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PERISTALTIC FLOW OF SOME SELECTED FOOD SUPPLEMENTS IN A MODELED OESPHAGUS

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ABSTRACT

This paper presents thermal and hydrodynamic behaviours of some selected food supplements in a modelled oesophagus. These food supplements are orange juice and water melon juice while chyme was used as the base food supplement for comparison. Numerical method was adopted using Solid Works 2014 and Ansys fluent as working tools. The results obtained showed that at a distance of 0.25m from the inlet, the flow was hydrodynamically fully developed. Furthermore, the results revealed that Orange juice had the highest pressure build up in the tube while Water melon had the least. For Reynolds number Re less than 2100, the flow velocity was found to be independent of the food juice used but largely depends on flow Re. Based on hydrodynamic behaviours of the food supplements considered, orange juice is the best fluid, while water melon is the best food supplement based on thermal behaviour.

KEYWORDS: Peristaltic flow, Food Supplement, Fully developed, Modelled oesophagus, Reynolds number.

1. INTRODUCTION

Peristalsis is the means by which physiological fluids are transportation into human body via muscle contraction and relaxation of vessel walls (Singh et at, 2017, Tripathy D. and Osman A Be'g, 2013). It is the mechanism that is responsible for food transportation through the digestive tracts; in the flow of blood through the veins, capillaries and arteries and in lymph transportation in lymphatic vessels (Naha, Jeelani and Windhab, 2012), (Naha, 2012) and (Ferrura and Singh, 2010). Peristalsis aids in gastric digestion and mixing in human body. Over the years, research attention has been given to the mathematical and numerical modelling of peristaltic flow because of its complex and vital nature (Tripathy and Osman, 2014).

Numerous theoretical and experimental attempts have been made by researchers to study the physics of peristalsis. In 1966, the behaviour of a 2-D peristaltic pump was studied experimentally and analytically by Latham. Yin and Fung, 1969 investigated peristaltic wave in circular cylindrical tube. Kumar et al., 2010 studied peristaltic pumping in a permeable wall. While Burns and Parkes in 1967 shed more light to peristaltic pumping without considering its application; In a flexible tube, Barton and Raynor in 1968 examined analytically Newtonian fluid flow which is driven by peristaltic motion. Lew et al ., 1971 conducted a theoretical study of the characteristics of peristalsis with regards to the fluid dynamics involved in food mixing and propulsion in the small intestine. Singh in 2007 presented a method that can be used to characterise the mechanisms that promote digestion. More recently, Hussein et a l., 2015 analyzed heat transfer in peristaltic flow of magneto hydrodynamic Jeffery fluid involving variable thermal conductivity. Also Maraj et al., 2015 studied Rabinowitsch fluid model. Bayliss and Starling, 2000 were the first to clinically describe peristalsis as the transport of fluid inside a tube, endoscope arteries, or intestines by the action of wall. Lately the peristalsis mechanism in both mechanical and physiological situations has become the object of scientific investigation (Mekheimer KhS and Abd Elmaboud Y, 2008 and Srinivas et al., 2009). Fluid motion within the small intestine is generated by three movement patterns: (i) peristalsis, (ii) segmentation and (iii) pendular movements (Macagno and Christensen, 1980).

Also the research and engineering application of pulsating fluid flows have been established as a major branch of fluid dynamics. The research on pulsating flow includes the work of Azoury, 1992 on wind energy conversion systems and Tucker, 2001 investigated biomedical flow phenomena. Pulsating laminar flow mechanism has been found useful in practical heat transfer devices owing to its enhanced ability at the entrance of flow instability (Niceno and Nonile, 2001). According to Nichols and O'Rourke, 1997, in biomedical engineering, the pulsating flow is a vast growing research. Akbar and Nadeem, 2014 examined simulation of peristaltic flow of chyme in small intestine for couple stress fluids. Comprehensive mathematical model developed for the peristaltic transport of complex rheological visco-elastic fluids through a non-uniform porous medium channel, and simulation of chyme and undigested chyme hydrodynamics in the gastro-intestinal tract were studied by (Tripathi and Anwar, 2013). Adegun, et al., 2013 also studied the flow of non-Newtonian fluid, in elliptic ducts. In the work, dilatants, pseudoplastic and Newtonian fluids were specifically looked into. Berger and Jou, 2000 also examined intra-cardiac flow and blood vessel stenosis flow. Adegun and Oladosu, 2009 studied heat transfer and fluid flow in elliptic duct using scale analysis. Brasseur et al., 1993 considered the unsteady effects of peristaltic flow of hydrodynamics of viscous fluid through a sinusoidal channel and focused their model on oesophageal swallowing. Bello-Ochende and Adegun, 1993 also looked into fluid flow and heat transfer in tilted elliptic duct using perturbation technique.

