ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering
Tome XVII [2019] | Fascicule 1 [February]

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NUMERICAL SIMULATION OF LAMINAR FLOW OF NON-NEWTONIAN FLUIDS IN A RHYTHMICAL NON-PERMEABLE MEDIUM

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Abstract: This paper presents the flow of chyme, orange juice, and water melon juice through a modelled oesophagus. Computational Fluid Dynamics (CFD) technique was adopted for the study. ANSYS FLUENT commercial code was utilized in this investigation; a total of 4976 quadrilateral elements were generated with 11804 nodes. Solid Works 2014 was used for the drawing of the tube. The results indicated that a hydro-dynamically fully developed regime was achieved at a distance of 0.25m from the inlet. It was shown that orange juice recorded the highest pressure build up in the tube while water melon juice had the least, indicating it has a potential of high heat transfer rate. It was also discovered that the velocity of the flow is independent of the fluid used but significantly depends on the Reynolds number of the flow. The analysis predicted a flow velocity of 0.005 m/s for effective fluid flow and heat transfer in the tube. The research can be found useful in biomedical disciplines where investigation of gastrointestinal tract history can be understudied.

Keywords: Simulation, Non-Newtonian, Rhythmical

1. INTRODUCTION

Recently, understanding fluid flow and heat transfer components by utilizing the Computational Fluid Dynamics (CFD) has become a relatively cheap and accurate method that is becoming popular and reliable. Investigation has also shown a low predictive analysis of artificial feeding of patients. Low Reynolds number flow regime in a cylinder has been studied by many researchers over the decades. Scientists and researchers have keen interest in the investigation of fluid flow of steady-state, laminar, hydrodynamics, and viscous fluid in a non-permeable pulsating medium due to its extensive biomedical and engineering applications; as in the case of digestive systems of living organisms and chemical systems. Digestion is a complex process that involves the breakdown and conversion of food into substances that can be absorbed (Tharakan *et al.*, 2010). The process begins from the mouth down to the anus where waste is being discharged from the body. The small intestine is the lower part of the gastrointestinal tract and a vital part responsible for further digestion of food that passes through the stomach unbroken. Approximately 90% of digested food absorption occurs through the epithelial cells that line its surface. Its structure for the absorption of nutrients is as a result of many folds (*plicae circulares)* present on its inside surface from which tiny finger structure tissues (*villi*) are projected with their individual epithelial cells referred to as *microvilli.* The combination of *plicae circulares, villi,* and *microvilli* structures helps to increase the surface area available for absorption of nutrients. The small intestine is the longest thin tube of about 2.5cm to 5cm in diameter and about 2m to 6 m in length which connects the stomach and the anal passage in the digestion process (Guyton and Hall, 2006; Stoll *et al.*, 2000 and Widmaier *et al.*, 2006).

From a mechanical perspective, motility of food or chyme from the mouth down to the anal passage is central to proper nutrition (Horowitz *et al.*, 1994). This involves various forces and reactions that has led to the discovery of three vital motions in the digestive tract. They are peristalsis, segmentation, and pendular movements. In intestines, segmentation and peristalsis are two major movements in which the former does not propel the chyme along the intestinal tract but rather chops and mixes the contents so that it can be mechanically digested while the latter is a series of wave-like muscular contractions that propel chyme through the small intestine. In human anatomy, 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 its walls. 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).

The study of fluid dynamics involves the application of the fundamental principles of general mechanics to liquids and gases i.e. conservation of matter, energy and Newton's laws of motion. The stomach serves as a storage, for mixing, and an emptying tank in the digestive tract. It has a proximal part made of fundus and a body that acts as a reservoir (storage) for undigested material. The distal stomach (antrum) is the grinder, mixer, and sieve for solid food while pylorus acts as a pump for gastric emptying of solids by propelling actions (Arora *et al.*, 2005). Fluid motion within the small intestine is generated by three movement patterns: (i) peristalsis, (ii) segmentation and (iii) pendular movements (Macagno and Christensen, 1980). In peristalsis, the frequency and force of intestinal contractions is a function of slow waves and action potentials (Levy *et al.*, 2006). Peristalsis propels chyme through the small intestine in about 3 - 6 hours (Liu *et al.*, 2003) with an average velocity of 1.0 cm per minute (Guyton and Hall, 2006).

