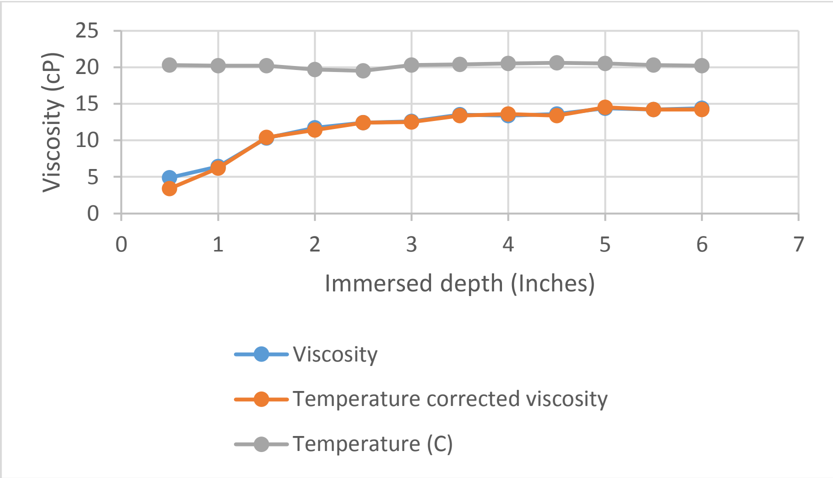
Table 6. Viscosity of Simply Thick

Viscosity of Simplythick (cP)	Viscosity of Simplythick after 24 hrs (cP)
974	975
973	973
976	975
975	974
977	975

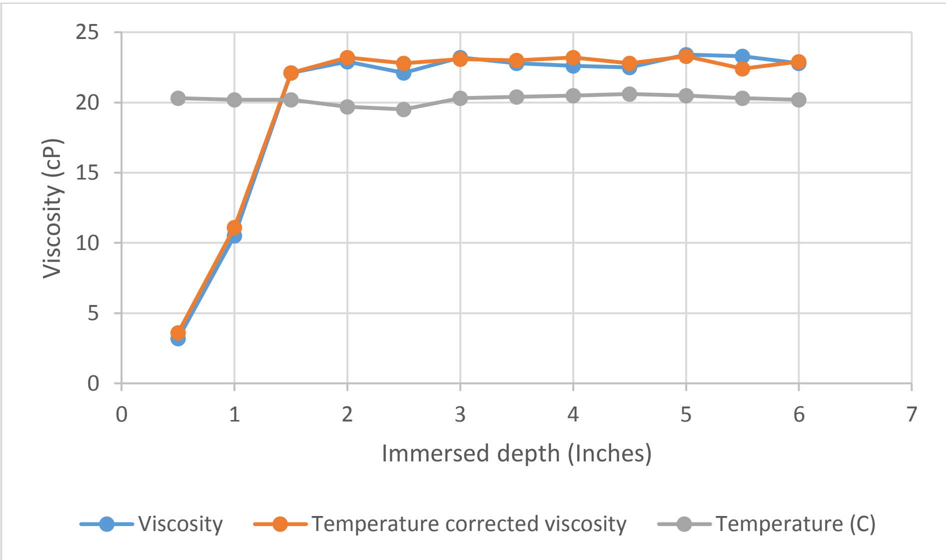
As discussed in the objective of the experimental study, the viscosity values ranging from 1 cP to 1750 cP were to be recorded to determine the volumetric measures of the fluid samples. According to the user's manual provided by the manufacturers of the viscometer used in this study, the probe of the viscometer needs to be immersed in the fluid up to the directed depth for getting accurate results. The vessels suitable for carrying out experiments as directed in the user's manual were not available. Hence, for the same reason, it was then decided to immerse the probe to limited depth to record the readings. But in order to proceed with the decided experimental procedure, it was necessary to experimentally confirm that there is no significant difference in the readings of the viscosity values regardless of the depth of probe immersed.

Graphs 1 to 6 represent the values of the viscosities at various probe depths immersed in honey thick samples with water, milk, Pediasure 1.0, Pediasure 1.5, Pediasure Peptide 1.0 and nectar thick sample with water, respectively. For better repeatability and consistency, for each depth, the readings were taken for three times and the values were averaged. The readings can be found in the appendix.

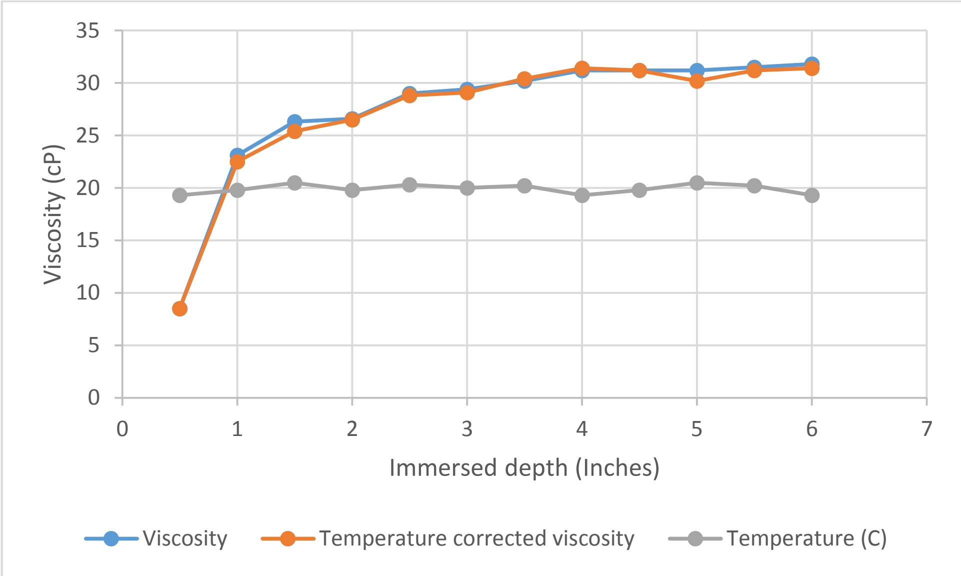
Graph 1. Probe depths-viscosity reading for Water samples (honey thick)



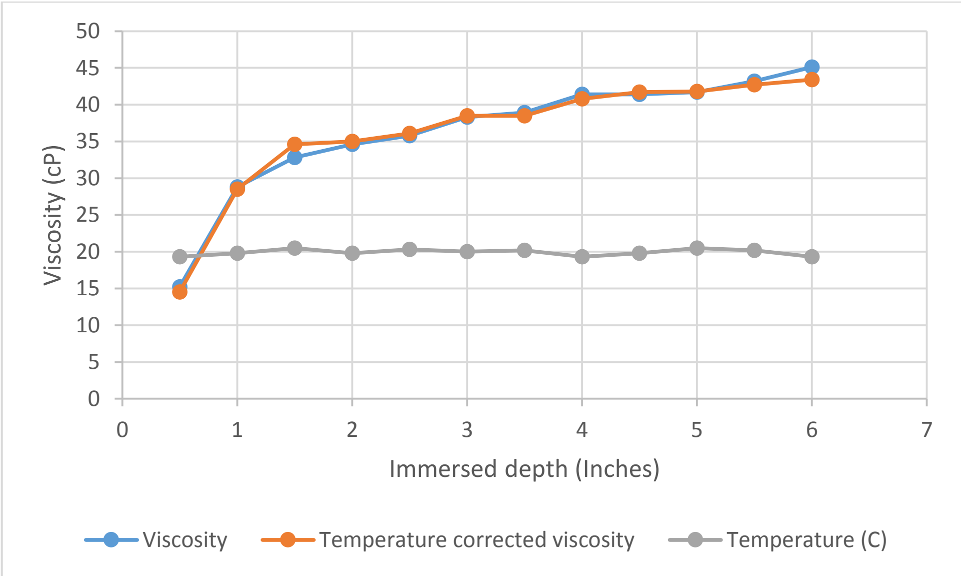
Graph 2. Probe depths-viscosity reading for Milk samples (honey thick)



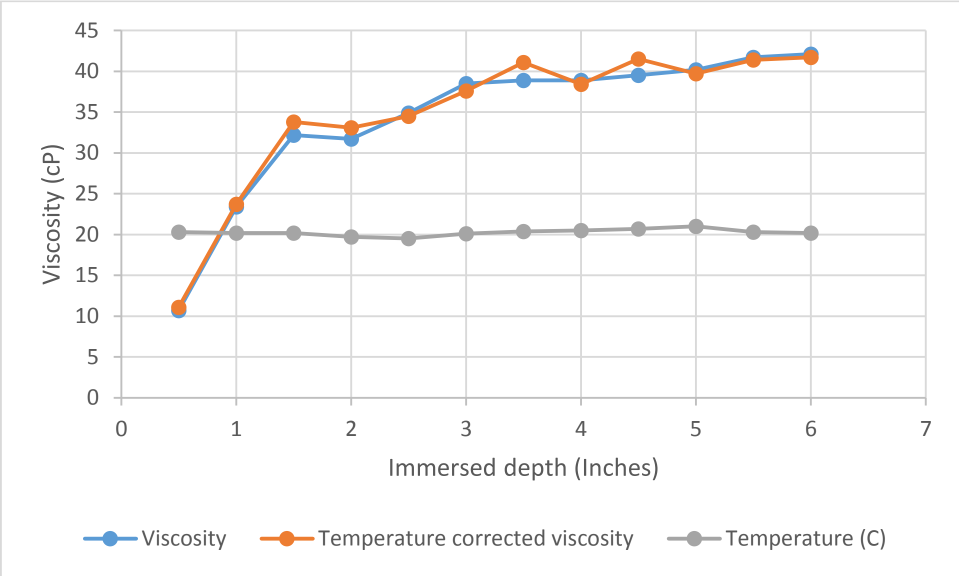
Graph 3. Probe depths-viscosity reading for Pediasure 1.0 samples (honey thick)



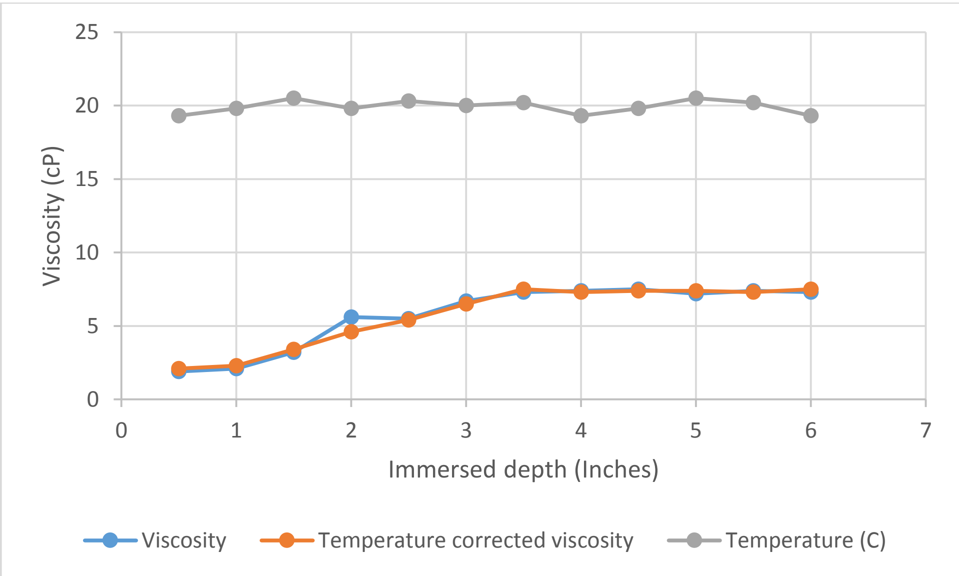
Graph 4. Probe depths-viscosity reading for Pediasure 1.5 samples (honey thick)



Graph 5. Probe depths-viscosity reading for Pediasure Peptide 1.0 samples (honey thick)



Graph 6. Probe depths-viscosity reading for water samples (nectar thick)



From these graphs representing the readings, it was found that after 2.5 inches of immersed depth, the readings are considerably stable. Thus, it was decided to immerse 2.5 inches of the probe length in the samples for the experiments.

3.d Numerical Study Setup

For the numerical portion of the study, STAR CCM+ software was used. For carrying out Computational Fluid Dynamics (CFD) study, below are the necessary models required:

- CAD Model
- Mesh Model
    - Prism Layer Mesher
    - Trimmer
    - Surface Remesher
    - Surface mesh
    - Volume mesh
- Physical Model

Once these models are set, the cases can be put for the iterative process of converging the residuals in the solution. Then, after the solution convergence, the cases are treated with post-processors. The post processors selected here for our cases are as follows:

- Velocity Vectors
- Streamlines
- Isosurface

In order to carry out the numerical study, having an accurate geometry of the throat is of most importance. A literature search for anthropometric data was conducted but no specific data points were found. This was likely due to fact that oropharyngeal geometry is variable between individuals. As further effort, a medical half head model was brought from the hospital and was set up in a 3D scanning machine.

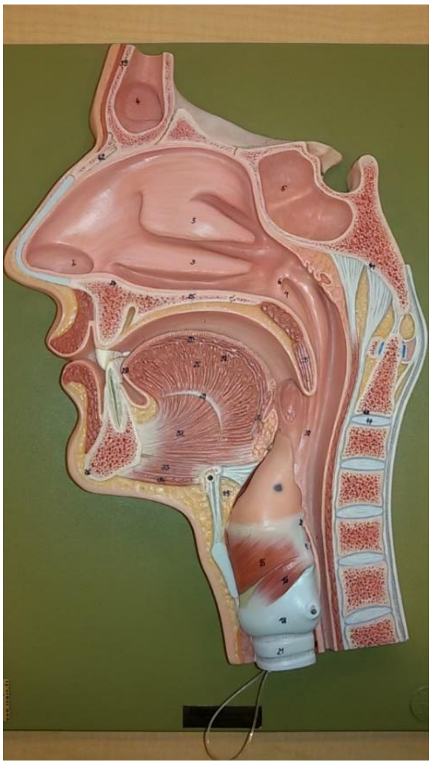


Figure 3. Medical Half head model

The machine used for 3D scanning is Roland LPX600.

Figure 4. Roland LPX600 3D scanner

Below are the details of the scanner.

Model of 3D scanner: Roland LPX600

Table size: Diameter 254mm

Maximum scanning area: Plane scanning (Width = 254 mm, Height = 406.4 mm)

Scanning pitch: Width direction 0.2 to 254 mm, height direction 0.2 to 406.4 mm

Repeat accuracy: $\pm$ 0.05 mm

Sensor: Noncontact laser sensor

Scanning method: Spot-beam triangulation

Figure 5 depicts the result of 3D scanning on the half head model. It was found that the resulting file of this 3D scanned model was not compatible with the Solidworks software and it was then concluded that the throat model has to be created from scratch.

Figure 5. 3D scanned medical half head model

As discussed above, the anthropometric data points were not found, the profile dimensions were taken using a Vernier calliper and the medical half head model. It was noticed that most part of the oropharyngeal track consisted of a series of ellipses. It was observed that the cross section of the track had variations in the profile at a few places and that is why 14 different planes were selected where there was a change in cross sectional area. Each plane was located at different distance from the datum. Each plane contains one sketch. The table below contains the profile dimensions for the final geometry. Profile number 1 corresponds to the profile of mouth opening.

Table 7. Esophagus profile geometry values

Profile No.	Major axis (mm)	Minor axis (mm)
1	11	10
2	9	7
3	11.5	7.5
4	11.5	10
5	35.66	26.68
6	38.12	32.90
7	30.09	30
8	36.3	11.44
9	32.38	8.83
10	29.4	4.59
11	18.44	4.23
12	14.2	3
13	13.42	2.86
14	6.71	3.36

Figure 6 depicts the planes and their corresponding geometries. Once these sketches were created, the entire geometry was generated using the Loft function in the SolidWorks software. The Loft function connects the sketches drawn on to various planes and then generates one solid geometry.