The present study seeks to investigates the peristaltic flow of some selected food supplements (chyme, orange juice and water melon juice) in a modeled oesphagus that can be used for patients who cannot eat through the mouth as a result of either mouth or oesophagus ailments. Interactions with medical personnel revealed that there is indiscriminate deposit of food through the NasoGastric (NG) tube without recourse to flow rate; heat transfer and pressure drop which if not considered may lead to serious complications or even death. Artificial oesophagus lead to the stomach where digestion will first take place in their own case and further movement to the small intestines where nutrient absorption is found.

2. METHODOLOGY

The physical problem envisaged in this research is the flow of a simple, incompressible and viscous fluid through the modelled oesophagus. To tackle this problem, a numerical model of the physical domain was built and the Navier–Stokes equations were solved numerically with appropriate initial and boundary conditions. The tool employed is CFD in two dimensions. The complex mechanical behaviours of physiological fluids can be characterized by either Newtonian or non-Newtonian (rheological) models. Most physiological fluids exhibit both elastic and viscous properties through simultaneous storage and dissipation of mechanical energy. Chyme is a semi-liquid, homogeneous, creamy-like substance formed as a result of mechanical mixing of the food with gastric juices on ingested food. Orange juice and Water melon juice are both extracted from their parent fruits. The properties of the fluid are listed below in Table 1.

Table 1. Properties of the working fluids.

Fluid	Density (kg/m^3)	Viscosity (Pa.s)	Specific Heat Capacity (J/kgK)	Thermal Conductivity, k (W/mK)
Chyme	1000	1.0	4180	0.6
Orange juice	1040	1.078767	3915	0.59
Water Melon juice	1030	0.728	4058	0.618

Source: (Ikegwu and Ekwu, 2009)

A numerical model consists of three basic steps: data pre-processing, solving process and data post-processing. In the pre-processing step, the computational domain was sketched with the aid of Solid Works 2014 and the meshing of the model is built in the Design Modeller, and the initial and boundary conditions are fixed. Next, a suitable numerical scheme is implemented to solve the governing equations of the model. Lastly, in the post-processing step, a correct analysis and visualization of the data are required to ensure a proper discussion of the results.

2.1. Physical Model

The domain shown in Fig. 1 is an artificial tube used to pass food to patient with weak or poor storage organ (stomach). For the purpose of this study, the geometry is assumed to be thinned wall. The wall properties is culled from soft Rubber (density=1100 kg/m^3, Specific Heat Capacity=2010 J/kgK and its Thermal Conductivity=0.13 W/mK)

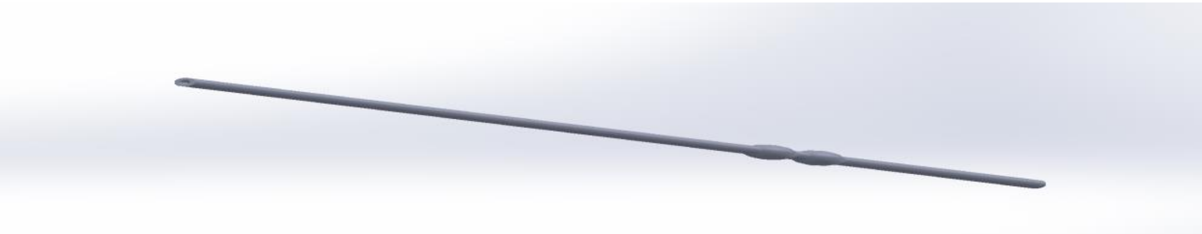

Fig. 1. Artificial Food passage tube.

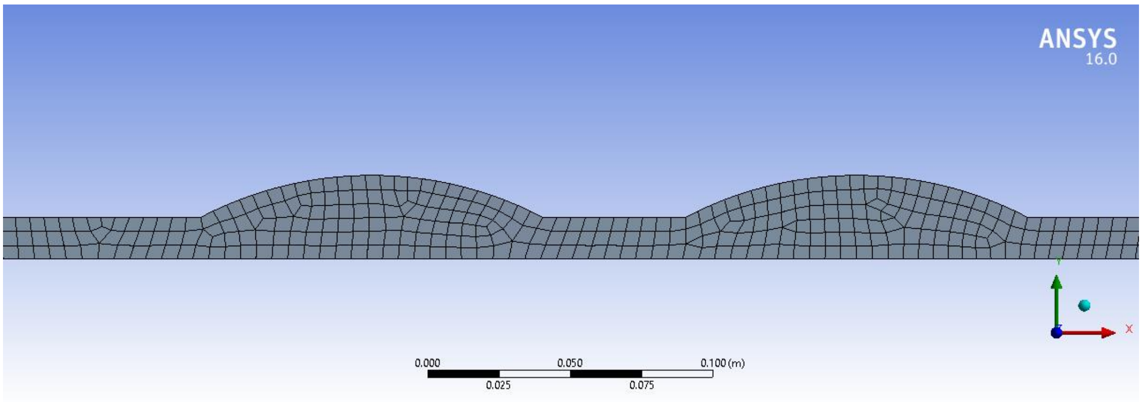

Fig. 2. Mesh generated domain with 0.005m Element size.