There are many health challenges associated with the digestive tract which includes: congenital disorder (*hirschsprung*), indigestion (*dyspepsia*), *diabetes melitus*, ulcers, etc. Most of these conditions are caused as a result of motility disorder of the stomach or small intestine (a condition of malfunctioning of the muscles of the stomach and/or small intestine). In some cases, it causes the obstruction of both the small and large intestines in which partial small bowels has been attributed to the mechanical impedance of chyme transported in the small intestine owing to detachments of cells from diseased walls, internal wall adhesions, partially treated food particles etc. (Kulaylat and Doerr, 2011).

The research and engineering application of pulsating fluid flows have been established as a major branch of fluid dynamics. The research in 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), the pulsating flow is a vast growing research in Biomedical Engineering. Berger and Jou (2000) also examined intra-cardiac flow and blood vessel stenosis flow. Brasseur *et al.*, (1993) considered the unsteady effects of peristaltic flow of hydrodynamics for a viscous fluid through a sinusoidal channel and focused their model on oesophageal swallowing. A comprehensive mathematical model was developed for the peristaltic transport of complex rheological visco-elastic fluids through a non-uniform porous medium channel, the simulation of chime, and the hydrodynamics of undigested chyme in the gastro-intestinal tract were studied by Tripathi and Anwar (2013). Akbar and Nadeem (2014) examined the simulation of peristaltic flow of chyme in the small intestine for a couple of stress fluids. Adegun and Oladosu (2009) studied the heat transfer and fluid flow in an elliptic duct using scale analysis. Bello-Ochende and Adegun (1993) also looked into fluid flow and heat transfer in tilted elliptic duct using the perturbation technique. Adegun, *et al.* (2013) also studied the flow of Non-Newtonian fluids in elliptic ducts. Dilatants, pseudoplastics, and Newtonian fluids were specifically looked into.

The present study aims at investigating the fluid flow and heat transfer in a modelled oesophagus which is basically the study of flow of heat and semi-solid fluids (chyme, orange juice, and water melon juice) in an artificial oesophagus 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 an 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. The artificial oesophagus leads to the stomach where digestion will first take place and further movement to the small intestines where nutrient absorption is found.

2. MATERIAL AND METHOD

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 an 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, and creamy-like substance formed as a result of mechanical mixing of the ingested food with gastric juices. Orange juice and water melon juice are both extracted from their parent fruits. The properties of the fluid are listed 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.

Figure 1: Artificial Food Passage Tube

A numerical model consists of three basic steps: data pre-processing phase, solving process phase, and data post-processing phase. 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 with the initial and boundary conditions fixed. A suitable numerical scheme was implemented to solve the governing equations of the model. Lastly in the post-processing phase, a correct analysis and visualization of the data was required to ensure a proper discussion of the results.

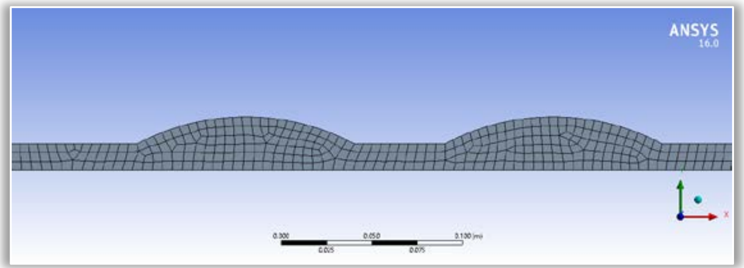

Figure 2: Mesh Generated Domain with 0.005m Element Size

3. PHYSICAL MODEL

The domain shown in Figure 1 is an artificial tube used to pass food to a patient with a weak or poor storage organ (stomach). For the purpose of this study, the geometry is assumed to be thinned wall. The wall property is culled from soft rubber (density = 1100 kg/m^3, specific heat capacity = 2010 J/kgK, and its thermal conductivity = 0.13 W/mK)

4. GOVERNING EQUATIONS

The model is governed by the continuity equation and Navier–Stokes equations.