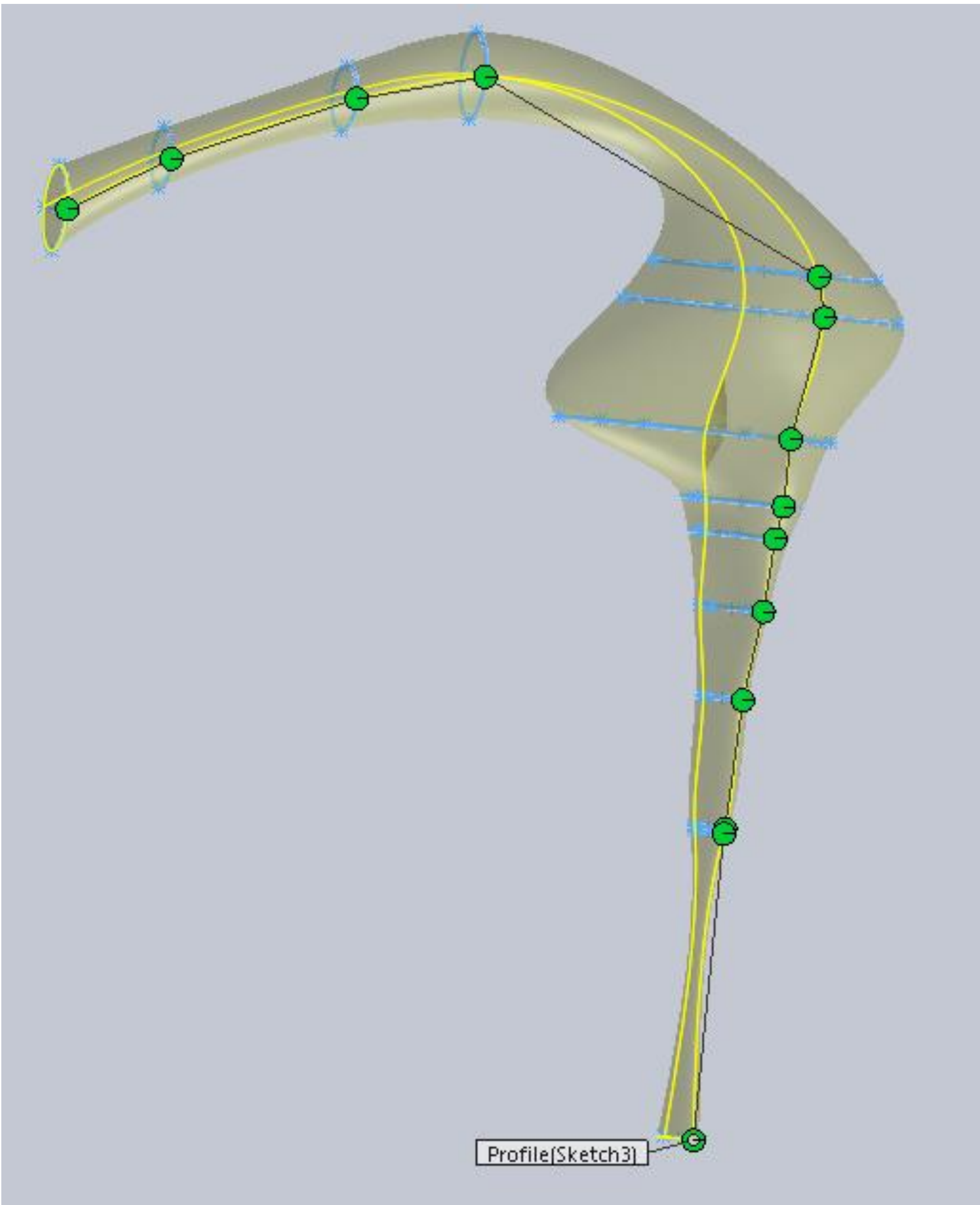


Figure 6. Esophagus geometry – Planes

Since many planes were created, any future corrections in the geometry can be easily done, by changing the distances between the planes and their corresponding sketches. Hence, for our cases with the Cleft palate, a tube was extruded from the top plane of the oral geometry. The hole in the palate was decided to be of the size of a pea with the diameter of 5 mm. That way, the whole geometry was considered to be one with the Cleft palate where the palate connects to the nasal track. Since the study was only limited to oropharyngeal regions, the details of nose were not added to the CAD model. Furthermore, the CAD model for poor VPROM case was generated by altering the dimensions at the velum region. Again, using the Loft function from SolidWorks software, all the profiles, including the changed one, were connected to obtain the CAD model for poor VPROM case.

CAD Models

Below are the CAD models for the selected cases.

Figure 7 below depicts the CAD model for Regular case.

Figure 7. CAD model of Regular case

Figure 8 below depicts the Cleft palate case CAD model.

Figure 8. CAD model of Cleft Palate case

Figure 9 below depicts the poor VPROM case CAD model.

Figure 9. CAD models of Poor VPROM case

Surface Mesh

For meshing, the reference values used are listed below:

- Base size = 0.009 m
- Number of Prism Layers = 15
- Surface Curvature = 100 points
- Surface size
    - Relative minimum size (Percentage of Base) = 0.1%
    - Relative Target size (Percentage of Base) = 50%

Figure 10 below depicts the surface mesh of the Regular case.

Figure 10. Surface mesh of Regular case model

Figure 11 below depicts the surface mesh of the Cleft palate case.

Figure 11. Surface mesh of Cleft palate case

Figure 12 below depicts the surface mesh of poor VPROM case.

Figure 12. Surface mesh of poor VPROM case

Volume mesh

Figure 13 below depicts the volume mesh of the Regular case.

Figure 13. Volume mesh of Regular case (6.45 Million cells)

Figure 14 below depicts the volume mesh for Cleft palate case.

Figure 14. Volume mesh of Cleft palate case (5.66 Million cells)

Figure 15 depicts the volume mesh of poor VPROM case.

Figure 15. Volume mesh of poor VPROM case (5.9 Million cells)

Physical Model

The selection of the physical model is very important step in the numerical study. It contains many important parameters the study is based on with regards to following aspects:

- Geometry
- Steady or unsteady flow of the fluid
- State of fluid material (Gas or Liquid)
    - Viscosity of the fluid can be entered through this model
- Material density specifications
- Nature of Flow (Laminar or Turbulent)

These models help to define each case separately. The only change in the model was to change the geometry of the CAD and to change the viscosity of the fluid in the physical model. The physical model selected for the cases of this study is as follows:

- Three Dimensional
- Steady case
- Liquid
- Constant Density
- Gradients
- Laminar
- Segregated Flow

Since the velocity of the flow is 5 cm/s as per the literature, the flow considered in this study is Laminar. Three cases are discussed in this study. Each case is further altered to three different cases where the fluid has three different consistencies which are mentioned below:

- Thin consistency (1 cP)
- Nectar consistency (340 cP)
- Honey consistency (1600 cP)

The numerical study consists of following nine cases:

- Regular case
    - Thin consistency
    - Nectar consistency
    - Honey consistency
- Cleft palate case
    - Thin consistency
    - Nectar consistency

    - Honey consistency
- Poor VPROM case
    - Thin consistency
    - Nectar consistency
    - Honey consistency

All the cases mentioned above were run in Star-CCM+ software for residual plot convergence to ensure that the errors in the numerical are negligible. For consistency, each case was run for 1000 iterations and until they converge. Figures 16-18, depicts the residuals of regular cases with thin, nectar and honey consistency respectively.

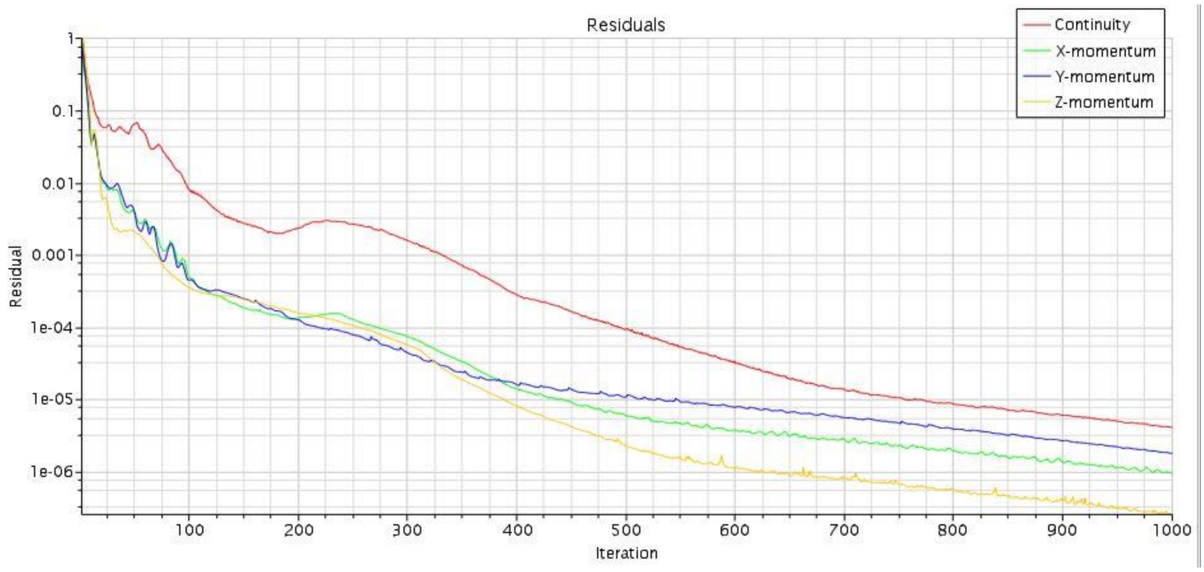


Figure 16. Residuals Regular case (Thin)

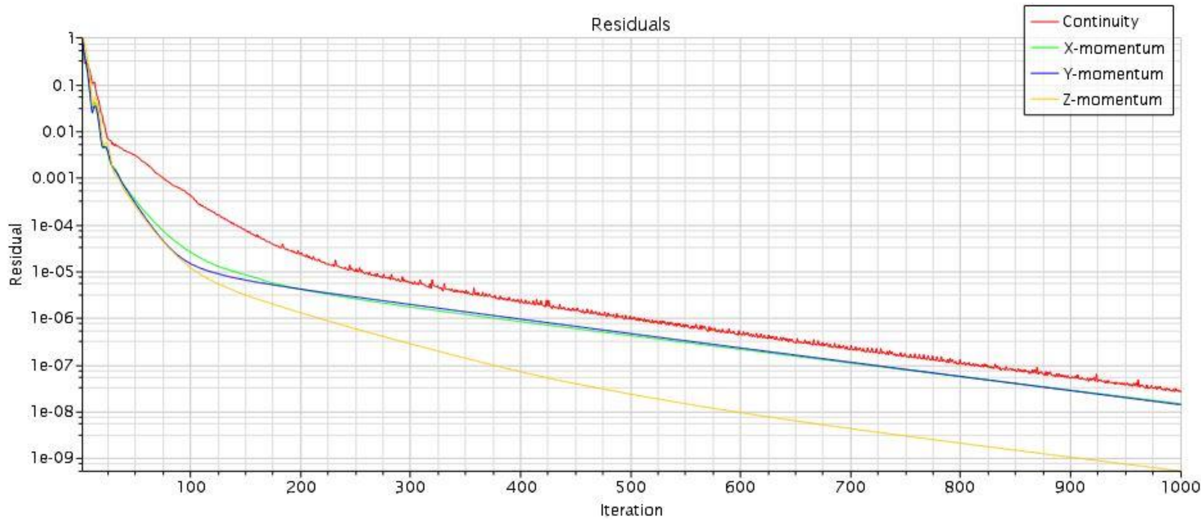


Figure 17. Residuals Regular case (Nectar)

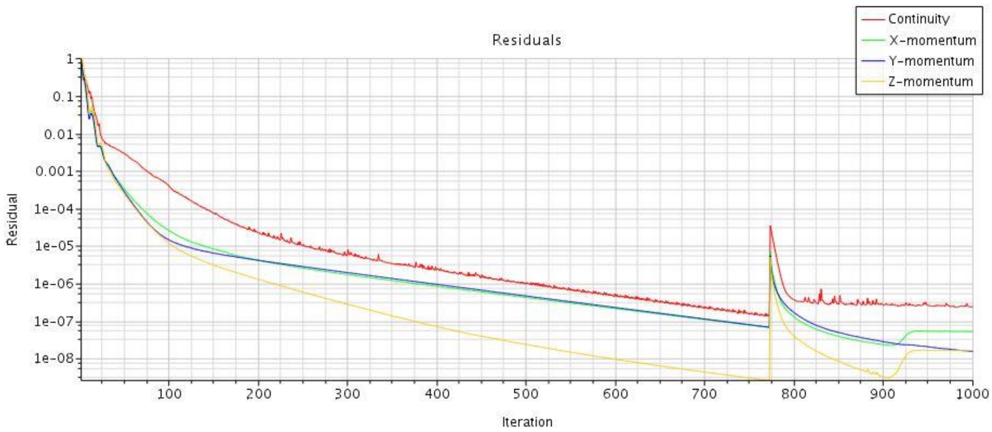


Figure 18. Residuals Regular case (Honey)

Figures 19-21 depict the residuals plot for cleft palate case for thin, nectar and honey consistencies respectively.

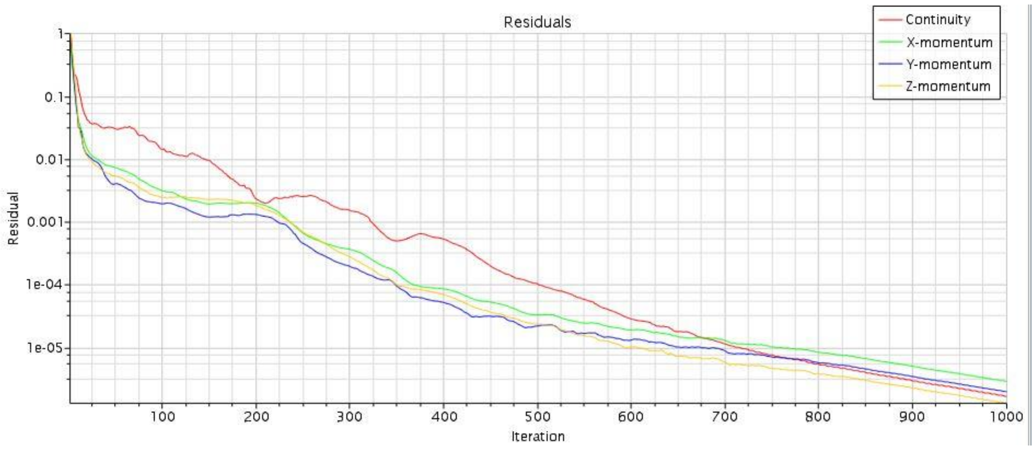


Figure 19. Residuals Cleft palate case (Thin)

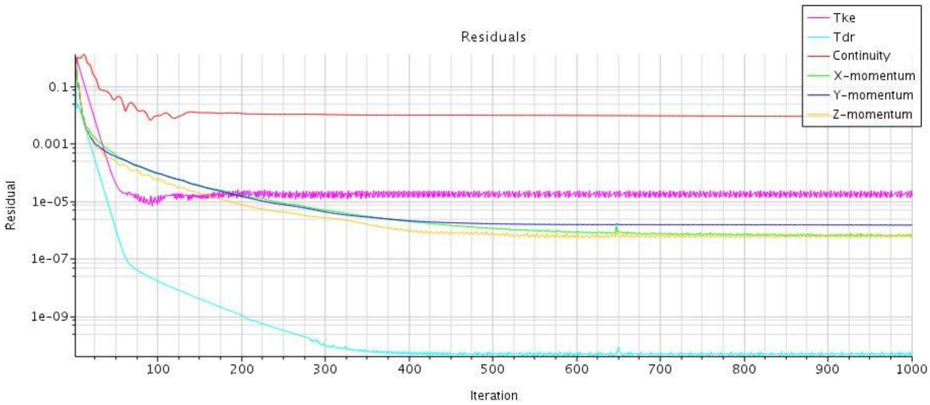


Figure 20. Residuals Cleft palate case (Nectar)

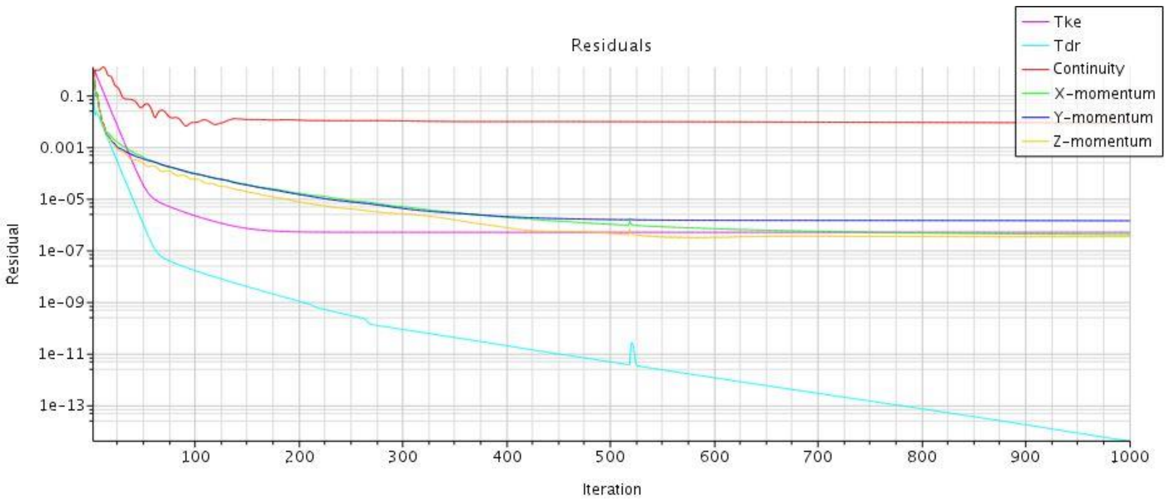


Figure 21. Residuals Cleft palate case (Honey)

Figures 22-24 represent the residuals graph for poor VPROM case for thin, nectar and honey consistency respectively.