2.2. Formulation of the Governing Equations

Following Srinivas et al., 2009, the governing equations in the fixed frame of reference for an incompressible Williamson fluid model are as follows:

2.2.1. Continuity Equation:

$$\frac{\partial \bar{U}}{\partial \bar{R}} + \frac{\bar{U}}{\bar{R}} + \frac{\partial \bar{W}}{\partial \bar{Z}} = 0 \tag{1}$$

2.2.2. Momentum Equations:

$$\rho\left(\frac{\partial}{\partial \bar{t}} + \bar{U}\frac{\partial}{\partial \bar{R}} + \bar{W}\frac{\partial}{\partial \bar{Z}}\right)\bar{U} = -\frac{\partial \bar{P}}{\partial \bar{R}} + \frac{1}{\bar{R}}\frac{\partial}{\partial \bar{R}}\left(\bar{R}\bar{\tau}_{\bar{R}\bar{R}}\right) + \frac{\partial}{\partial \bar{Z}}\left(\bar{\tau}_{\bar{R}\bar{Z}}\right) \tag{2}$$

$$\rho\left(\frac{\partial}{\partial \bar{t}} + \bar{U}\frac{\partial}{\partial \bar{R}} + \bar{W}\frac{\partial}{\partial \bar{Z}}\right)\bar{W} = -\frac{\partial \bar{P}}{\partial \bar{Z}} + \frac{1}{\bar{R}}\frac{\partial}{\partial \bar{R}}\left(\bar{R}\bar{\tau}_{\bar{R}\bar{Z}}\right) + \frac{\partial}{\partial \bar{Z}}\left(\bar{\tau}_{\bar{Z}\bar{Z}}\right) \tag{3}$$

2.2.3. Energy Equation:

The energy transport equation for transient flow is;

$$\rho c_P\left(\frac{\partial \bar{T}}{\partial \bar{t}} + \bar{U}\frac{\partial \bar{T}}{\partial \bar{R}} + \bar{W}\frac{\partial \bar{T}}{\partial \bar{Z}}\right) = \bar{\tau}_{\bar{R}\bar{R}}\frac{\partial \bar{U}}{\partial \bar{R}} + \bar{\tau}_{\bar{R}\bar{Z}}\frac{\partial \bar{W}}{\partial \bar{R}} + \bar{\tau}_{\bar{Z}\bar{R}}\frac{\partial \bar{U}}{\partial \bar{Z}} + \bar{\tau}_{\bar{Z}\bar{Z}}\frac{\partial \bar{W}}{\partial \bar{Z}} + K\left(\frac{\partial^2 \bar{T}}{\partial \bar{R}^2} + \frac{1}{\bar{R}}\frac{\partial \bar{T}}{\partial \bar{R}} + \frac{\partial^2 \bar{T}}{\partial \bar{Z}^2}\right) \tag{4}$$

The constitutive equation for the shear stress tensor $\bar{\tau}$ for Williamson fluid is given by

(Dapra and scapi, 2007):

$$\bar{\tau} = \left[\mu_\infty + (\mu_0 + \mu_\infty)\left(1 - \Gamma|\bar{\dot{\gamma}}|\right)^{-1}\right]\bar{\dot{\gamma}} \tag{5}$$

The rate is expressed in terms of second invariant strain tensor

$$|\bar{\dot{\gamma}}| = \sqrt{\frac{1}{2}\sum_i\sum_j \bar{\dot{\gamma}}_{ij}\bar{\dot{\gamma}}_{ji}} = \sqrt{\frac{1}{2}\Pi} \tag{6}$$

and

$$\prod = tr(grad\boldsymbol{V} + (grad\boldsymbol{V})^T)^2 \tag{7}$$

$$\bar{\tau}_{\bar{R}\bar{R}} = 2\mu_0\left(1+\Gamma|\bar{\dot{\gamma}}|\right)\frac{\partial\bar{U}}{\partial\bar{R}} \tag{8}$$

$$\bar{\tau}_{\bar{R}\bar{Z}} = \mu_0\left(1+\Gamma|\bar{\dot{\gamma}}|\right)\left(\frac{\partial\bar{U}}{\partial\bar{Z}}+\frac{\partial\bar{W}}{\partial\bar{R}}\right) \tag{9}$$

$$\bar{\tau}_{\bar{Z}\bar{Z}} = 2\mu_0\left(1+\Gamma|\bar{\dot{\gamma}}|\right)\frac{\partial\bar{W}}{\partial\bar{Z}} \tag{10}$$

2.3. Computational Procedure

Considering the symmetry of the flow, only a half of the whole cross-section was used in the numerical computation. An element size of 0.0001m was selected for the mesh size thereby generating 11804 nodes and 4976 Elements. To ensure accuracy of the numerical result, numerical tests were carried out with different grid sizes to determine the effect of grid size in the numerical results, before arriving at an appropriate mesh size. Computed values for average velocity, average pressure, average temperature, fluid velocity, fluid pressure, fluid temperature, and wall shear stress were evaluated.