- Continuity Equation:

$$\frac{\partial U_r}{\partial r} + \frac{1}{r}\frac{\partial U_\emptyset}{\partial \emptyset} + \frac{\partial U_x}{\partial x} = 0 \tag{3.1}$$

- Momentum Equations:
  - Radial direction

$$\rho\left(\frac{\partial U_r}{\partial t} + U_r\frac{\partial U_r}{\partial r} + \frac{U_\emptyset}{r}\frac{\partial U_r}{\partial \emptyset} + U_x\frac{\partial U_r}{\partial x} + \frac{{U_\emptyset}^2}{r}\right) = \rho g_r - \frac{\partial P}{\partial r} + \mu\left[\frac{\partial^2 U_r}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2 U_r}{\partial \emptyset^2} + \frac{\partial^2 U_r}{\partial x^2} + \frac{1}{r}\frac{\partial U_r}{\partial r} - \frac{2}{r^2}\frac{\partial U_\emptyset}{\partial \emptyset} - \frac{U_r}{r^2}\right] \tag{3.2}$$

  - Azimuthal direction

$$\rho\left(\frac{\partial U_\emptyset}{\partial t} + U_r\frac{\partial U_\emptyset}{\partial r} + \frac{U_\emptyset}{r}\frac{\partial U_\emptyset}{\partial \emptyset} + U_x\frac{\partial U_\emptyset}{\partial x} + \frac{{U_\emptyset}^2}{r}\right) = \rho g_\emptyset - \frac{\partial P}{\partial \emptyset} + \mu\left[\frac{\partial^2 U_\emptyset}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2 U_\emptyset}{\partial \emptyset^2} + \frac{\partial^2 U_\emptyset}{\partial x^2} + \frac{1}{r}\frac{\partial U_\emptyset}{\partial r} + \frac{2}{r^2}\frac{\partial U_r}{\partial \emptyset} - \frac{U_\emptyset}{r^2}\right] \tag{3.3}$$

  - Axial direction

$$\rho\left(\frac{\partial U_x}{\partial t} + U_r\frac{\partial U_x}{\partial r} + \frac{U_\emptyset}{r}\frac{\partial U_x}{\partial \emptyset} + U_x\frac{\partial U_x}{\partial x}\right) = \rho g_x - \frac{\partial P}{\partial x} + \mu\left[\frac{\partial^2 U_x}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2 U_x}{\partial \emptyset^2} + \frac{\partial^2 U_x}{\partial x^2} + \frac{1}{r}\frac{\partial U_x}{\partial r}\right] \tag{3.4}$$

- Energy Equation:

The energy transport equation for a steady for flow is;

$$k\frac{\partial^2 T}{\partial r^2} + \frac{k}{r^2}\frac{\partial^2 T}{\partial \emptyset^2} + \frac{\partial^2 T}{\partial x^2} + \frac{k}{r}\frac{\partial T}{\partial r} + \emptyset_{(i)} = \rho C_p\left[U_r\frac{\partial T}{\partial r} + U_\emptyset\frac{\partial T}{\partial \emptyset} + U_x\frac{\partial T}{\partial x}\right] \tag{3.5}$$

since U_x is the only non-zero velocity component, removing the viscous dissipation term $\emptyset_{(i)}$ from Equation (3.5) gives a new equation which is:

$$k\frac{\partial^2 T}{\partial r^2} + \frac{k}{r^2}\frac{\partial^2 T}{\partial \emptyset^2} + \frac{\partial^2 T}{\partial x^2} + \frac{k}{r}\frac{\partial T}{\partial r} = \rho C_p\left[U_r\frac{\partial T}{\partial r} + U_\emptyset\frac{\partial T}{\partial \emptyset} + U_x\frac{\partial T}{\partial x}\right] \tag{3.6}$$

5. COMPUTATIONAL PROCEDURE

Considering the symmetry of the flow, only half of the whole cross-section was used in the numerical computation. An element size of 0.0001m was selected for the mesh size which generated 11804 nodes and 4976 elements. To ensure accuracy of the numerical results, numerical tests were carried out with different grid sizes to determine the effect of grid size on 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.