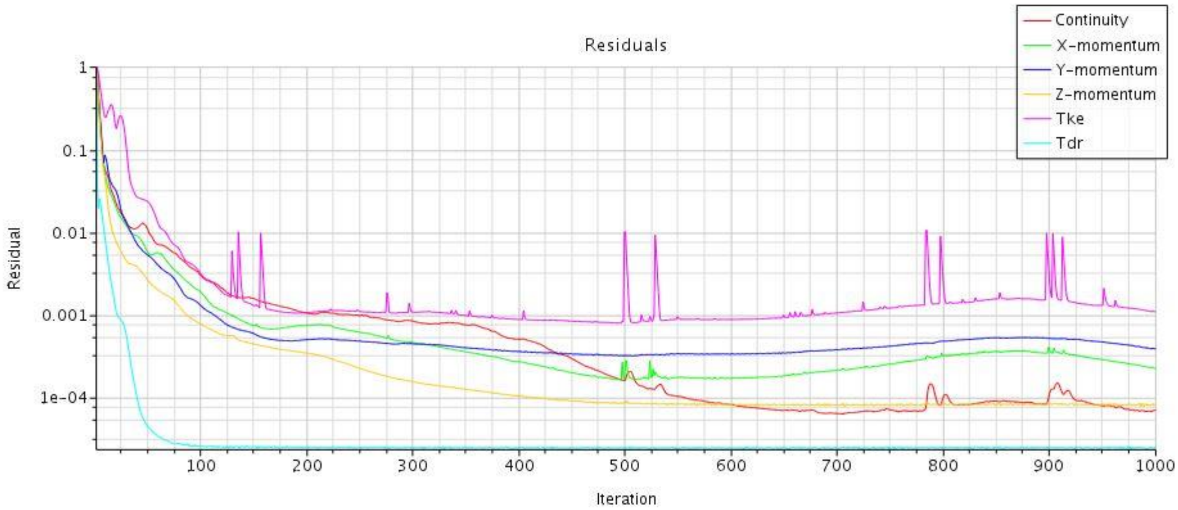


Figure 22. Residuals Poor VPROM case (Thin)

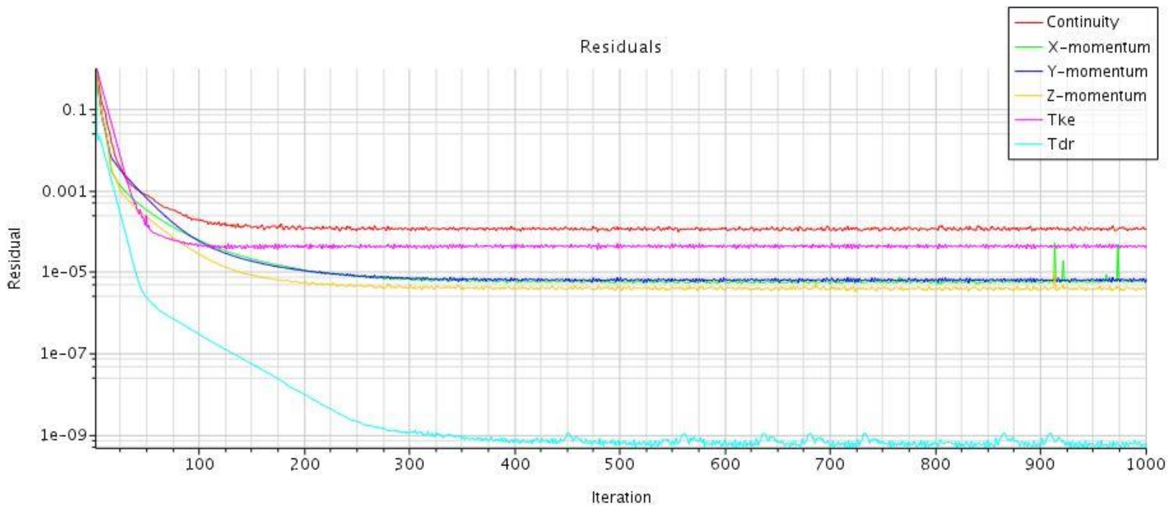


Figure 23. Residuals Poor VPROM case (Nectar)

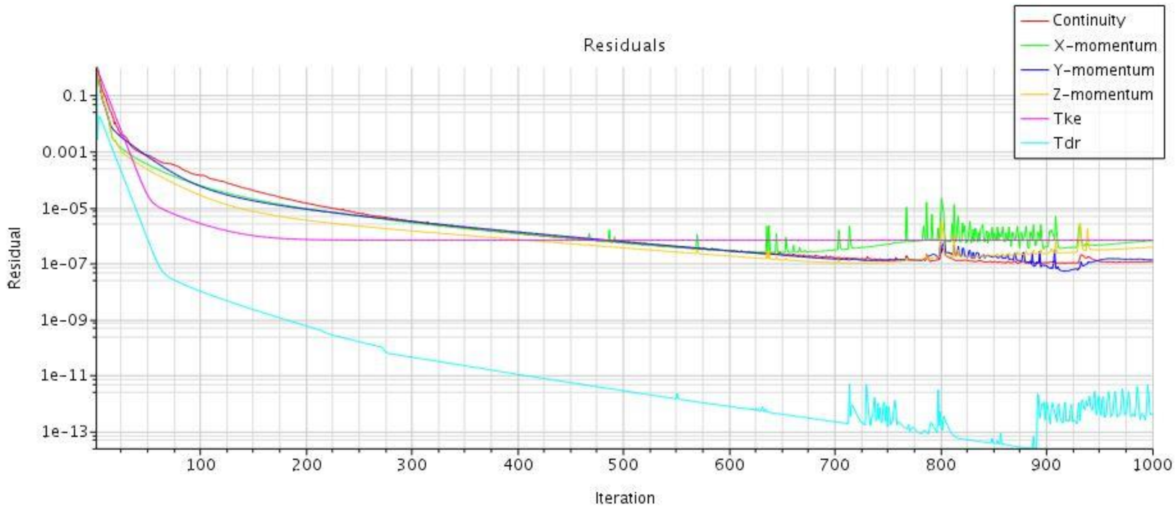


Figure 24. Residuals Poor VPROM case (Honey)

Once the setup for experimental and numerical study was done, all the cases were reviewed to analyse the results obtained. Next section contains results and discussions of Experimental and Numerical study of Dysphagia.

4 Results and Discussion

4.1 Experimental Results and Discussion

As per the setup, it was decided to make samples and record the viscosity using the validated and calibrated viscometer.

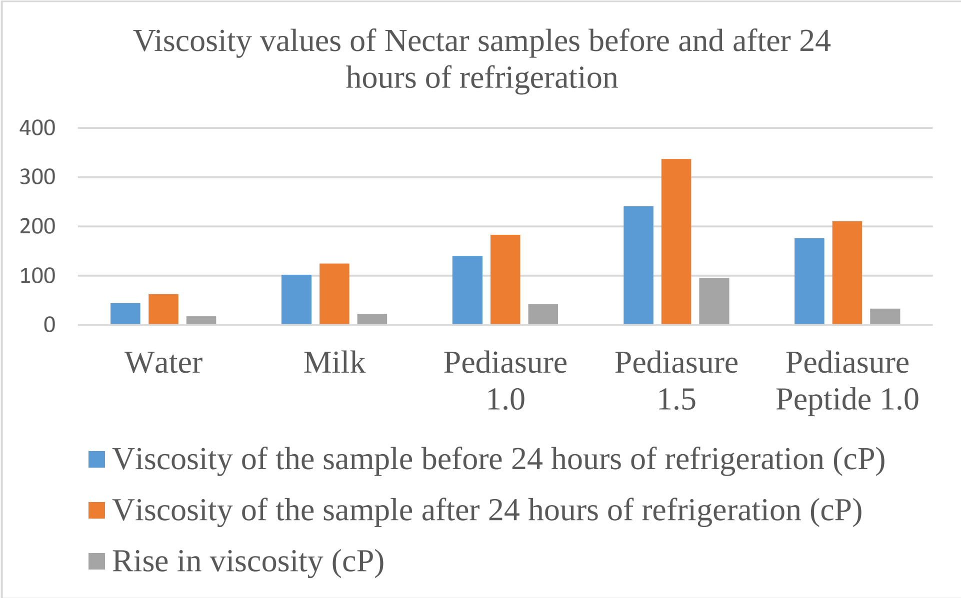
4.1.1 Nectar consistency results and discussion

Sample preparation was done as mentioned in the experimental setup and procedure. Below are the results for the five fluids for nectar consistency.

Table 8. Viscosity values of Nectar samples before and after 24 hours of refrigeration

Base fluid in Nectar sample preparation	Viscosity Sample 1 (cP)	Viscosity Sample 2 (cP)	Viscosity Sample 3 (cP)	Viscosity after24 hours of refrigeration (cP)	Increase in Viscosity after 24 hours of Refrigeration (cP)
Water	45.1	44.3	44.7	62.8	17.7
Milk	102.1	101.7	102.2	124.9	22.7
Pediasure 1.0	140.4	140.1	140.4	183.5	43.1
Pediasure 1.5	241.6	241.5	240.7	337.1	95.5
Pediasure Peptide 1.0	176.0	175.8	176.3	210.9	33.7

Chart 1. Viscosity values of Nectar samples before and after 24 hours of refrigeration



For repeatability, the viscosity was measured using three distinct samples. Samples were prepared and the third sample was refrigerated at 6 C for 24 hours. As we know, according to the National Dysphagia Diet (NDD), the Nectar samples should fall within viscosity range of 51 cP – 350 cP. Here, from above results, it is seen that all the fluids except water as a base fluid, were in the expected range of viscosities to be called as of Nectar consistency. As a result, for water, it was decided to add thickener with the increment of 5 ml in addition to 15 ml of basic sample preparation.

Table 9. Viscosity values of Nectar sample with water as base fluid before and after 24 hours of refrigeration

Volume of Simply thick in 120 ml of base fluid (ml)	Viscosity Sample 1 (cP)	Viscosity Sample 2 (cP)	Viscosity Sample 3 (cP)	Viscosity after24 hours of refrigeration (cP)	Increase in Viscosity after 24 hours of Refrigeration (cP)
20	66.7	65.2	67.8	85.8	20.2

Here, from the above table, it was noticed that adding just 5 more ml of simply thick to the basic Nectar sample preparation recipe, the sample was found to be in Nectar class of consistency as per NDD.

With regards to time and temperature studies on the viscosity of the samples, from the results obtained from table 8 and table 9, it was obvious that after 24 hours of refrigeration, the viscosity was increased in each case. It is quite evident that the base fluids have their own viscosity that contributes to the overall sample's viscosity. It is found that Pediasure 1.5 has the thickest consistency of all the fluids, followed by Pediasure 1.0, followed by Pediasure Peptide 1.0, followed by milk and at last, the water.

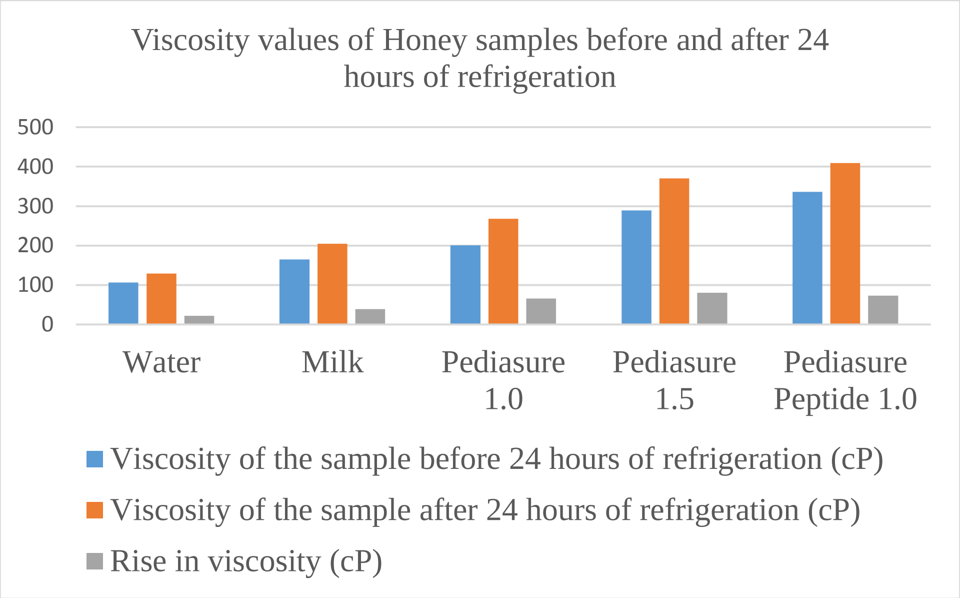
4.1.2 Honey consistency results and discussion

Sample preparation was done as mentioned in the experimental setup and procedure. Below are the results for the five fluids for Honey consistency. For repeatability, the viscosity was measured using three distinct samples. Samples were prepared and the third sample was refrigerated at 6 C for 24 hours.

Table 10. Viscosity values of Honey samples before and after 24 hours of refrigeration

Base fluid in Honey sample preparation	Viscosity Sample 1 (cP)	Viscosity Sample 2 (cP)	Viscosity Sample 3 (cP)	Viscosity after24 hours of refrigeration (cP)	Increase in Viscosity after 24 hours of Refrigeration (cP)
Water	107.0	105.3	107.1	129.6	22.5
Milk	165.7	163.2	165.7	205	39.3
Pediasure 1.0	201.8	199.7	201.7	267.7	65.9
Pediasure 1.5	289.8	287.6	289.5	370.7	80.9
Pediasure Peptide 1.0	337	335.3	335.7	409.5	73.8

Chart 2. Viscosity values of Honey samples before and after 24 hours of refrigeration



Here, it was noticed that none of the samples were in the Honey category right after the sample preparation, where the expected range of viscosity for a sample to be called as of Honey consistency is 351 cP to 1750 cP. However, Pediasure 1.5 and Pediasure Peptide 1.0 were considered to be in the Honey category after 24 hours of refrigeration. Considering the rise in viscosity after 24 hours of refrigeration, the samples followed a similar trend as the Nectar sample preparation but, the samples with base fluid as Pediasure 1.5 and Pediasure Peptide 1.0 did not exhibit the properties as they did in the Nectar sample preparation, right after the preparation, or in other words, before 24 hours of refrigeration. In the case of Honey preparation, the viscosity of the sample with Pediasure Peptide 1.0 was noted to have highest viscosity among all the samples, having more than that of the honey sample with base fluid as Pediasure 1.5, unlike the results from Nectar samples. This change may be because of the reaction between the ingredients of Pediasure Peptide 1.0 and ingredients of Simply Thick thickener.

Furthermore, as the samples were not considered to be in Honey category, further experiments were necessary. Given the huge range of Honey category as per NDD, which is from 351 cP to 1750 cP, it was decided to have increments of 15 ml to the addition of basic recipe for honey sample preparation, as mentioned in the experimental procedure. It was then decided to target for the viscosity until the sample viscosity falls within the Honey class as described by NDD. The sample will be refrigerated once the sample is considered as of Honey consistency.

Table 11. Viscosity values of Honey sample with water as base fluid

Volume of Simply Thick (ml) in 120 ml of base fluid	Viscosity Sample 1 (cP)	Viscosity Sample 2 (cP)	Viscosity Sample 3 (cP)
45	177.4	180.0	178.3
60	239	235.4	239.4
75	299.3	301.5	300.7
90	364.0	361.2	358.3

It can be seen from the table above that the viscosity of the sample increases approximately by 60 cP each time the thickener is added in increments of 15 ml. As decided, the increments were stopped right at the moment where the sample exhibited the viscosity of Honey category as per NDD. Here, it is considered obvious that the water being the base fluid, will not add viscosity to the sample as the water itself has very low viscosity. The next table presents the results obtained for Honey thick samples with milk as base fluid.

Table 12. Viscosity values of Honey sample with Milk as base fluid

Volume of Simply Thick (ml) in 120 ml of base fluid	Viscosity Sample 1 (cP)	Viscosity Sample 2 (cP)	Viscosity Sample 3 (cP)
45	302.3	302.1	301.1
60	355.8	361.2	358.3

The table above represents the values of viscosities of Honey thick samples with milk as base fluid. Here, it is observed that the viscosity of the sample increases approximately by 55 cP. As decided, the increments were stopped right at the moment where the sample exhibited the viscosity of Honey category as per NDD. It can be noted here that the rise in viscosity of the samples with milk as base fluid is less than that of the rise in viscosity of the samples with water as base fluid. It is an unexpected result as the viscosity of the water is less than that of the viscosity of the milk. Given that, the rise in the viscosity should be more as the base fluid should add viscosity to the sample in association with the thickener. Whereas, on the other hand, the total amount of thickener required in milk based samples, is less as compared to water based samples. Here, it can be assumed that the interaction of the contents of the thickener with base fluid is responsible for such behaviour.

Table 13. Viscosity values of Honey sample with Pediasure 1.0 as base fluid

Volume of Simply Thick (ml) in 120 ml of base fluid	Viscosity Sample 1 (cP)	Viscosity Sample 2 (cP)	Viscosity Sample 3 (cP)
45	322.1	322.0	321.4
60	391.9	388.4	389.3

The table above represents the viscosity values of Honey thick samples with Pediasure 1.0 as base fluid. It was noted that the fluid had the viscosity near the honey thick scale NDD has described. As decided, the increments were stopped right after the sample exhibited the viscosity of Honey category as per NDD.

Table 14. Viscosity values of Honey sample with Pediasure 1.5 as base fluid

Volume of Simply Thick (ml) in 120 ml of base fluid	Viscosity Sample 1 (cP)	Viscosity Sample 2 (cP)	Viscosity Sample 3 (cP)
45	468.4	468.3	465.2

The table above contains the viscosity values of honey thick samples with Pediasure 1.5 as base fluid. With addition of 15 ml to the basic procedure of honey thick samples as per Simply Thick thickener’s directions, the required honey thick consistency was achieved. Since the expected results were obtained, the increments were stopped. It is quite obvious that the Pediasure 1.5 added much of its own viscosity to the sample along with the thickener and that is why the sample exhibited honey thick viscosity with addition of extra 15 ml to the sample.