2.3.4. Evaluation of the Mean Nusselt Number

Nusselt number represents the rate of heat transfer across the wall. Nusselt number is interpreted as the ratio of heat transfer by convection to conduction across the fluid layer of thickness. According to Ozisik, 1985 a large value of Nusselt number implies enhanced heat transfer by convection and that heat transfer coefficient can be expressed as:

$$h = \frac{q}{T_w - T_b} \tag{11}$$

$$Nu = \frac{h * d_h}{k} \tag{12}$$

Equation (12) is the local Nusselt number evaluated at the instance of wall temperature and bulk fluid temperature.

Where

$$d_h = \frac{4A}{P} \tag{13}$$

3. RESULTS AND DISCUSSION

Fig. 3 shows the velocity profile has the maximum value at the centre point of the considered region. On the boundary with a no-slip condition, velocity equals zero. This shows that the implemented method meets the imposed boundary conditions.

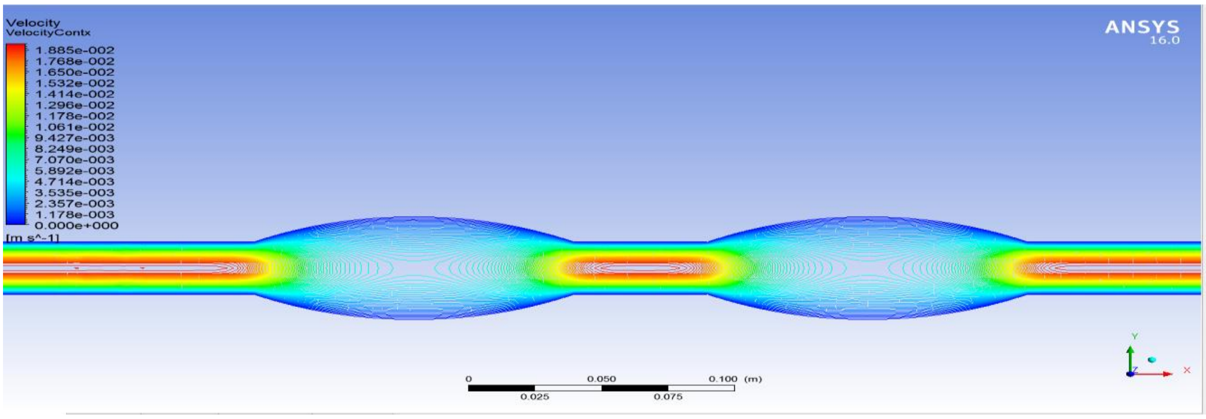

Fig. 3. Velocity Profile across the length of the Tube.

Figs. 4 and 5 show the typical flow velocity about the centreline along axial position for different inlet velocities. The plots reveal that velocity increases steadily to a point of 0.25m for the inlet velocities and subsequently maintain a uniform velocity up to the pulsating part of the tube where the velocity suddenly drops and retain the uniform velocity after the pulsating part till the end of the tube.

Fig. 6 shows a steady drop in pressure from inlet to the exit of the tube along axial position. At the pulsating part of the tube, the pressure remains constant throughout the part as a result of sudden expansion of the tube diameter. Fig. 7 shows that the change in pressure remain uniform until it approach the pulsating part of the tube where it drops to zero and then rise again after the pulsating parts. The higher the inlet velocity the higher the change in pressure and the more rapid the fluid flow is.