- 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, L. A large value of Nusselt number implies an enhanced heat transfer by convection (Ozisik, 1985). The tendency of the tube and the pulsating part in providing heat transfer augmentation is critically examined. Ozisik, (1985) expressed heat transfer coefficient as:

$$h = \frac{q}{T_w - T_b} \tag{3.7}$$

where, T_w is wall temperature, T_b is the bulk fluid temperature

$$Nu = \frac{h * d_h}{k} \tag{3.8}$$

Equation (3.8) is the Nusselt number evaluated at the instance of wall temperature and bulk fluid temperature.

where, d_h is the hydraulic diameter of the Tube.

$$d_h = \frac{4A}{P} \tag{3.9}$$

6. RESULTS AND DISCUSSION

Figure 3 shows that the velocity profile has its 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. Figures 4 and 5 shows a typical flow characteristic along the tube for different inlet velocities. It could be observed from the figures that the streamlines settled into strata which implies that the flow is laminar. For the pulsating part, the velocity of flow reduced and it is an indication that the fluid flow obeyed continuity equation.

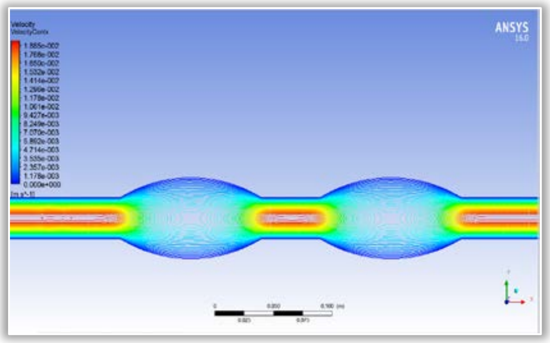

Figure 3: Velocity Profile across the Length of the Tube

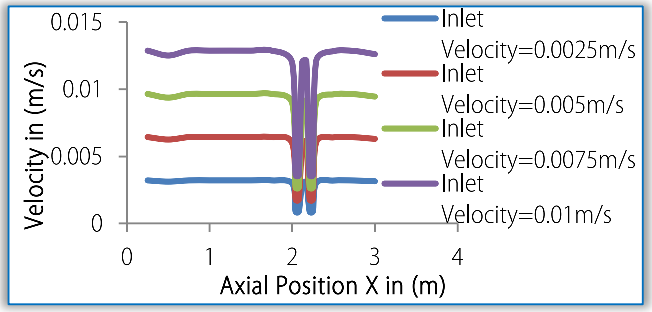

Figure 4: Average Velocity against Axial Position for Different Inlet Velocities

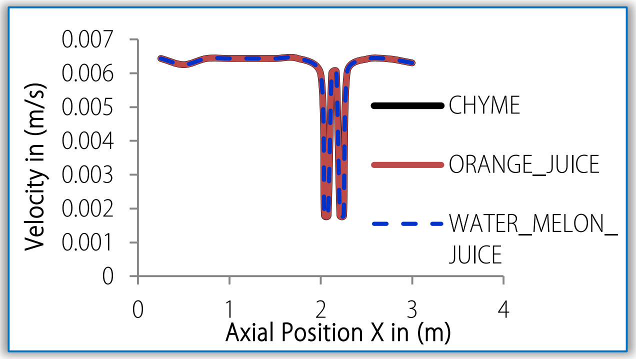

Figure 5: Average Velocity against Axial Position for Different Fluids

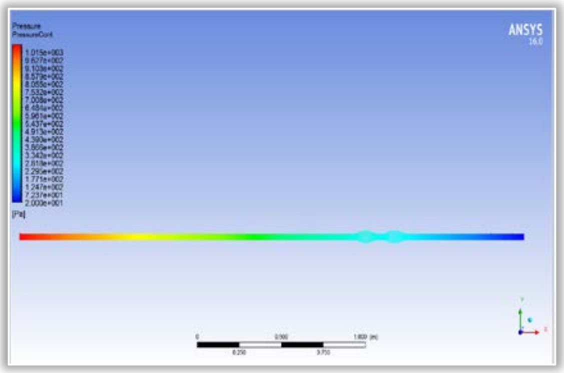

Figure 6: Pressure Profile along the Length of the Tube

Figure 6 shows the pressure contour of flow in the modelled tube with the pressure decreasing from the inlet of the flow to the outlet and this indicated that the flow is a fully developed laminar flow.