Table 15. Viscosity values of Honey sample with Pediasure Peptide 1.0 as base fluid

Volume of Simply Thick (ml) in 120 ml of base fluid	Viscosity Sample 1 (cP)	Viscosity Sample 2 (cP)	Viscosity Sample 3 (cP)
45	361.8	367.2	363.4

From tables 11-15, the required volumes of Simply Thick to be added to 120 ml of the base fluids were obtained. Table 16 below has the necessary volumetric measures needed to be added to the base fluids in order to get them in to the Honey class.

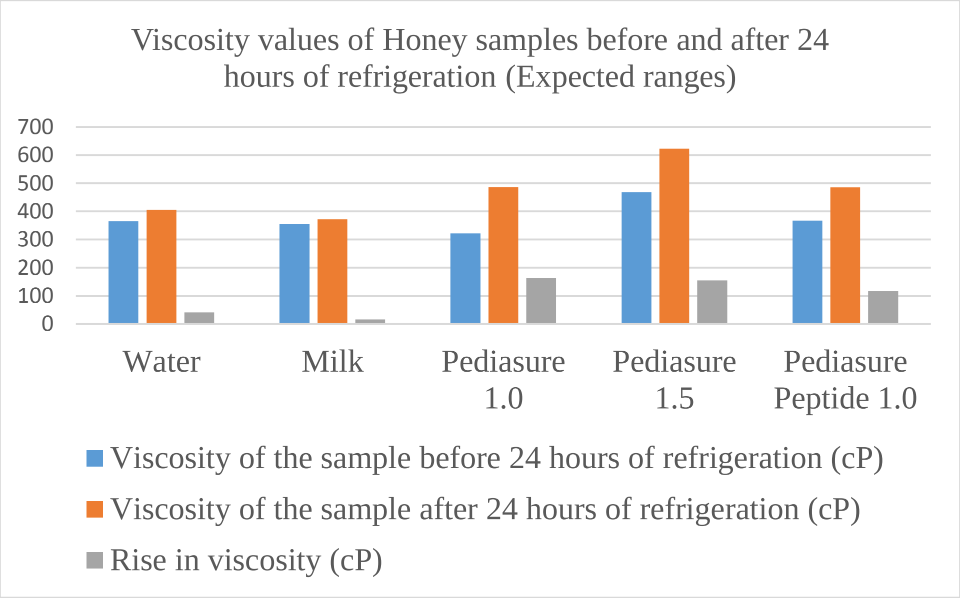
Table 16. Base fluid and amount of SimplyThick to be added for Honey thick samples

Base Fluid (120 ml)	Volume of Simply Thick to be added (ml)
Water	90
Milk	60
Pediasure 1.0	60
Pediasure 1.5	45
Pediasure Peptide 1.0	45

Table 17. Viscosity of Honey Thick samples before and after 24 hours of Refrigeration

Base Fluid	Viscosity of sample before 24 hours of refrigeration (cP)	Viscosity of sample after 24 hours of refrigeration (cP)	Total amount of Simply Thick in the base fluid (ml)	Increase in Viscosity after 24 hours of refrigeration (cP)
Water	364.8	406	90	41.2
Milk	355.8	372.2	60	16.4
Pediasure 1.0	389.86	486.6	60	96.73
Pediasure 1.5	468.4	623	45	154.6
Pediasure Peptide 1.0	367.2	485	45	117.8

Chart 3. Viscosity values of Honey samples (Expected Ranges)



Here, from table 17, it was seen that the highest rise in the viscosity after 24 hours of refrigeration was in case of Pediasure 1.0 and lowest was in case of milk, which was even lower than that of water being the base fluid. It can be seen here that the reason for this inconsistent behaviour of the honey samples is because the volume of Simply thick added is not uniform amongst the base fluids and the individual viscosities of the base fluids interact with the thickener depending on the ingredients of each of them.

4.2 Numerical Study Results and Discussion

4.2.1 Regular case results and discussion

As discussed above in the report, this study focusses on three different post processors which will be used to analyse and study the effect of viscosity on the oropharyngeal geometry.

Figure 25-27 depict the velocity vectors of the cases with thin, nectar and honey consistency respectively.

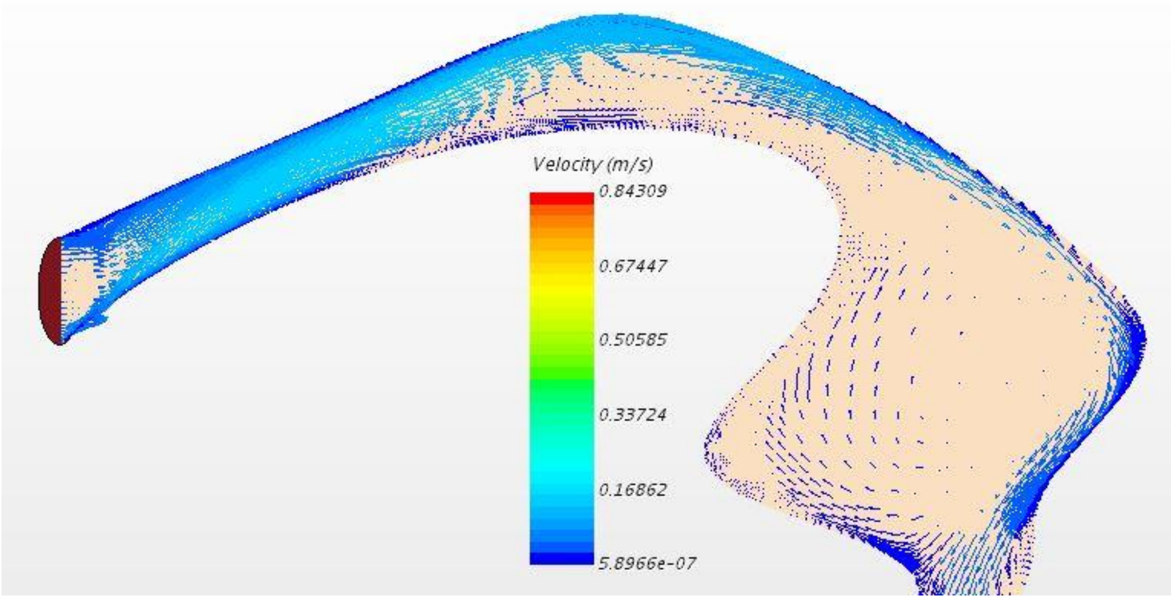


Figure 25. Vectors Regular case (Thin)

It can be seen in figure 25, where the fluid is of thin consistency, the vector formations represent significant amount of turbulence. The vectors on the palate surface are of higher velocity than that of the vectors along the tongue. This is possibly because of the flow direction specification. The flow enters normally to the opening of the mouth and then it follows the oropharyngeal profile. Furthermore, the flow separates from the profile and hits the epiglottis where the flow gets further separated. This separated flow again generates the turbulence. The reason behind this behaviour of the flow is because of the low viscosity of the fluid which causes dispersion of the fluid thereby causing more turbulence.

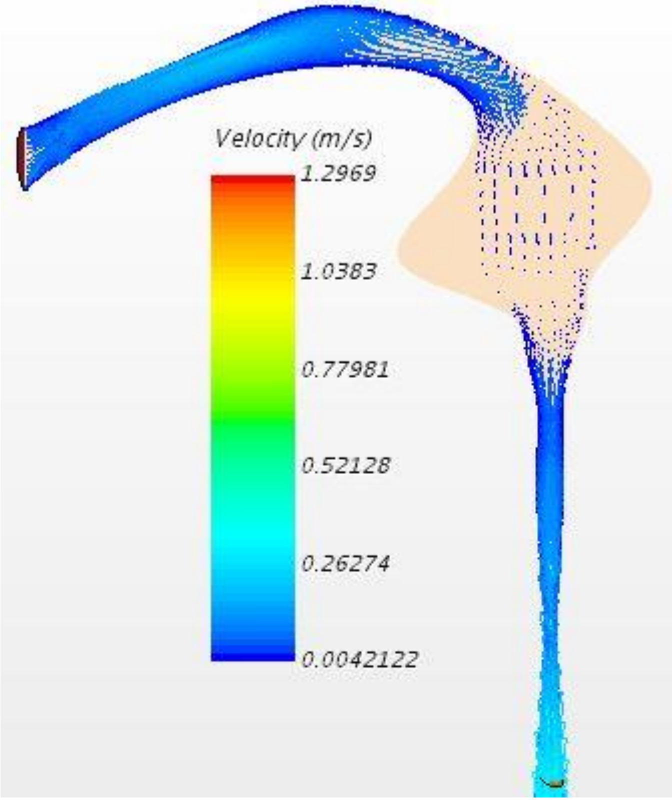


Figure 26. Vectors Regular case (Nectar)

Unlike the results from the figure 25, the vector formations in figure 26 that represent the flow of a fluid with nectar consistency, the turbulence is significantly reduced. Since the viscosity of the fluid is more than that of the water, the vectors do not separate from the main streamline and enter directly in to the pharynx. Similar pattern can be seen in the figure 27 which represents the fluid flow with honey consistency. Although, it can be seen that in case of honey consistency, the flow is more smooth and less turbulent.

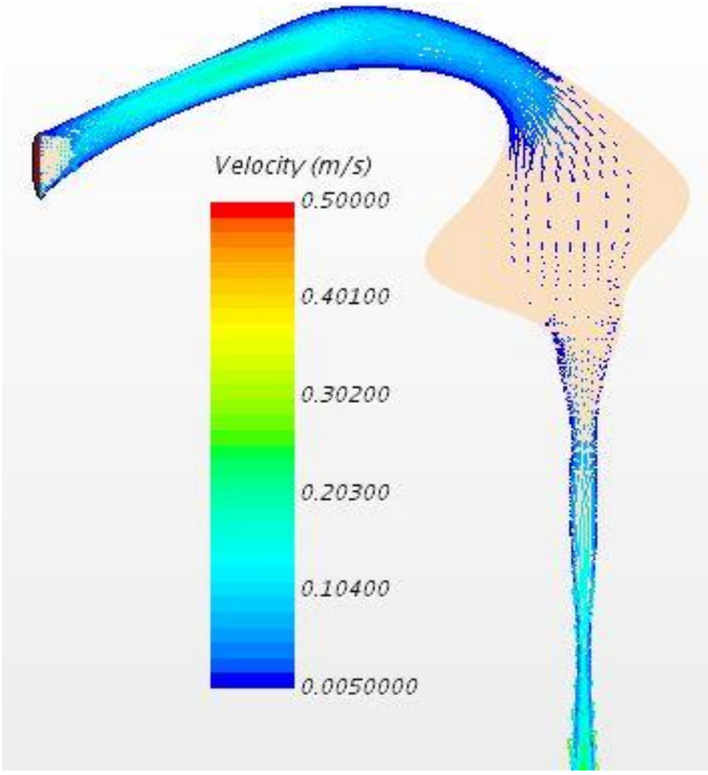


Figure 27. Vectors Regular Case (Honey)

Here, from the figures above, it can be seen that in case of the thin consistency, there is little turbulence at the epiglottis where the fluid is reversed and then is sent to the pharynx. On the other hand, in case of Nectar and Honey consistencies, the fluid stream expands after oral phase and then again contracts as it goes down the pharynx. Also, it should be noted that due to reduction in the cross sectional area of the pharynx, the velocity of the vectors is increased.

Figures 28-30 below depict streamline formations in the cases with thin, nectar and honey consistency respectively.

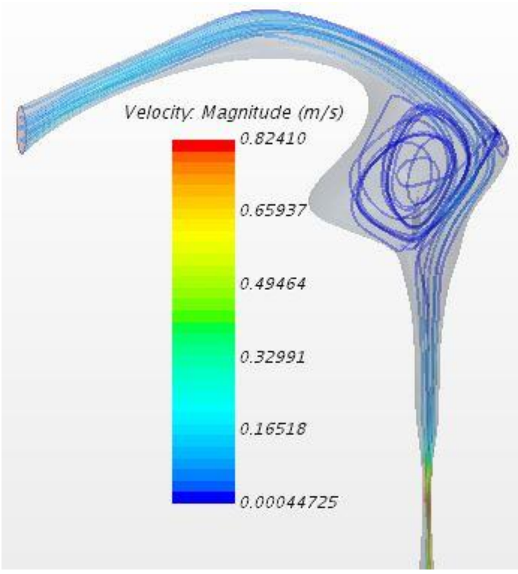


Figure 28. Regular case streamlines (Thin)

As discussed in the previous post processor where the vectors were analysed to study the flow of the fluid, similar pattern is observed in the streamline post processor. The flow being of thin consistency, follows the oropharyngeal profile and generates the turbulence after separation. Also, the velocity of the fluid increases at the end of the pharynx as the cross sectional area decreases. Also, the danger of fluid getting in to the lungs is more in this case, if the epiglottis is not properly closed.

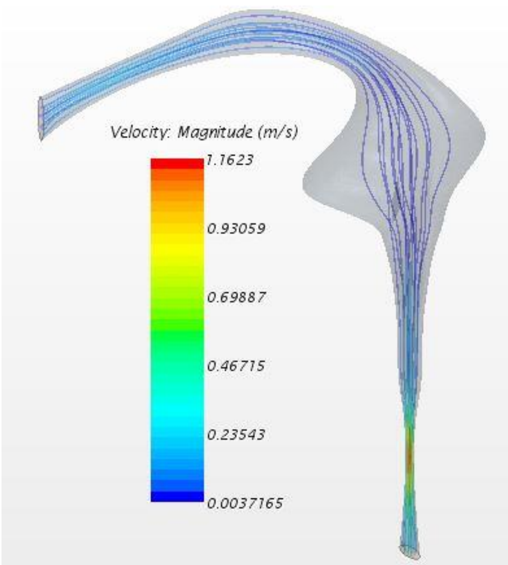


Figure 29. Regular case streamlines (Nectar)

Similar results are noticed in streamline formations as that of vector formations where the viscosity of the fluid is of nectar thick. Due to more viscosity, the streamlines tend to be cohesive and enter the pharynx very smoothly. But also, the velocity increases at the later journey of the fluid due to decrease in cross sectional area. Here, the danger of fluid getting into the lungs is overcome because of the greater viscosity of the fluid.

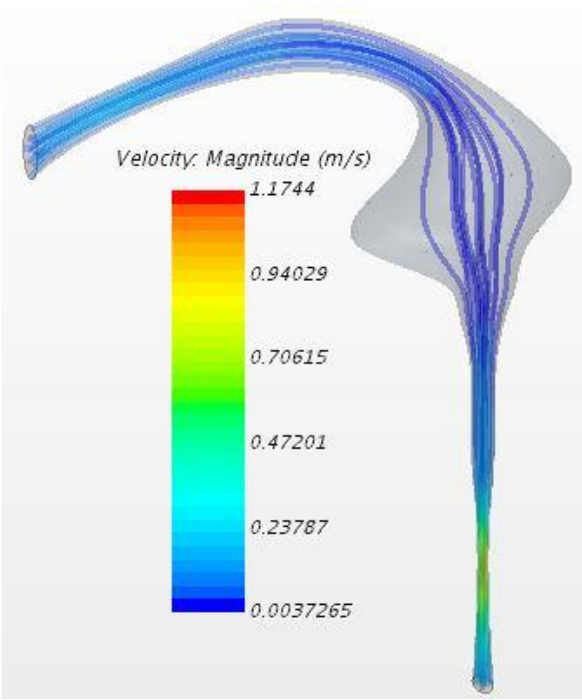


Figure 30. Regular case streamlines (Honey)

From the figures above which depict the streamline formations, it can be seen that in the case of thin consistency, there is a significant amount of turbulence as compared to other consistency results. Also in case of honey thick fluid flow streamlines, the danger of fluid getting in to the lungs is overcome, as the viscosity of the fluid is more than that of the fluid with thin consistency and also of nectar consistency. This result concludes that as the viscosity increases, the turbulence decreases. Also, these results support the results obtained in previous post processor which was vector formations.

Figure 31-33 depict the isosurface formations for the regular case with thin, nectar and honey consistencies respectively.

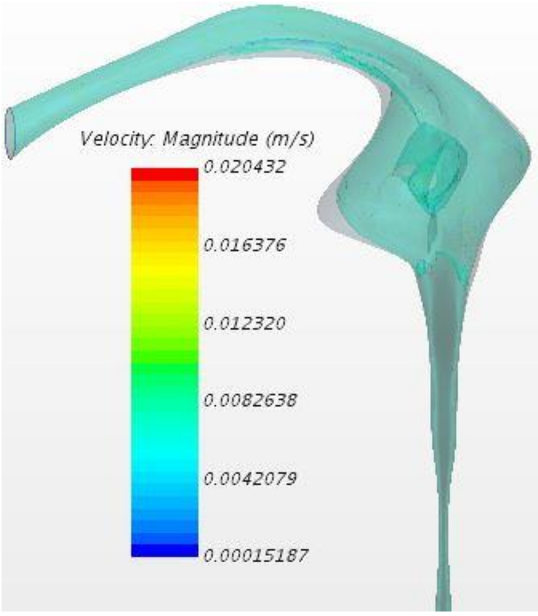


Figure 31. Isosurface in Regular case (Thin)

It can clearly be seen from figure 31 that represents the isosurface formation of the fluid with thin consistency, that the fluid occupies entire geometry given that the viscosity is very low (1 cP). As discussed in the previous results, the danger of fluid getting in to the lungs is more if the epiglottis is not closed properly.