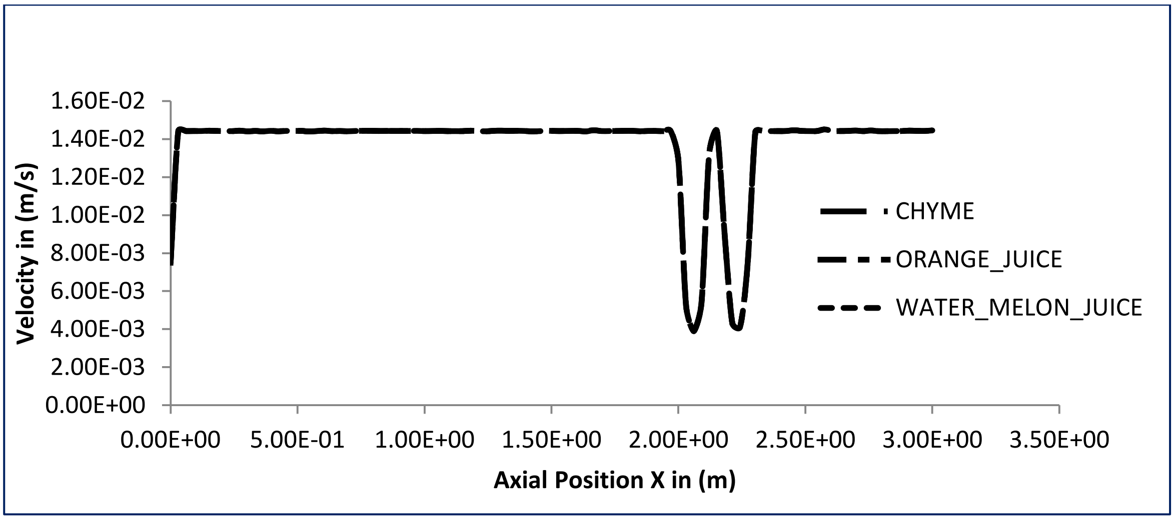

Fig. 4. Variation of Flow Velocity with Axial position along the centreline of the domain for Inlet Velocity of 0.0075 m/s.

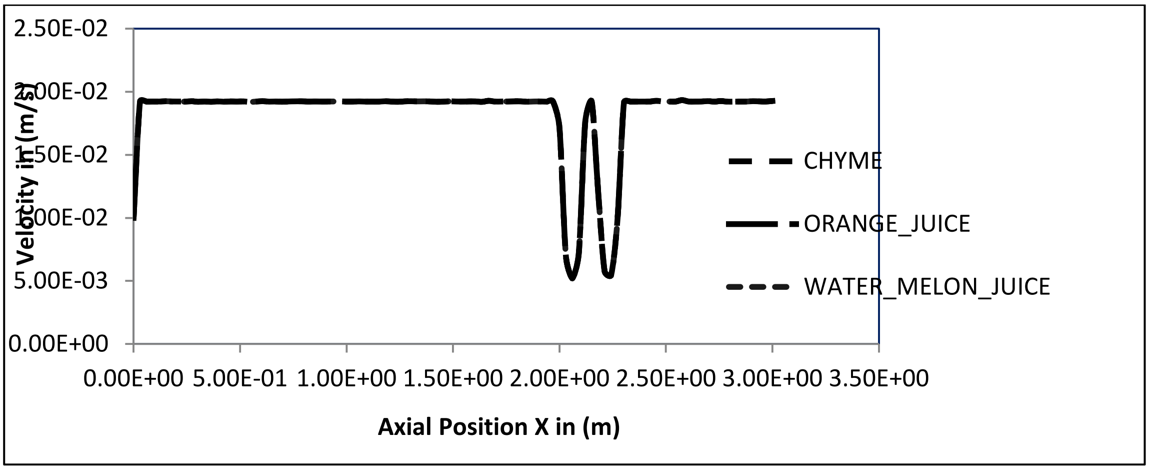

Fig. 5. Variation of Flow Velocity with Axial position along the centreline of the domain for Inlet Velocity of 0.01 m/s.

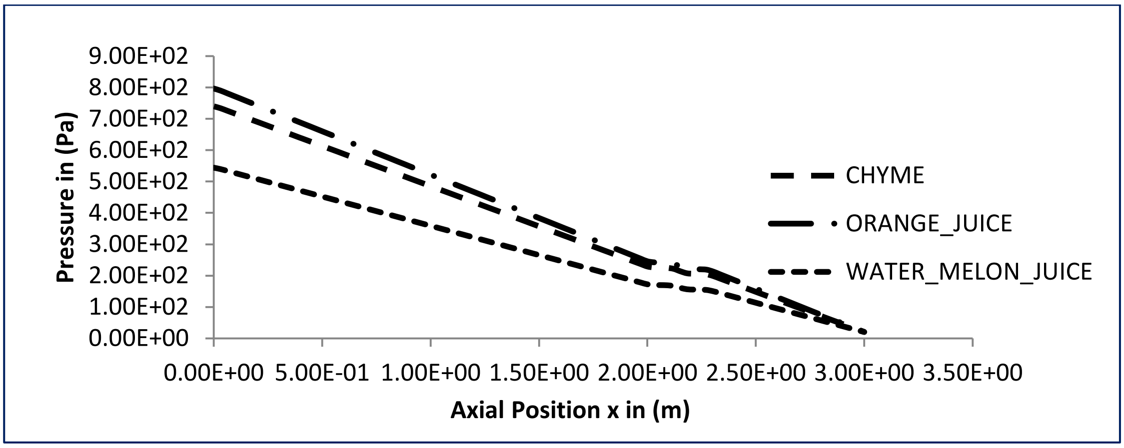

Fig. 6. Variation of Flow Pressure with Axial position along the centreline of the domain for Inlet Velocity of 0.0075 m/s.