Figure 7 shows that the change in pressure remains uniform until it approached the pulsating part of the tube where it drops to zero and then rises again after the pulsating parts. The higher the inlet velocity, the higher the change in pressure and the more rapid the fluid flow is.

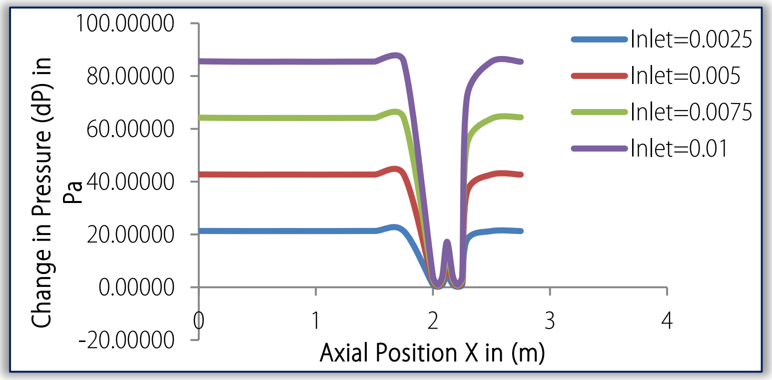

Figure 7: Change in Pressure against Axial Position for Different Inlet Velocities

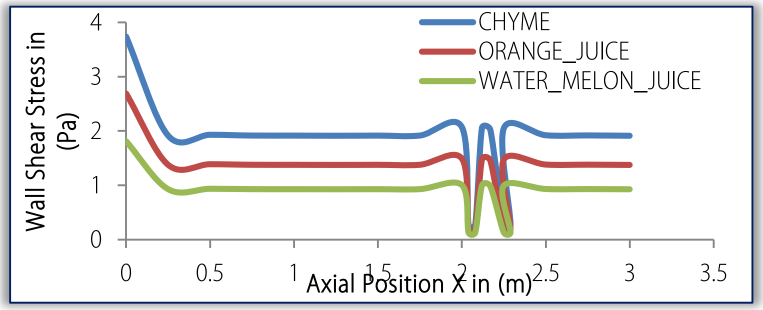

Figure 8: Average Wall Shear Stress against Axial Position

The simplest possible deviation from the Newtonian fluid behaviour occurs when the simple shear data does not pass through the origin and/or does not result into a linear relationship between shear stress and shear strain as obtained from Chhabra and Richardson, (2008). From Figure 8, the wall shear stress dropped to the tune length of 0.25 m before it remained constant and also dropped at the pulsating parts of the tube and chyme had the highest wall shear along the length of the tube. While the shear stress and shear strain relationship does not pass through the origin indicating that the fluid is Non-Newtonian as observed and obtained in Figure 9 and Quoc-Hung and Ngoc-Diep (www.intechopen.com) respectively, water melon juice had the lowest wall shear stress in both cases as observed from Figures 8 and 9. The three fluids are in low Reynolds number flow regime.

Figure 10 shows the temperature contours of fluid flow within the tube and it can be observed that the 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.

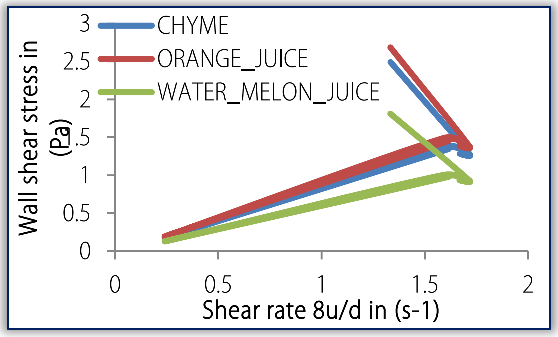

Figure 9: Average Wall Shear Stress against Shear Rate

It can be observed from Figure 11 that the 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.