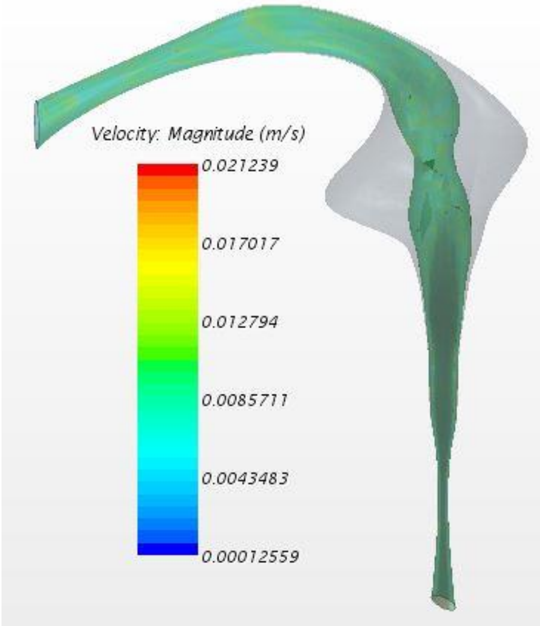


Figure 32. Isosurface in Regular case (Nectar)

Figure 32 depicts the isosurface formation of fluid with nectar consistency and it is noted that the fluid follows the expected motion. Also in figure 33, which depicts the isosurface formation of the case where the fluid is of honey consistency, the flow has the similar trend as it was noted in the previous case with nectar thick consistency. Here, it can be seen that the danger of fluid getting in to the lungs is far less in both the cases with nectar and honey consistency as compared to that of thin consistency.

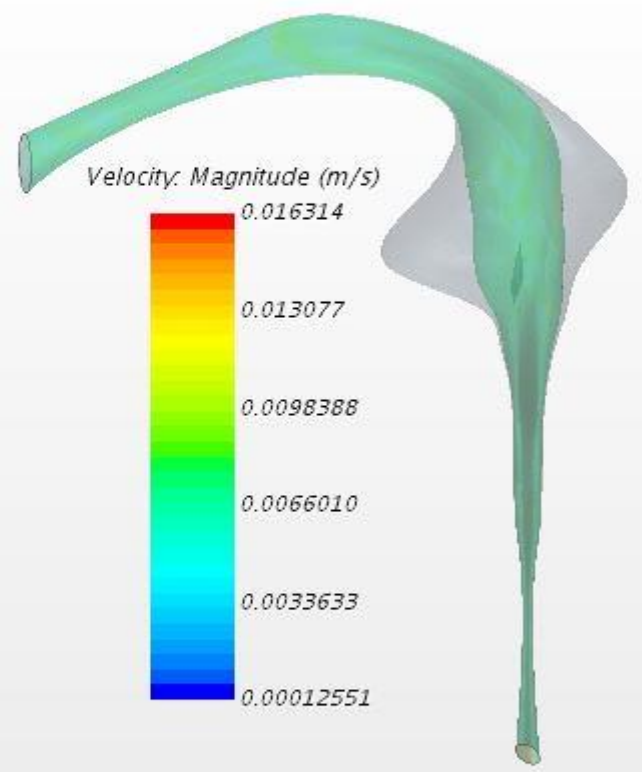


Figure 33. Isosurface in Regular case (Honey)

From the figures above that represent the isosurface formations in the regular case, it is observed that that as the viscosity increases, the fluid tends to stay compressed while in motion. With respect to the statement made above, if noticed at the isosurface formation in the regular case with thin consistency, the fluid is spreading out in the whole selected geometry, however, in the other two cases, the fluid tends to stay cohesive. Also the isosurface formations were in resemblance with the vector formations in corresponding cases.

4.2.2 Cleft Palate results and discussion

Figures 34-36 represent the vectors formations in cleft palate case vectors with fluid consistencies thin, nectar and honey respectively.

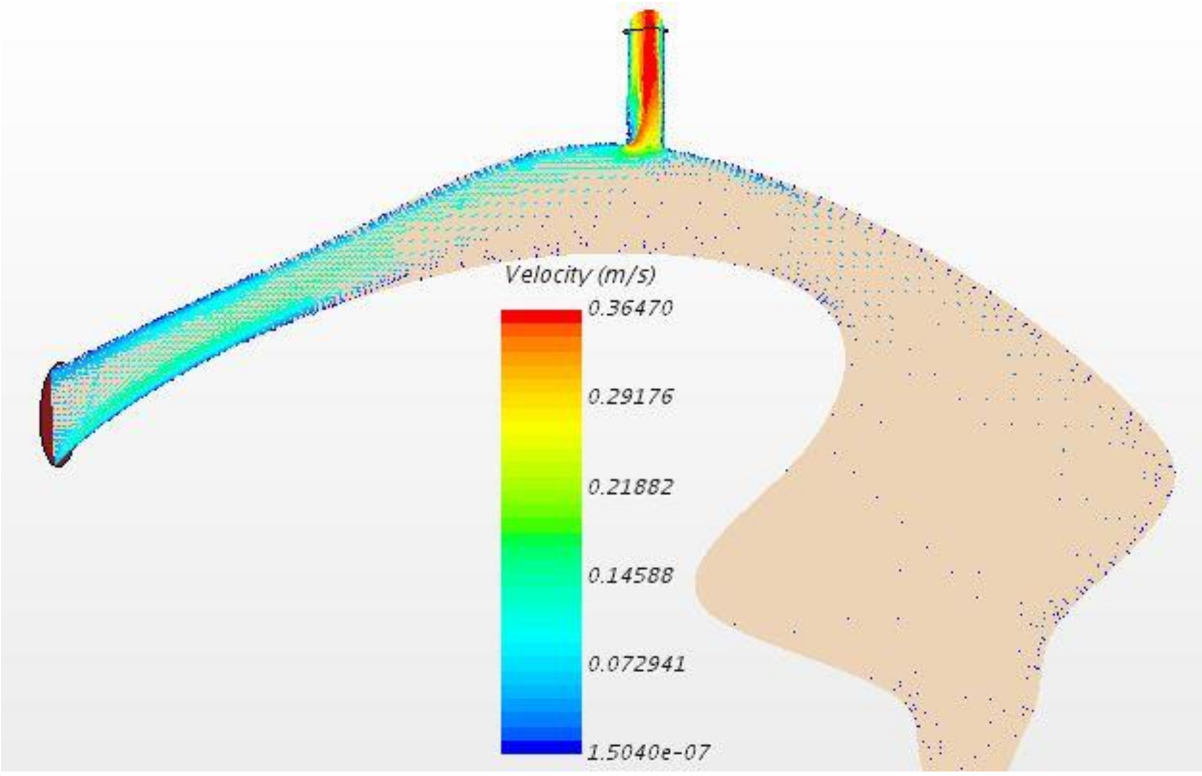


Figure 34. Cleft palate case vectors (Thin)

The figure above depicts the vector formations in cleft palate case with fluid having thin consistency. As the fluid begins its journey in the oropharyngeal track, the velocity of the flow is low but consistent. Vectors along the boundaries are of least magnitude. As the fluid reaches cleft palate, significant amount of turbulence is observed due to separation. As the flow separates from its stream, the velocity is increased tremendously and the magnitude reaches the maximum value. It means that the fluid enters the cleft palate with high velocity, which can possibly harm the walls of the palate. Also, there is a high risk of that fluid entering in to the nose. In order to avoid this entry of the fluid in to the nose, the viscosity needs to be increased. Here in this case, the fluid being least viscous does not hold onto the boundaries (walls of the track) and due to the same reason, the turbulence occurs.

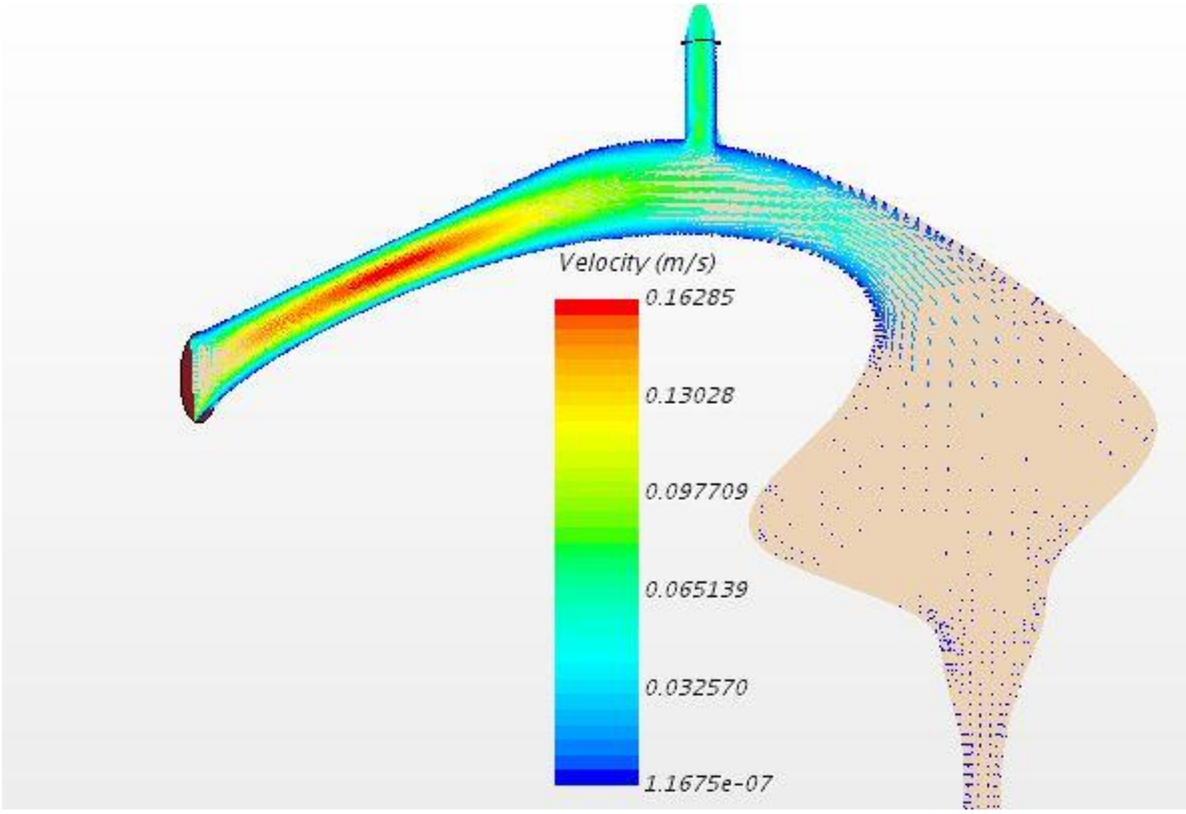


Figure 35. Cleft palate case vectors (Nectar)

As discussed above, after increasing the viscosity of the fluid, the flow tends to hold onto the boundaries. The vectors possess very high velocity at the entry in to the track and then the velocity is lowered after passing the cleft palate. As noted above in the previous case, the velocity of the flow increases after the entry in to the cleft palate. However, the magnitude of this velocity is lower than that of the magnitude observed in flow with thin consistency. Also, the number of vectors are noticeably less in number, lower in magnitude and consistent with the flow. Even though the flow enters the cleft palate, the possible harm is much lesser than that of the case with thin consistency. In order to improve the expected result, the viscosity of the fluid needs to be increased even more than that of nectar consistency.

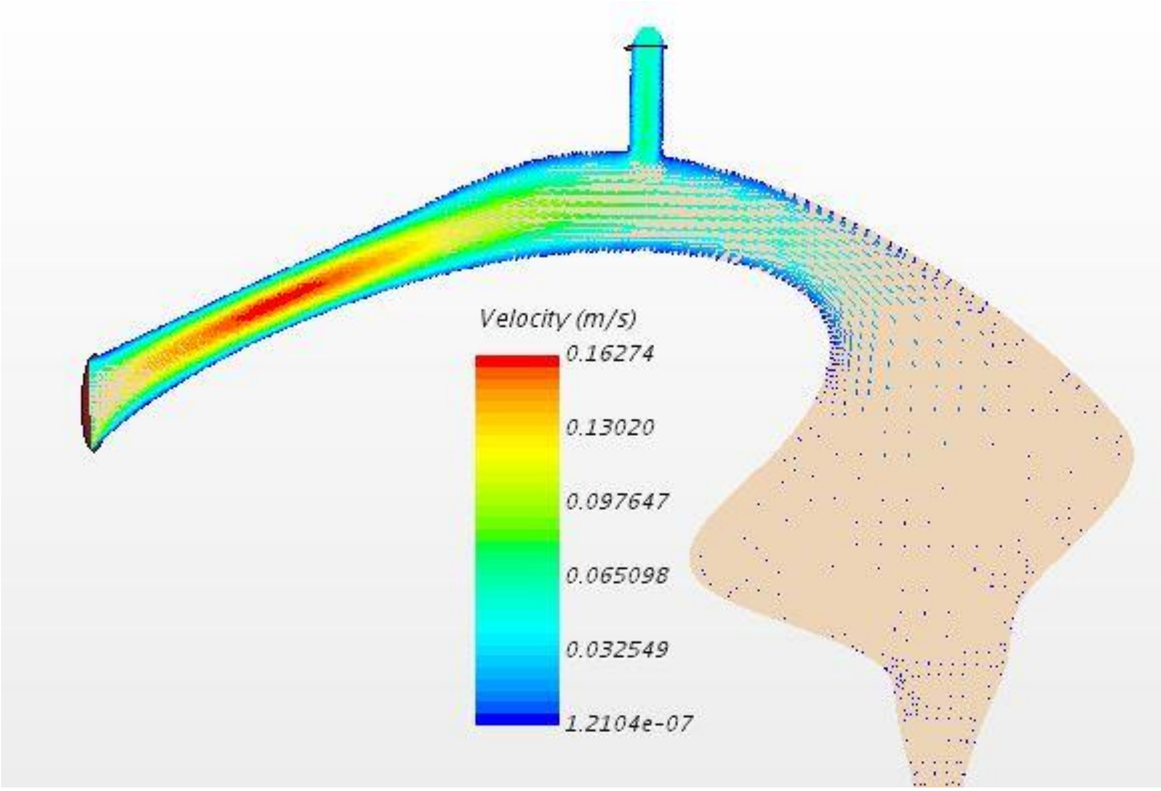


Figure 36. Cleft palate case vectors (Honey)

From figures above that depict the vector formations, it was observed that the fluid tends to enter the cleft (a pea sized hole in the upper soft palate) as the viscosity is reduced. When the fluid is of thin consistency, the fluid tends to enter the cleft. It is a general practice to increase the viscosity of the fluid so that the fluid bypasses the cleft and prevents it from entering in to the nasal region. The figures 35 and 36 support the statement above as the vectors in those cases, are of less magnitude and in less number, which tends to drag the fluid in the motion as expected in the normal case.

Figures 37-39 below represent the streamlines for cleft palate case for thin, nectar and honey consistencies.

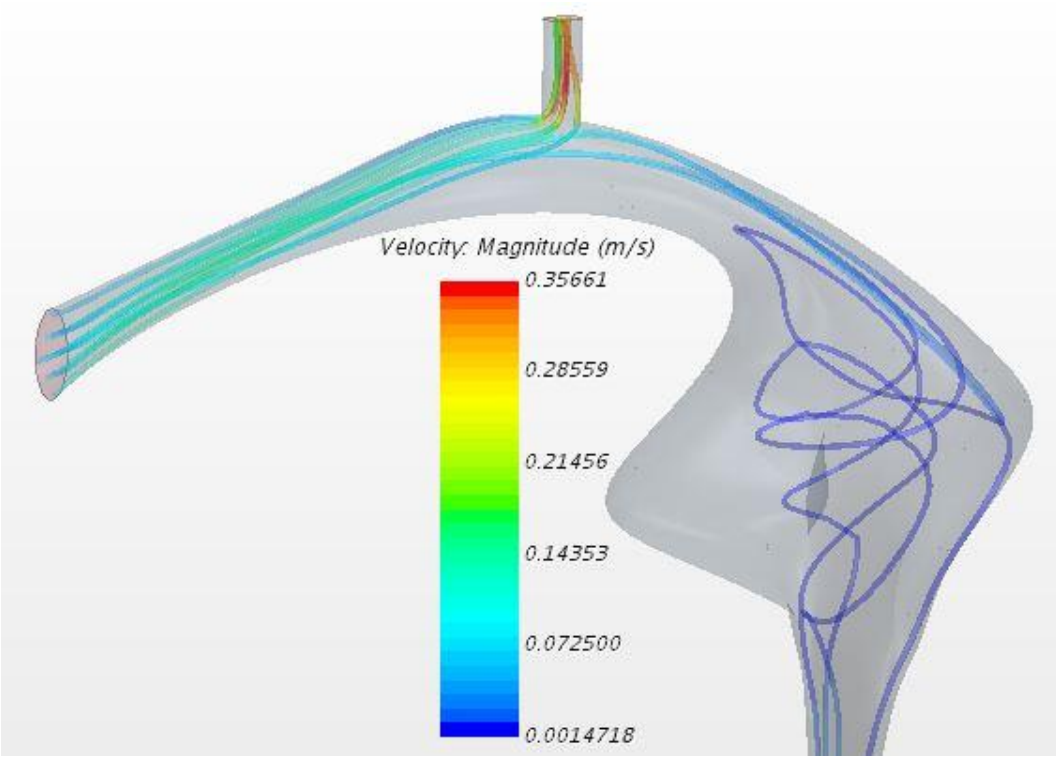


Figure 37. Cleft palate case streamlines (Thin)

Similarly, like observed in vector formation results, the velocity of the streamlines increases when they enter the cleft palate. As the viscosity of the fluid is less, it tends to react to sudden changes in the path and that is the reason, the fluid enters the cleft palate. Here, it should be noticed that four streamlines are entering into the cleft palate, one of them with highest velocity. As discussed earlier, such entry of the fluid in to the cleft palate is not desirable and to avoid that, viscosity of the fluid needs to be increased.