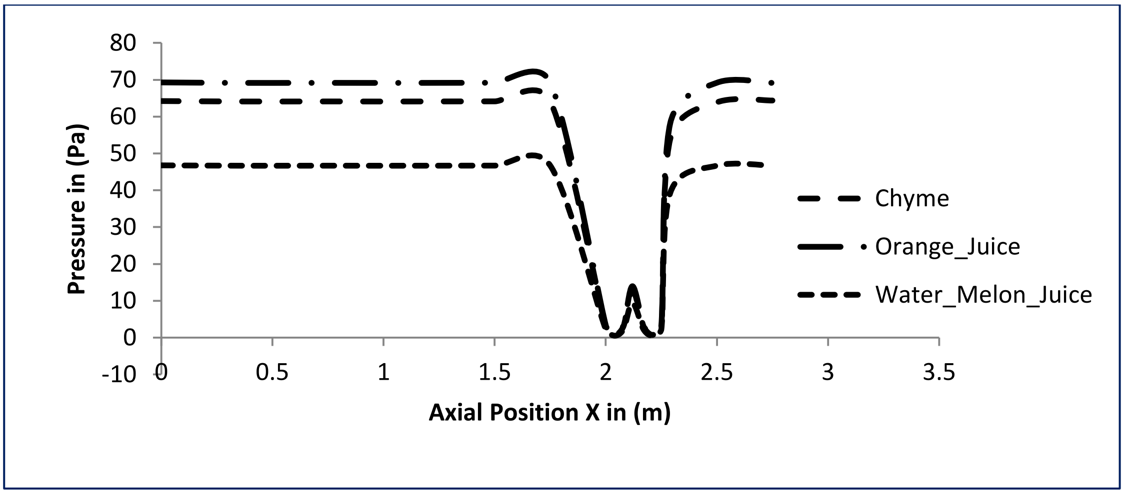

Fig. 7. Change in Pressure against Axial position for different Inlet Velocities.

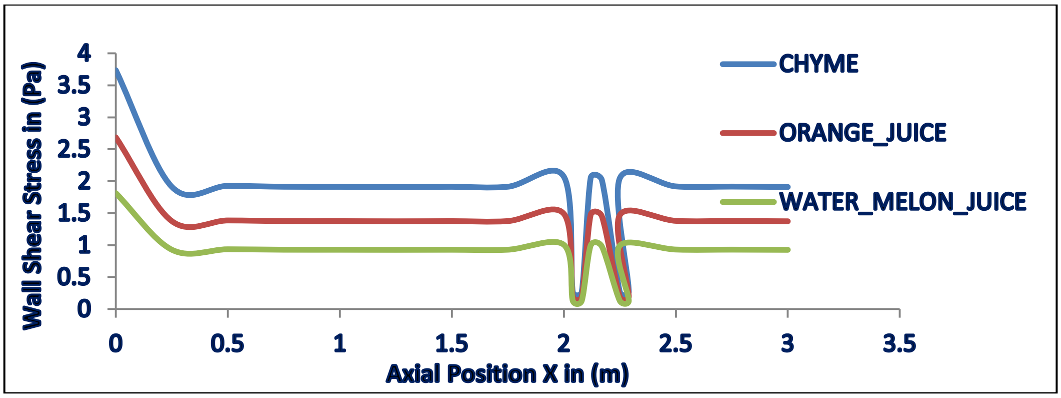

Fig. 8. Average Wall shear stress against Axial Position.

As evident in Fig. 8, the wall shear stress drops to the tune length of 0.25 m before it remain constant and also drops at the pulsating parts of the tube and chyme has the highest wall shear along the length of the tube.

It can be observed in Fig. 9 that the shear stress and shear strain relationship does not pass through the origin indicating that the fluid is non-Newtonian as pointed out by Quoc-Hung and Ngoc-Diep, www.intechopen.com respectively, and Water Melon juice has the lowest wall shear stress in both cases as observed from Figs. 8 and 9.