Nusselt number is the ratio of heat convection to heat conduction of the fluid. Since the same geometry was used, the fluid convective capacity is the prime area of interest. Water melon juice had the highest convective heat capacity as observed from Figure 12. Though the recommended value of Nusselt number for Newtonian fluids is 4.36 for a constant wall heat flux, however, the Nusselt number for non-Newtonian fluids behaves abruptly.

7. VALIDATION OF RESULTS

The numerical code used for the present study is ANSYS FLUENT 16.0. The current results were validated using the work of Arrieta *et al.,* (2015) as shown in Figure 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.

8. CONCLUSIONS

The following conclusions were arrived at:

- For steadiness of the fluid flow, the feeding tube 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 the effective feeding of patients.
- Out the three fluids, 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.

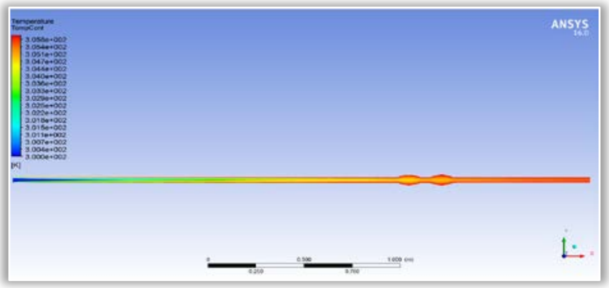

Figure 10: Temperature Flow Profile across the Length of the Tube

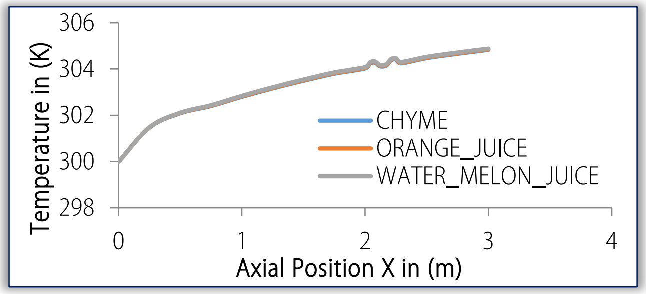

Figure 11: Variation of Average Temperature with Axial Position for Different Fluids at 0.005m/s

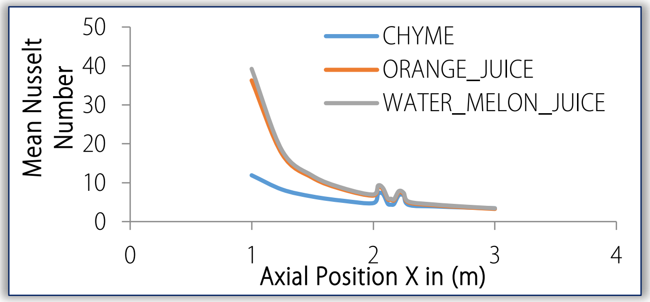

Figure 12: Variation of Mean Nusselt Number along Axial Position of the Tube for Different Fluids at Inlet Velocity of 0.005m/s

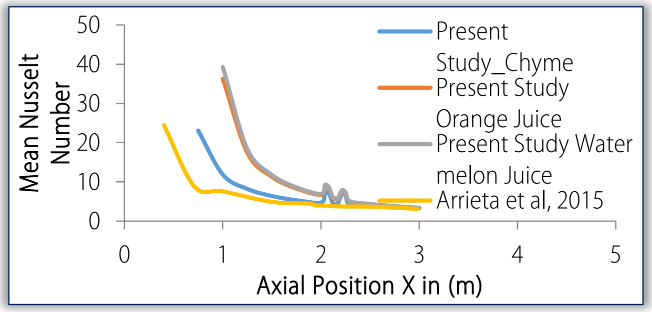

Figure 13: Comparison of Results

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