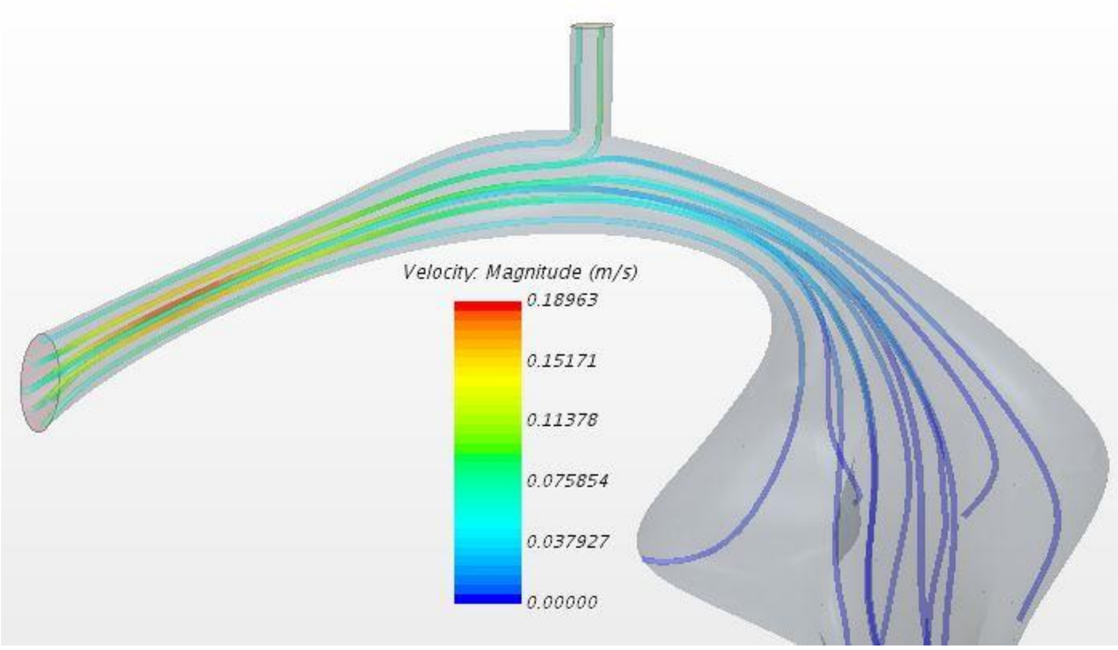


Figure 38. Cleft palate case streamlines (Nectar)

After altering the fluid viscosity to nectar thick consistency (340 cP), the streamlines were observed to be entering the geometry with high velocity and then gradually decreasing the velocity as they slightly bypass the cleft palate. Also, it should be observed that the number of streamlines entering the cleft palate has reduced to two from four as in previous case with thin consistency. It means that due to rise in viscosity, the amount of fluid that was entering the cleft palate was reduced, which is desirable. But, in order to get better results, the viscosity needs to be increased even more to honey thick consistency, as per earlier discussion.

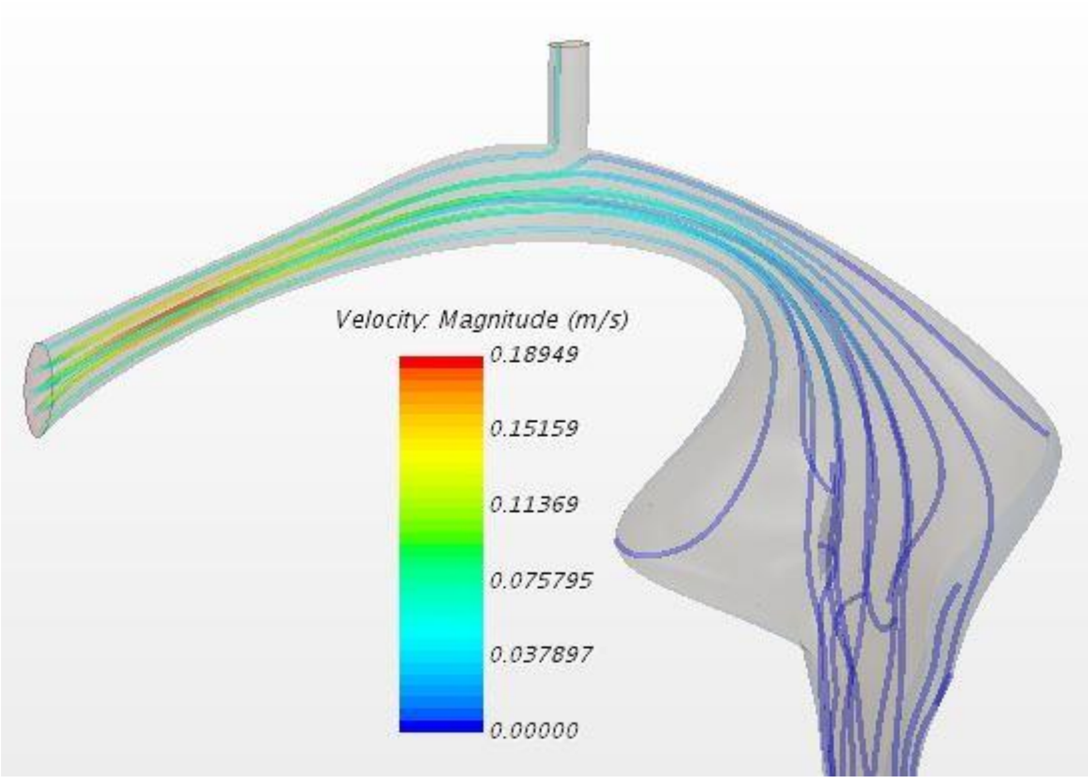


Figure 39. Cleft palate case streamlines (Honey)

As discussed in the previous results case of cleft palate, it is essential to have the fluid bypass the cleft where the viscosity of the fluid is greater. Based on the streamlines results, it can be seen that in the case of the thin consistency, the streamlines enter the cleft with high velocities. Whereas in the case of nectar consistency, significant amount of streamlines bypassed the cleft and furthermore, with honey consistency, there was even more improvement as the number of streamlines reduced to one and with less velocity. The results found in vectors and streamlines section, were as expected and satisfactory.

Figures 40-42 represent the isosurface formations in cleft palate case with thin, nectar and honey consistencies respectively.

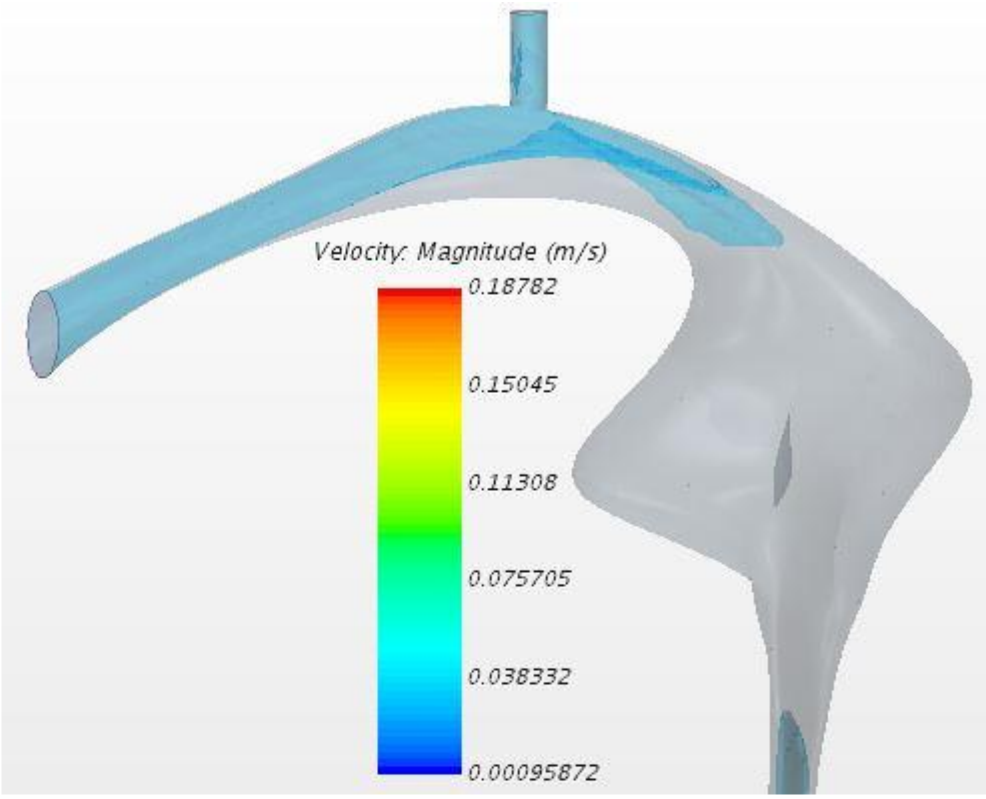


Figure 40. Cleft palate case isosurface (Thin)

Here, in case of thin consistency, the fluid tends to enter the cleft and very little is travelled further. As per earlier discussions, the viscosity of the fluid needs to be raised in order to avoid the entry of the fluid into the cleft palate. The viscosity is raised to 340 cP to observe further results.

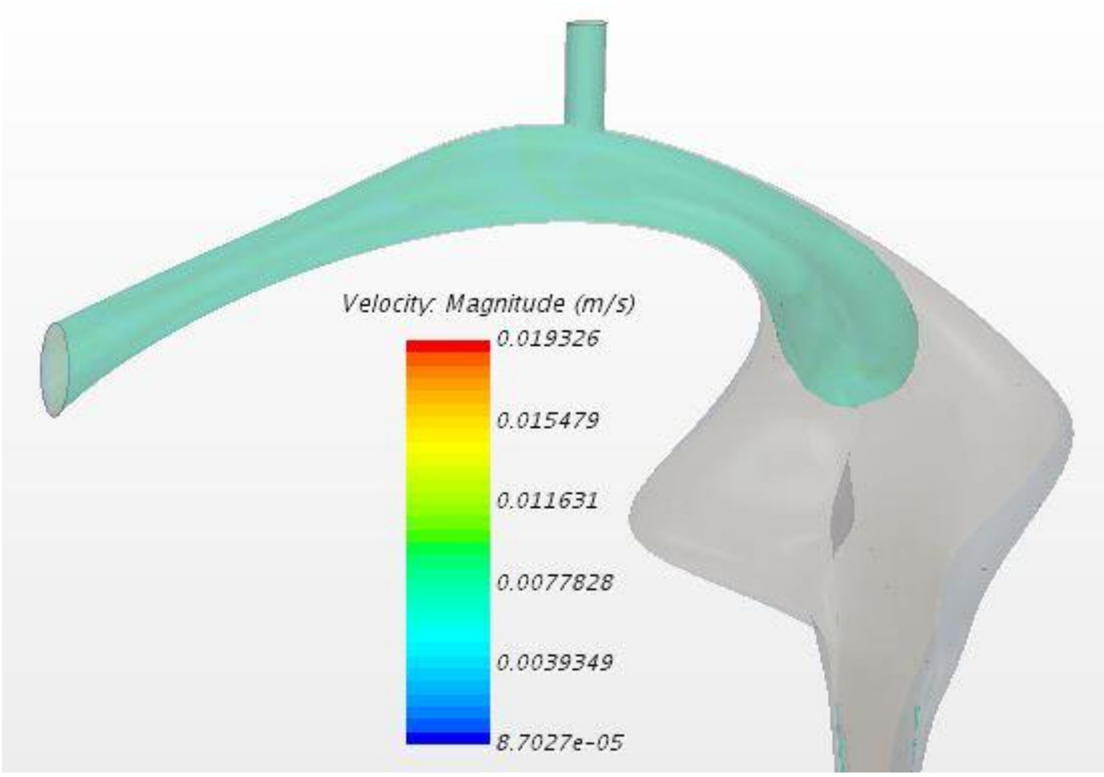


Figure 41. Cleft palate case isosurface (Nectar)

After altering the viscosity of the fluid to 340 cP, it was observed that the amount of fluid travelled further than that of the case with thin consistency. It was also observed that the velocity of the fluid was varying throughout the pharynx. The velocity of the fluid in oral region was observed to be higher than that of previous case with thin consistency. This result matches with the results obtained from the vector formations for the corresponding case. On further note, the viscosity of the fluid was raised to 1600 cP and the results were observed.

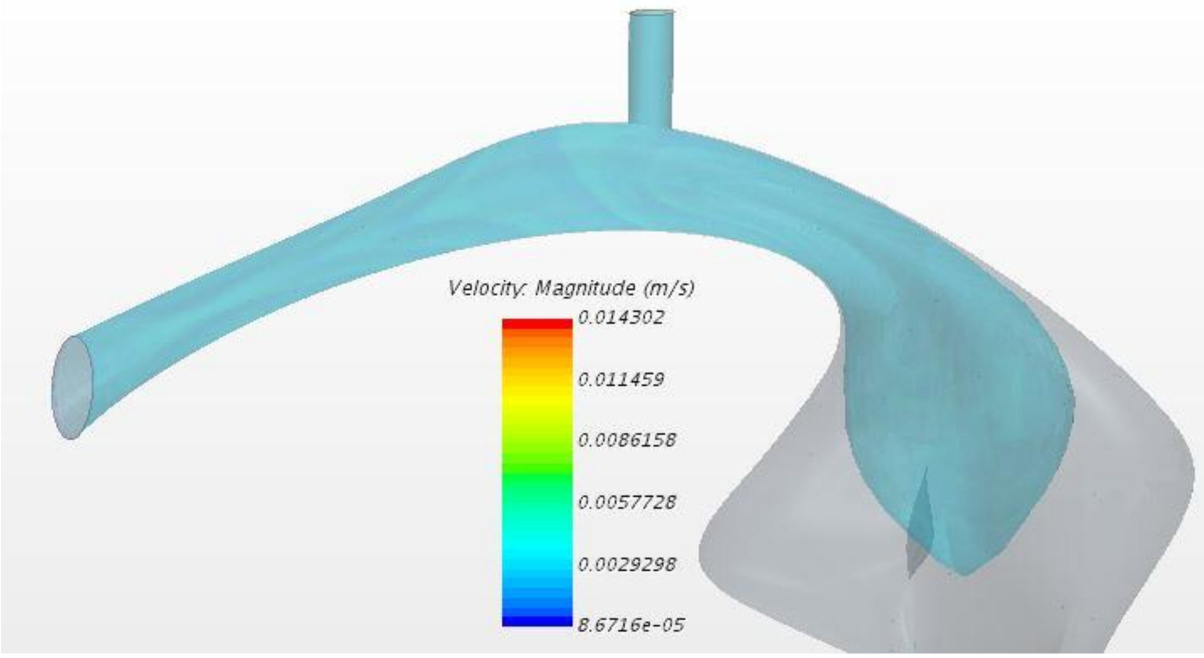


Figure 42. Cleft palate case isosurface (Honey)

The isosurface results above indicate that as the viscosity of the fluid was increased, the fluid bypassed the cleft. The results with thin consistency indicated that most of the fluid entered the cleft and with nectar consistency, the fluid was dragged further as compared to the thin consistency results, while in the case of honey consistency, the fluid was pulled even further than both rest of the cases. The results were as expected and satisfactory with this post processor as well.

4.2.3 Poor VPROM case results and discussion

From figures above, it was confirmed that the solutions converged and then post processors were used to analyse the poor VPROM case. Figures 43-45 represent the vectors for Poor VPROM case for thin, nectar and honey consistency respectively.