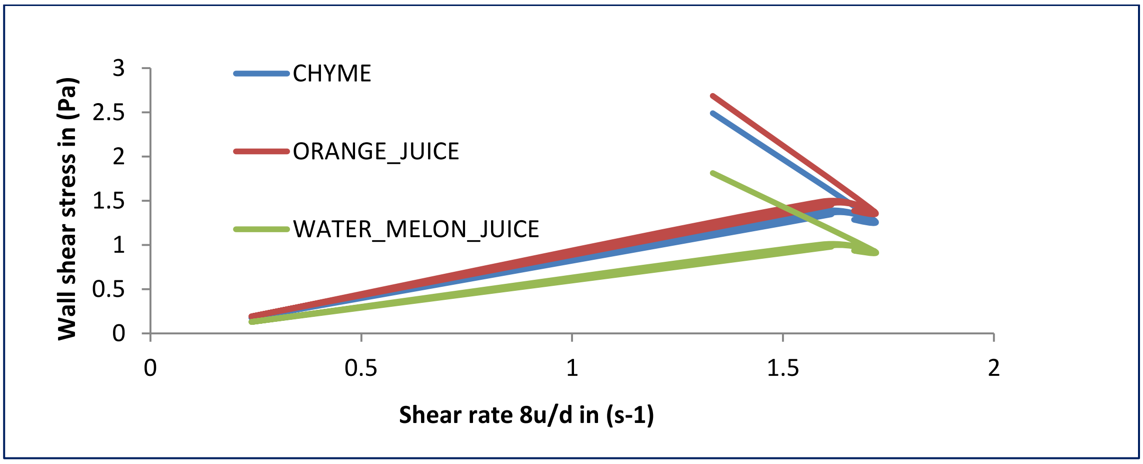

Fig. 9. Average Wall shear stress against Shear rate.

Fig. 10 shows the temperature contours of fluid flow within the tube and it can be observed that temperature increases from the inlet to the exit of the tube. Among the three fluids, Water Melon juice has the highest temperature at any inlet velocities.

Fig. 11 presents the plot of temperature against axial position. From the plot, it can be noticed that temperature increases from the inlet of the tube to the exit and notably the temperature increases and drops sharply at the pulsating part of the tube.

From Fig. 12, Water melon juice has the highest convective heat capacity. Though, the recommended value of Nusselt number for Newtonian fluids is 4.36 for constant wall heat flux, however, for non-Newtonian fluids, the Nusselt number behaves abruptly.

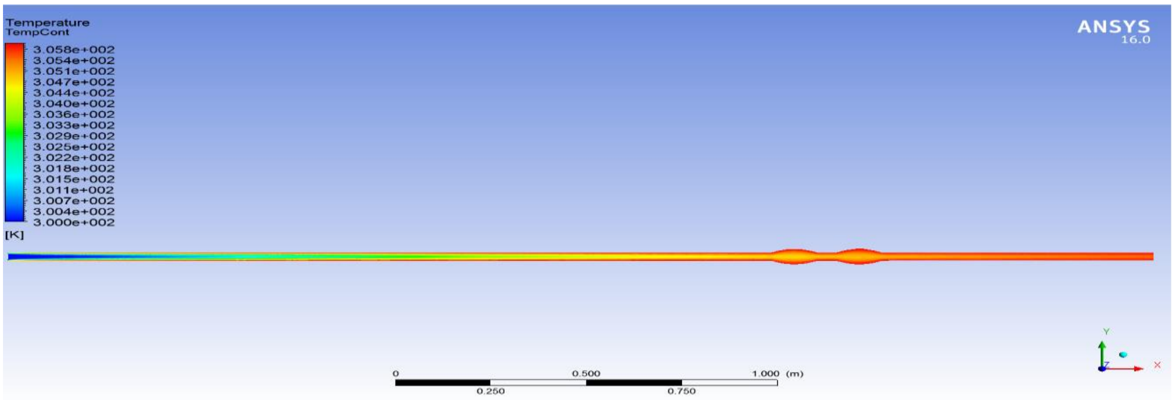

Fig. 10. Temperature flow profile across the length of the tube.

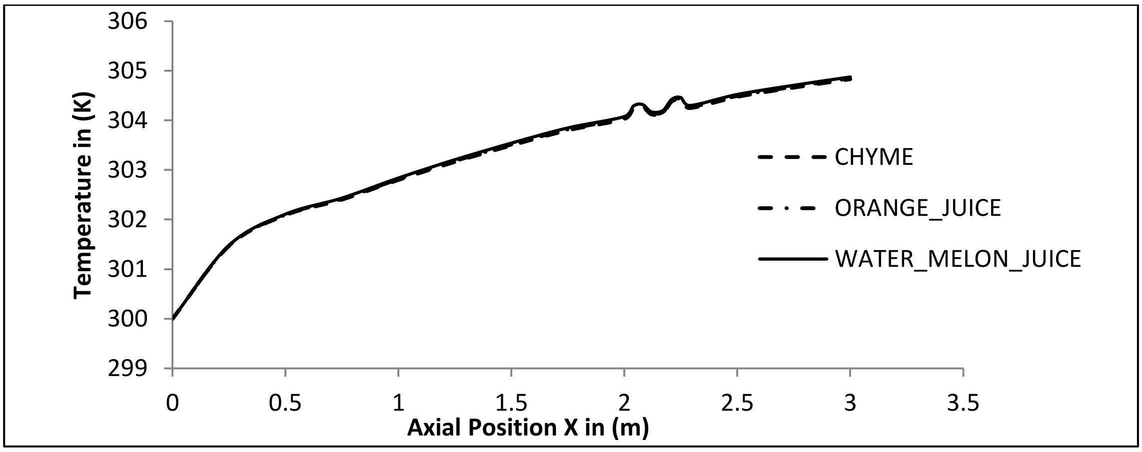

Fig. 11. Variation of Average Temperature with axial position for different fluids at 0.005m/s.

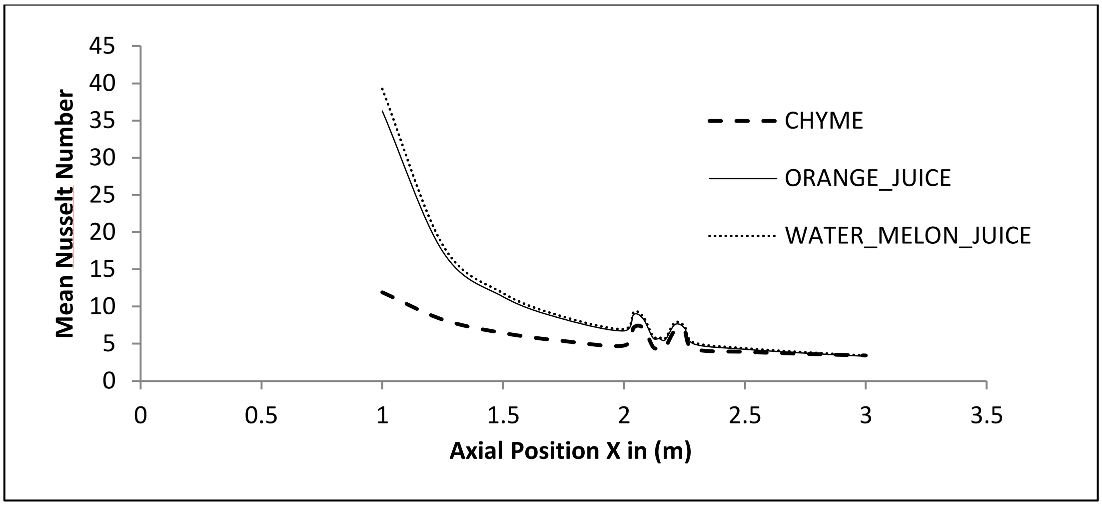

Fig. 12. Variation of Mean Nusselt Number along axial position of the tube for different fluids at Inlet Velocity of 0.005m/s.

4. VALIDATION OF RESULTS

The current results were validated using the work of Arrieta *et al*., (2015) as shown in Fig. 13. It could be observed from the figure that for Chyme, the heat transfer pattern is similar to that of Arrieta *et al.;* but for X> 2 m, the Nusselt number are in agreement.

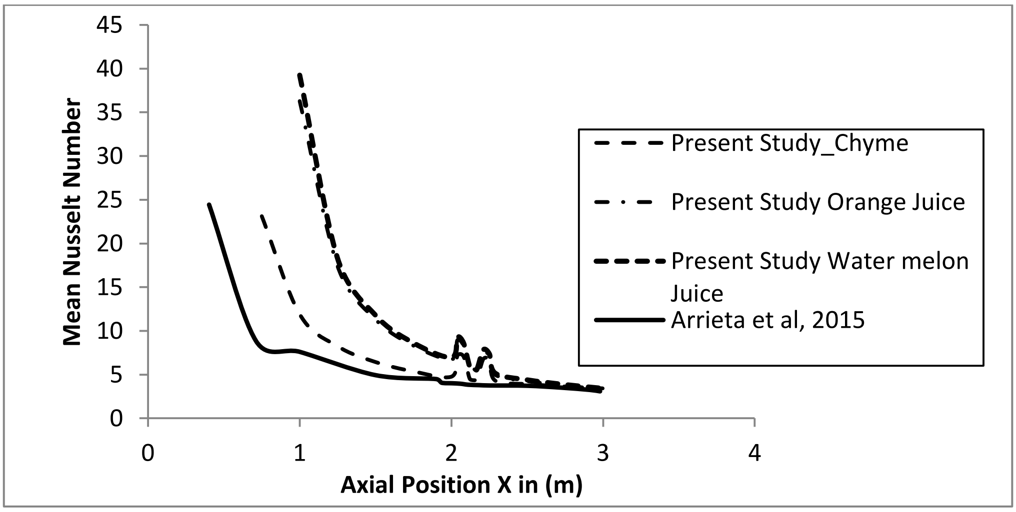

Fig. 13. Comparison of Results.

5. CONCLUSION

The following conclusions were arrived at:

- From the study conducted, For steadiness of the food supplements, feeding tube length should not be less than 0.25 m (250mm)

- The velocity of the flow should be within the range of 0.0025-0.01 m/s for effective feeding of patients.
- Out of the food supplements considered, orange juice is the best fluid when considering flow of fluids in the oesophagus while water melon juice is the best for thermal behaviour.
- Water melon juice could serve as an antioxidant because of its high pressure drop.

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