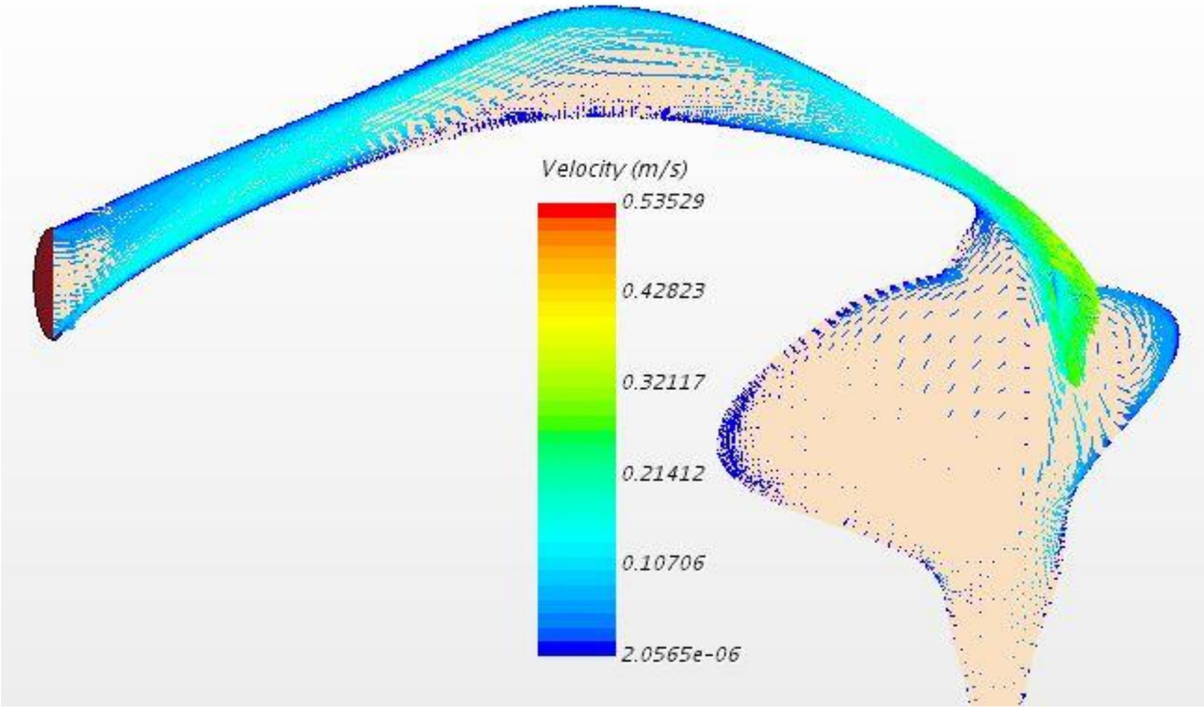


Figure 43. Poor VPROM case vectors (Thin)

As noticed in previous cases, the vectors follow along the palate with low velocity. As the vectors reach the velum, due to sudden change in cross sectional area, the magnitude of the vectors increase. As the magnitude of the vectors increase, the separation takes place the stream of vectors split into two streams. One of the stream is with lowest velocity and another stream is of greater velocity. The vectors with low velocity generate small turbulence and keep rotating under the velum. On the other hand, the vectors with higher velocity enter the pharynx without generating turbulence. It should be noted here that the fluid entered the pharynx despite of poor VPROM. Furthermore, this set of higher velocity vectors again separates into two sets of vectors. One of this vectors set is of low velocity and another one is of velocity equal to the velocity of vectors from which it is separated from. Here, the vectors set with lower velocity created another turbulence behind the high velocity vectors. These two small turbulences are not affecting the overall flow of fluid as their velocity is the lowest.

In order to study the flow of fluid with nectar consistency, the viscosity of the fluid was altered to 340 cP.

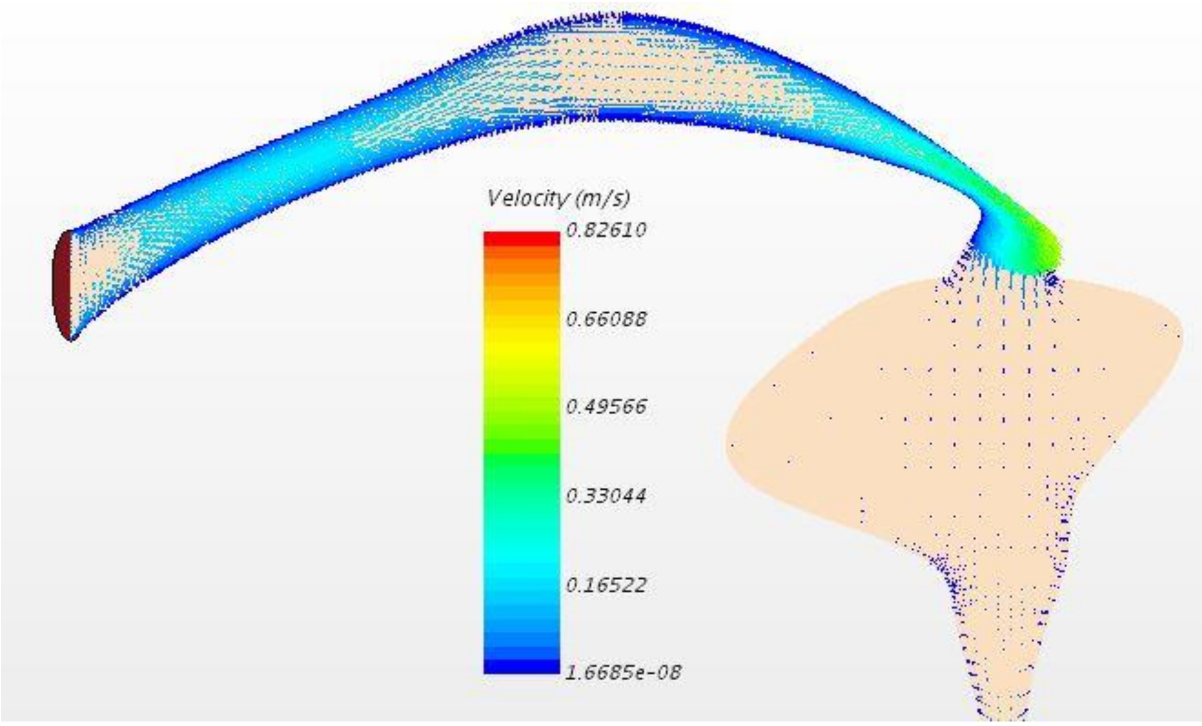


Figure 44. Poor VPROM case vectors (Nectar)

In this case, the vectors tend to shear along the boundaries as the viscosity of the fluid is more. As the vectors move along, they are obstructed at the velum. This obstruction leads to small turbulence with vectors having greater magnitude of velocity. A very few vectors are separated from this turbulence which then travel into the pharynx. Since the magnitude of these vectors is small and length is short, these vectors can be considered negligible. The turbulence caused by higher velocity vectors act as an obstruction to the flow and no further motion takes place. Since no fluid enters the pharynx, it is not desired. Further results depict the vectors formation with viscosity of the fluid as 1600 cP.

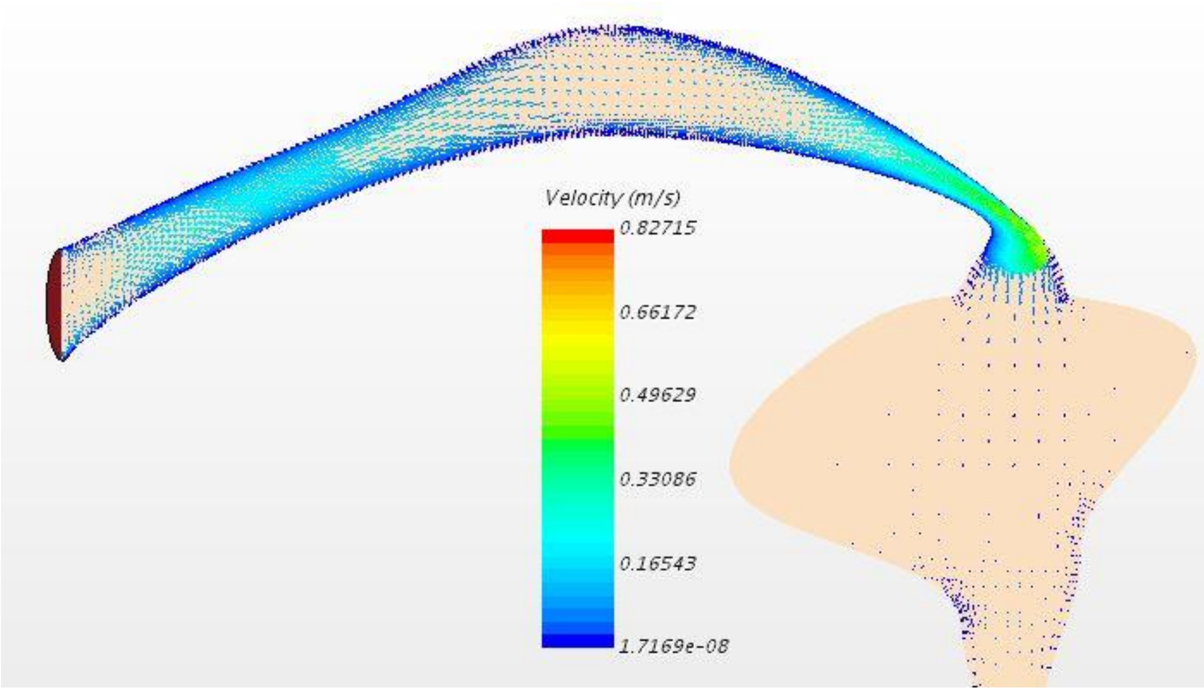


Figure 45. Poor VPROM case vectors (Honey)

From the results above, it was noted that the higher viscosity for this particular geometry is not suitable unlike the case with cleft palate. In case of the thin consistency, the fluid was able to flow past the narrow region of the pharynx as the fluid was less viscous and had the ability to change its motion as per the passage. On the other hand, the fluid vectors in the case of nectar consistency and honey consistency were not able to flow through the narrow part of the velum. Similarly, like nectar consistency vectors analysis, the flow in the honey consistency is obstructed due to the same reason of higher velocity turbulence at the velum blocking the incoming flow. As a result, it is recommended to use less viscous fluids for people with poor VPROM.

Figures 46-48 represent the streamlines for Poor VPROM case for thin, nectar and honey consistency.

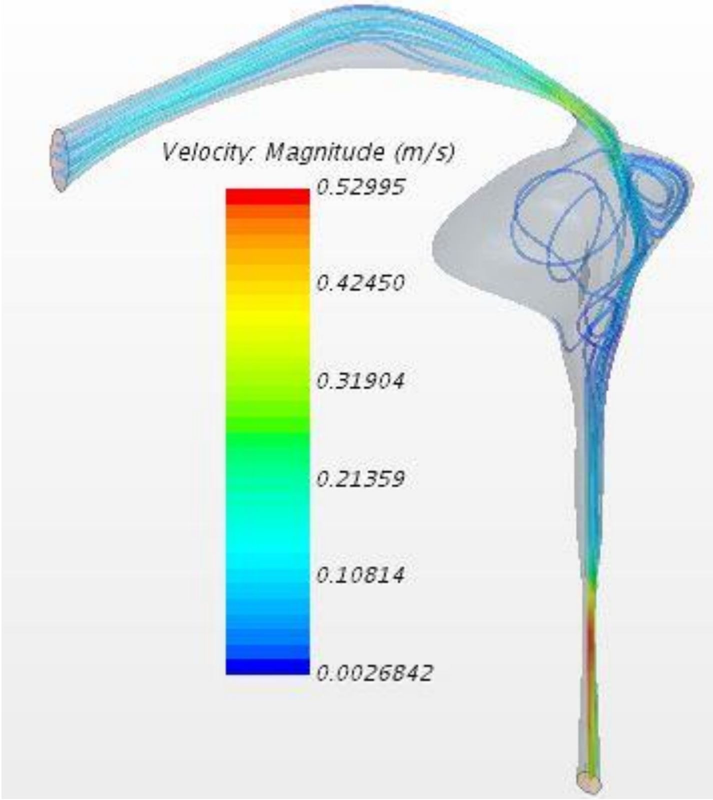


Figure 46. Poor VPROM case streamlines (Thin)

As discussed in the vectors post processor analysis, the streamlines hit the velum and are then separated from the main stream. A part of the streamlines that separated is of low velocity and it keeps rotating behind the velum. Rest of the streamlines which are more in number enter into the pharynx, as desired. The results in the vectors analysis and streamlines analysis were found similar and satisfactory as per the expectation.

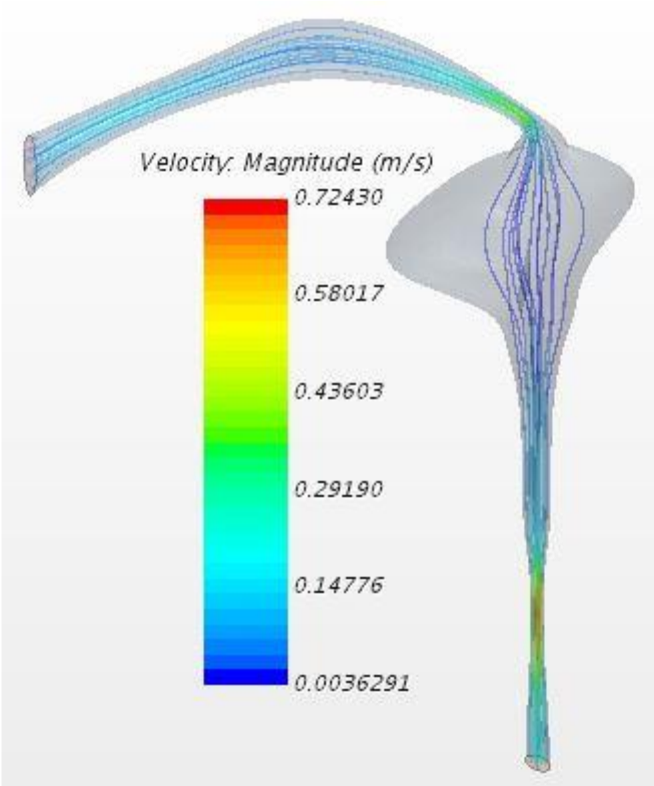


Figure 47. Poor VPROM case streamlines (Nectar)

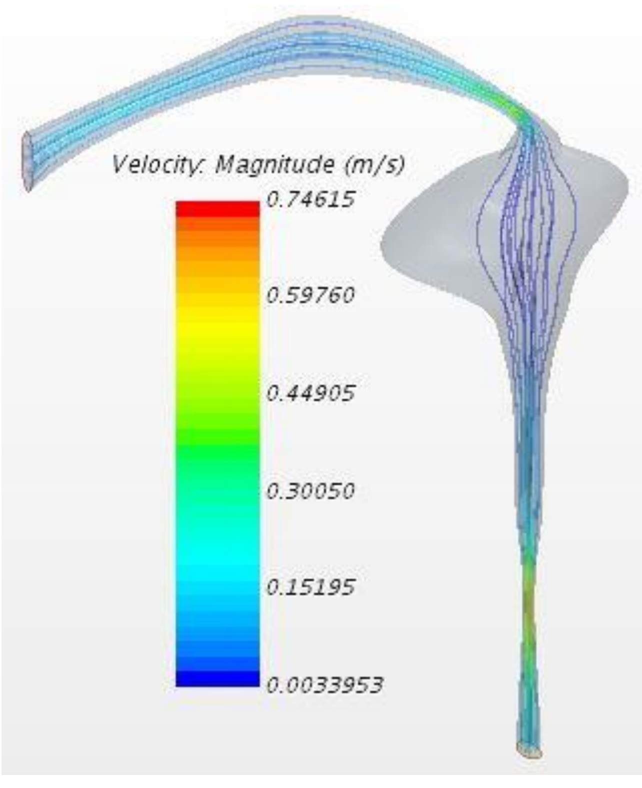


Figure 48. Poor VPROM case streamlines (Honey)

It can be seen from the figure 46 that the thin fluid was able to pass past the narrow region, whereas, in cases where the viscosity of the fluid was higher, like in cases of nectar and honey consistency, considerably less fluid was passed. Although the results in streamlines did not match entirely for nectar and honey thick consistencies, the results can be considered true and satisfactory. Also, it can be seen that due to sudden change (reduction) in the cross sectional area, the velocity of the streamlines has increased, meaning, the flow can be harmful on the fluid track.

Figures 49-51 represent the isosurface results for Poor VPROM case for thin, nectar and honey consistency.

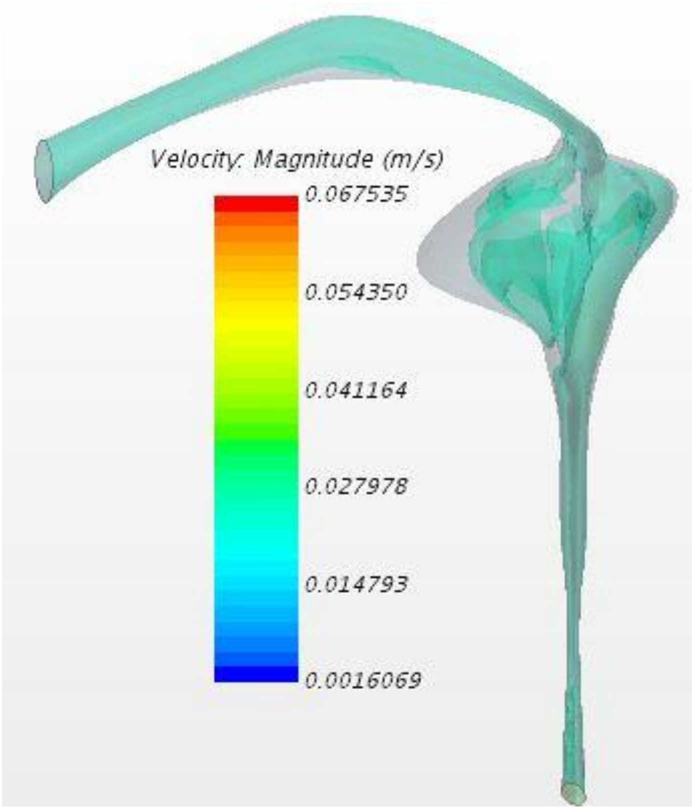


Figure 49. Poor VPROM case Isosurface (Thin)

In isosurface results for poor VPROM case with thin consistency, the fluid velocity is constant until it reaches the velum, meaning, the flow is steady until then. Once it reaches the velum, the velocity changes and turbulence starts to occur. The flow then enters the pharynx as desired. The results of isosurface represent similar trend as they represented in vectors post processor.

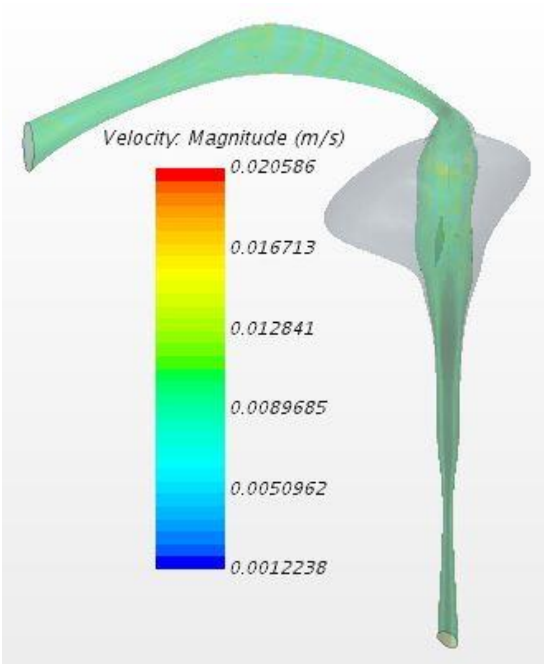


Figure 50. Poor VPROM case Isosurface (Nectar)

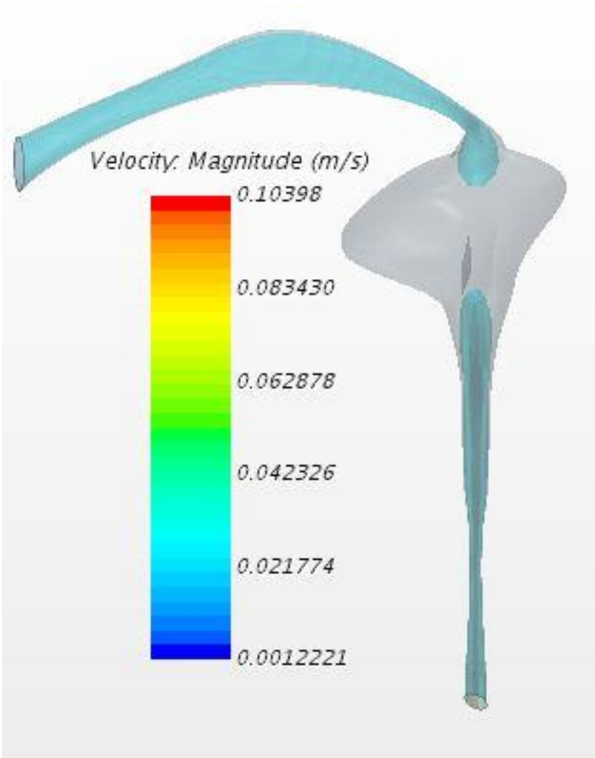


Figure 51. Poor VPROM case Isosurface (Honey)

The isosurface results indicated similar outcomes as that of the previous post processors. In the case of thin consistency, the fluid passed through the narrow region with ease. Whereas, in case of nectar consistency, the amount of fluid that passed was quite less than that of the case with thin consistency. Furthermore, the results with the honey consistency showed that the fluid had difficulties in passing through the narrow region or in other words, the fluid itself blocked the passage of its own travel down the esophagus.

5 Conclusion

Literature review indicated that the National Dysphagia Diet (NDD) has classified the dysphagia fluids in to four different categories, namely, Thin (0-50 cP), Nectar (51-350 cP), Honey (351-1750 cP) and Pudding (1751 cP and above). The experimental setup was confirmed by calibrating and validating the viscometer with an accuracy of $\pm$100 cP and objective was set to finding the volumetric measures of Simply Thick thickener by keeping the base fluids volume constant, for Nectar thick and Honey thick classes decided by NDD, where the base fluids were water, whole milk, Pediasure 1.0, Pediasure 1.5 and Pediasure Peptide 1.0. For numerical study using Computational Fluid Dynamics (CFD) approach, the numerical study setup was set with the CAD model of oropharyngeal geometry, which was developed using a half head model and a loft function in Solidworks, with the physical model of K-Omega turbulence and three different fluid viscosities set at 1 cP, 340 cP and 1600 cP for thin, nectar and honey consistencies respectively. The experiments were carried out and the results were obtained, thereby accomplishing the primary objective of evaluating the volumetric measures with regards to Simply Thick thickener and a time-temperature study on the same fluids was done. It was observed that after 24 hours of refrigeration, the viscosities of the fluid samples increased. This rise in the viscosities was not consistent for all the samples as the base fluids were different in nature and in content, having their own physical properties. Pediasure 1.5 was found to have the highest viscosity of all liquids tested and water having the lowest. The results with nectar samples and honey samples were slightly different when the nature of Simply Thick was observed. It was then concluded that the reason behind this behaviour could be because of the interaction between the ingredients of Simply Thick and the ingredients of the selected base fluids. With regards to the numerical study, all nine cases were iterated until the solution was found to be converged. First study with the regular case was studied and the flow patterns of the fluid were noted using three post processors, namely, Vectors, Streamlines and Isosurface. Similar post processors were used for next study with the case with the cleft palate. The results were satisfactory and were as expected where it was confirmed that the honey consistency suits well for a person with cleft palate. Third study was regarding the case with poor VPROM, where the results indicated that having high viscosity does not suit in all cases, as the results with the honey consistency indicated that the passage was blocked by the fluid itself for its desired motion towards the esophagus.

6 Future Work

Considering the results of this study, further work can be done which is suggested below:

- Studying the effect of larger volume on the viscosity.
- Studying the interaction between the ingredients of Simply Thick and Water as a base fluid, from small volume to larger volumes.
- Numerically studying the fluid flow with the person having Cerebral Palsy

Appendices

Ingredients of the Fluid liquids

Basic Ingredients of Pediasure 1.0: Water, Sugar, corn maltodextrin, milk protein concentrate, high oleic safflower oil, canola oil, soy protein isolate.

Basic Ingredients of Pediasure 1.5: Water, Sugar, corn maltodextrin, milk protein concentrate, high oleic safflower oil, soy oil, medium chain triglycerides.

Basic Ingredients of Pediasure Peptide 1.0: Water, corn maltodextrin, whey protein hydrolysate, structured lipid, hydrolysed sodium caseinate, medium chain triglycerides, canola oil.

Table 18. Viscosity values from the references

Ref. No.	Thin (cP)	Nectar(cP)	Semi Honey(cP)	Honey(cP)	Pudding(cP)
2	50	350		1750	>1750
3	50	350		1750	>1750
4	50	350		1750	>1750
5	4	300	1500	3000	5000
6	50	350		1750	>1750
7	50	350		1750	>1750
8	50	350		1750	>1750
9		58		310	844
10		27			107
11		54		213	
12		295.02			3682.21
13		615		1480	3340

Table 19. Probe depths-viscosity reading for Water samples (honey thick)

Height (Inches)	Viscosity (cP)	Temperature corrected viscosity (cP)	Temperature (C)
0.5	4.9	3.4	20.3
1	6.4	6.2	20.2
1.5	10.3	10.4	20.2
2	11.7	11.4	19.7
2.5	12.4	12.4	19.5
3	12.6	12.5	20.3
3.5	13.5	13.4	20.4
4	13.4	13.6	20.5
4.5	13.6	13.4	20.6
5	14.4	14.5	20.5
5.5	14.2	14.2	20.3
6	14.4	14.2	20.2

Table 20. Probe depths-viscosity reading for Milk samples (honey thick)

Height (Inches)	Viscosity (cP)	Temperature corrected viscosity (cP)	Temperature (C)
0.5	3.2	3.6	20.3
1	10.5	11.1	20.2
1.5	22.1	22.1	20.2
2	22.9	23.2	19.7
2.5	22.1	22.8	19.5
3	23.2	23.1	20.3
3.5	22.8	23	20.4
4	22.6	23.2	20.5
4.5	22.5	22.8	20.6
5	23.4	23.3	20.5
5.5	23.3	22.4	20.3
6	22.8	22.9	20.2

Table 21. Probe depths-viscosity reading for Pediasure 1.0 samples (honey thick)

Height (Inches)	Viscosity (cP)	Temperature corrected viscosity (cP)	Temperature (C)
0.5	8.5	8.5	19.3
1	23.1	22.5	19.8
1.5	26.3	25.4	20.5
2	26.6	26.5	19.8
2.5	29	28.8	20.3
3	29.4	29.1	20
3.5	30.2	30.4	20.2
4	31.2	31.4	19.3
4.5	31.2	31.2	19.8
5	31.2	30.2	20.5
5.5	31.5	31.2	20.2
6	31.8	31.4	19.3

Table 22. Probe depths-viscosity reading for Pediasure 1.5 samples (honey thick)

Height (Inches)	Viscosity (cP)	Temperature corrected viscosity (cP)	Temperature (C)
0.5	15.2	14.5	19.3
1	28.8	28.5	19.8
1.5	32.8	34.6	20.5
2	34.6	35	19.8
2.5	35.8	36.1	20.3
3	38.3	38.5	20
3.5	38.9	38.5	20.2
4	41.4	40.8	19.3
4.5	41.4	41.7	19.8
5	41.7	41.8	20.5
5.5	43.2	42.7	20.2
6	45.1	43.4	19.3

Table 23. Probe depths-viscosity reading for Pediasure Peptide 1.0 samples (honey thick)

Height (Inches)	Viscosity (cP)	Temperature corrected viscosity (cP)	Temperature (C)
0.5	10.7	11.1	20.3
1	23.4	23.7	20.2
1.5	32.2	33.8	20.2
2	31.7	33.1	19.7
2.5	34.9	34.5	19.5
3	38.5	37.6	20.1
3.5	38.9	41.1	20.4
4	38.9	38.4	20.5
4.5	39.5	41.5	20.7
5	40.2	39.7	21
5.5	41.7	41.4	20.3
6	42.1	41.7	20.2

Table 24. Probe depths-viscosity reading for water samples (Nectar thick)

Height (Inches)	Viscosity (cP)	Temperature corrected viscosity (cP)	Temperature (C)
0.5	1.9	2.1	19.3
1	2.1	2.3	19.8
1.5	3.2	3.4	20.5
2	5.6	4.6	19.8
2.5	5.5	5.4	20.3
3	6.7	6.5	20
3.5	7.3	7.5	20.2
4	7.4	7.3	19.3
4.5	7.5	7.4	19.8
5	7.2	7.4	20.5
5.5	7.4	7.3	20.2
6	7.3	7.5	19.3

Table 25. Probe depths-viscosity readings for water samples (Honey thick)

Height (Inches)	Viscosity (cP)			Temperature corrected viscosity (cP)			Temperature (C)		
0.5	4.2	5.3	5.1	3.3	3.2	3.5	20.2	20.1	20.5
1	6	6.3	6.7	6.3	6.2	6.1	20.1	20.2	20.3
1.5	10.2	10.5	10	10.2	10.3	10.6	20	20.1	20.5
2	11.5	11.7	11.8	11.2	11.3	11.5	19.9	19.6	19.4
2.5	12.2	12.2	12.6	12.4	12.3	12.5	19.5	19.6	19.4
3	12.5	12.6	12.7	12.5	12.6	12.4	20.1	20.3	20.5
3.5	13.2	13.5	13.6	13.1	13.2	13.7	20.2	20.3	20.5
4	13.5	13.6	13.1	13.4	13.5	13.7	20.6	20.4	20.5
4.5	13.7	13.4	13.5	13.1	13.2	13.7	20.5	20.6	20.7
5	14.2	14.6	14.2	14.3	14.5	14.47	20.4	20.5	20.6
5.5	14.2	14.3	14.1	14.2	14	14.3	19.9	20.8	20
6	14.4	14.5	14.3	14.3	14.2	14.1	20	20.3	20.1

Table 26. Probe depths-viscosity reading for milk samples (honey thick)

Height (Inches)	Viscosity (cP)			Temperature corrected viscosity (cP)			Temperature (C)		
0.5	3.2	3.3	3.1	3	4.1	3.6	20.2	20.1	20.5
1	10.6	10.5	10.3	11	11.3	10.8	20.1	20.2	20.3
1.5	22	22	22.1	22.2	22.1	22	20	20.1	20.5
2	22.8	22.7	23	23.2	23.3	23.1	19.9	19.6	19.4
2.5	22.2	22.1	22	22.3	23.1	22.9	19.5	19.6	19.4
3	23.2	23.3	23.1	22.9	23.3	23	20.1	20.3	20.5
3.5	22.3	23.1	22.9	23.4	22.7	22.9	20.2	20.3	20.5
4	22.3	22.1	23.3	23.2	23.3	23.1	20.6	20.4	20.5
4.5	22.7	22.3	22.4	22.3	23.1	22.9	20.5	20.6	20.7
5	23.1	23.3	23.6	23.6	23.1	23	20.4	20.5	20.6
5.5	23.6	23.1	23	22.2	22.8	22.1	19.9	20.8	20
6	22.3	23.1	22.9	22.8	22.7	23	20	20.3	20.1

Table 27. Probe depths-viscosity reading for Pediasure 1.0 samples (honey thick)

Height (Inches)	Viscosity (cP)			Temperature corrected viscosity (cP)			Temperature (C)		
0.5	8.5	8.4	8.5	8.4	8.4	8.5	19.2	19.5	19.2
1	23	23.1	23.2	22	23	22.5	20	19.5	19.7
1.5	26	26.4	26.3	25.5	25.6	25.1	20.5	20.3	20.6
2	26.5	26.7	26.5	26.3	26.6	26.4	20	19.5	19.7
2.5	29	29.1	28.8	28.5	28.7	29	20.2	20.3	20.4
3	29.3	29.5	29.4	29.1	29.5	28.6	20.6	19.5	19.7
3.5	30.2	30.3	30.1	30.1	30.5	30.4	20.4	20	20.1
4	31	31.3	31.2	31.2	31.6	31.3	19.2	19.5	19.2
4.5	31	31.2	31.4	31.4	31.2	30.8	20	19.5	19.7
5	31.3	31.2	31	30.2	30.3	30.1	20.5	20.3	20.6
5.5	31.2	31.7	31.6	31	31.3	31.2	20.4	20	20.1
6	31.8	31.9	31.5	31.7	31.5	30.9	19.2	19.5	19.2

Table 28. Probe depths-viscosity reading for Pediasure 1.5 samples (honey thick)

Height (Inches)	Viscosity (cP)			Temperature corrected viscosity (cP)			Temperature (C)		
0.5	15	15.2	15.3	14	14.3	15.1	19.2	19.5	19.2
1	28.5	29	28.7	28.5	28.7	28.3	20	19.5	19.7
1.5	32.5	33	32.8	34.2	35	34.6	20.5	20.3	20.6
2	34.2	35	34.6	35	35	34.9	20	19.5	19.7
2.5	36	36.5	34.9	36.2	36.1	36	20.2	20.3	20.4
3	38.3	38.2	38.3	38.3	38	39.1	20.6	19.5	19.7
3.5	38.8	38.7	39	38.3	38	39.1	20.4	20	20.1
4	40.8	41.7	41.7	40	41.2	41.1	19.2	19.5	19.2
4.5	41.2	41.3	41.5	41	42.3	41.8	20	19.5	19.7
5	41.6	41.3	42.2	41.5	41.7	42	20.5	20.3	20.6
5.5	43.1	42.8	43.5	42.8	42.2	42.9	20.4	20	20.1
6	45	44.8	45.3	42.2	44	43.8	19.2	19.5	19.2

Table 29. Probe depths-viscosity reading for Pediasure Peptide 1.0 samples (honey thick)

Height (Inches)	Viscosity (cP)			Temperature corrected viscosity (cP)			Temperature (C)		
0.5	10.1	11	10.9	11	11.2	11	20.2	20.1	20.5
1	23.2	23.8	23.1	23.4	23.7	24	20.1	20.2	20.3
1.5	32	32.2	32.3	33.2	34	34.2	20	20.1	20.5
2	31.5	31.8	31.7	33	33.2	32.9	19.9	19.6	19.4
2.5	34.8	34.7	35.2	34.3	34.1	35	19.5	19.6	19.4
3	38.3	38.1	39	37	37.5	38.1	20.1	20.3	19.9
3.5	39.1	38.7	38.9	41	41.1	41	20.2	20.3	20.5
4	39	39.1	38.5	38	39	38	20.6	20.4	20.5
4.5	39.3	39.5	39.6	41.3	42.1	41.1	20.6	20.6	20.7
5	40	40.5	40.1	39.8	39.7	39.5	20.4	20.5	22
5.5	41	42	42.1	40.3	42.1	41.7	19.9	20.8	20
6	43	41	42.1	42	41.2	41.7	20	20.3	20.1

Table 30. Probe depths-viscosity reading for water samples (nectar thick)

Height (Inches)	Viscosity (cP)			Temperature corrected viscosity (cP)			Temperature (C)		
0.5	2	1.8	1.9	1.7	2.3	2.2	19.2	19.5	19.2
1	1.9	2.1	2.2	2.2	2.3	2.2	20	19.5	19.7
1.5	3	3.2	3.3	3.2	3.3	3.5	20.5	20.3	20.6
2	5.7	5.5	5.6	4.5	4.5	4.6	20	19.5	19.7
2.5	5.4	5.3	5.6	5.5	5.2	5.4	20.2	20.3	20.4
3	6.8	6.2	6.9	6.6	6.5	6.2	20.6	19.5	19.7
3.5	7.2	7	7.6	7.2	7.7	7.5	20.4	20	20.1
4	7.8	7.2	7	7	7.2	7.7	19.2	19.5	19.2
4.5	7.5	7.5	7.4	7.7	7.1	7.3	20	19.5	19.7
5	7	7.3	7.1	7.2	7.5	7.4	20.5	20.3	20.6
5.5	7.3	7.2	7.5	7.3	7.5	7.1	20.4	20	20.1
6	7.6	7.2	7	7.7	7.2	7.5	19.2	19.5	19.2

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