Chapter 2

A Brief Review of Literature and Objective of the Research

2.1 Literature review

Study of the mechanism of peristalsis in mechanical and physiological situations has been the objective of scientific research for long. Investigations on peristaltic flows with various considerations such as classes of fluids, types of waves and geometries of vessels have been extensively carried out for physiological and industrial applications.

Since the first attempt made by Latham (1966), numerous research papers published on theoretical and experimental investigations have enriched the literature on peristaltic transport. This large number of scientific contributions has consequently revolutionised this area of research. A few of them are focused on the physical and medical problems the mankind is facing; but many challenges are yet unsolved. Hence it is required to throw light on them. The relevant research and the milestones left behind during the long journey of investigation are presented here.

2.1.1 Early investigations with Newtonian fluids

Several investigations on the peristaltic transport of Newtonian fluid through channels or circular cylindrical tubes have been carried out by various researchers. In the early studies of peristalsis, most of the theoretical investigations were carried out by considering Newtonian fluid in tubes or channels of uniform cross sectional areas (Burns and Parkes, 1967; Fung and Yih, 1968; Barton and Raynor, 1968).

Investigations in the perspective of clinical observations took time to gain momentum. The study of Shapiro et al. (1969) may be considered as a pioneering work on peristaltic transport for two-dimensional and axisymmetric cases under the assumptions of low Reynolds number and long wavelength. They discovered the notions of reflux, trapping and mechanical efficiency. Chow (1970) presented a model that dealt with peristaltic transport through an axisymmetric tube by using perturbation technique. Some important contributions in the literature on peristaltic pumping of Newtonian fluids were made by Lykoudis and Roos (1970), Yin & Fung (1971), Jaffrin and Shapiro (1971) and Jaffrin (1973). Lykoudis and Roos (1970) observed that the shape of ureter during peristalsis is not sinusoidal and it may be best described by a polynomial expression corresponding to an arbitrary wall shape. Yin & Fung (1971) studied experimental peristaltic transport in a two-dimensional channel and compared experimental and theoretical results. Takabatake and Ayukawa (1982) and Takabatake et al. (1987) employed finite difference techniques to study creeping flows and discussed reflux, trapping and mechanical efficiency in detail. They (1987) also corrected pumping efficiency for the axisymmetric case given by Shapiro et al. (1969).

2.1.2 Non-Newtonian flows

With the development of medical and physical sciences, it has been recognized that the bio-fluids do not behave like Newtonian fluids and fail short to give a precise understanding when peristaltic mechanism is involved in small blood vessels, intestine, transport of spermatozoa in the cervical canal etc. It has now been accepted that most of the physiological fluids behave like non-Newtonian fluids. These considerations of non-Newtonian nature of fluids enriched the literature on peristalsis. Raju and Devanathan (1972) presented a theoretical investigation for blood flow by considering blood as a non-Newtonian power-law fluid and it was further extended for viscoelastic fluid by the same authors (1974) and observation were that the rate of discharge does not depend on the elasticity of the fluid. Bohme and Friedrich (1983) studied peristaltic flow of viscoelastic fluids and reported that the pumping efficiency decreases for fixed pressure with the memory parameter that represents viscoelastic characteristic. Srivastava and Srivastava (1984) modelled peristaltic flows of Casson fluids (blood) flowing inside small capillaries and blood vessels. Srivastava and Srivastava (1985) examined peristaltic flows of power law fluids in the vas deference by considering it a non-uniform diverging tube. Many more research papers taking non-Newtonian fluid are detailed in subsequent paragraphs.

A mathematical model for the flow of couple stress fluids was introduced by Stokes (1966). Srivastava (1986) studied the problem of peristaltic transport of couple stress fluids under the long wavelength and low Reynolds number approximations. Some mathematical and computational methods for couple stress fluid was carried out by Elshehawey and Mekheimer (1994), Elshehawey and Sebaei (2001) and Mekheimer (2004). Pandey and Tripathi (2011d) published a paper for swallowing of couple-stress fluids in oesophagus. Pandey and Chaube (2011a) investigated wall properties on peristaltic transport of couple stress fluids.

Peristaltic transport of different types of fluid models such as magneto-fluid was studied by Elshehawey and Husseny (2002). The moving boundary with a non-Newtonian fluid was discussed by Siddiqui et al. (2002). Propagation of peristaltic waves in a magnetic field was discussed by Katiyar and Basavarajappa (2002) which can be applied to studies pertaining to flow of physiological fluids. Sinha et al. (2015) presented a mathematical model for peristaltic flow of a MHD fluid and revealed that the velocity at the central region diminishes with increasing values of the velocity-slip parameter. Peristaltic transport of a MHD dusty Casson fluid in a rectangular duct has been examined by Zeeshan et al. (2017). They revealed that the Casson fluid parameter increases the fluid velocity near the walls of the duct and decreases the flow in the middle of the duct.

Muthu et al. (2003) studied peristaltic transport of micro-polar fluids in a two-dimensional channel and reported the effects of viscoelastic wall properties and micro-polar fluid parameters on the flow. Srinivasacharya et al. (2003) also investigated some more aspects of peristaltic flow of micro-polar fluids. Micro-polar flows in oesophagus were studied by Pandey and Tripathi (2011b).

Vajravelu et al. (2005a, 2005b) studied peristaltic pumping of Herschel-Bulkley fluids in channels and inclined tubes respectively. The effects of wave amplitude and yield stress on the flow characteristics were obtained and discussed. The results obtained for the flow characteristics revealed many interesting behaviours. Sanyal and Biswas (2010) presented a mathematical analysis for peristaltic flow of blood.

There were reports (Dean, 1928; Zalosh and Nelson, 1973, etc.) on flows through curved tubes without peristaltic considerations. Sato et al. (2000) investigated two-dimensional peristaltic flow of a viscous fluid in a curved channel. They also discussed reflux and trapping. Peterson (2010) extended the work of Zalosh and Nelson (1973) for wavy walls. Hayat et al. (2010) discussed the peristaltic transport in a curved flow configuration. Tripathi et al. (2014) investigated peristaltic propulsion with exponential variable viscosity. The peristaltic phenomenon for third order and Carreau-Yasuda materials in curved geometry has also been investigated by Abbasi et al. (2015). They observed that the size of trapped bolus decreases and finally vanishes for large values of magnetic parameter. Hayat et al. (2017a) studied numerically MHD peristaltic transport of Siskonano-fliud in a curved channel.

2.1.3 Flows with particulate suspensions: application to diseased ureter

Study of the theory of particle-fluid mixture is immensely useful for understanding a number of physical phenomena including transportation of solid particles by liquids, mixing operations, particulate suspension theory of blood, flow of food suspension through oesophagus and intestines, urine flow through the ureters, transportation of liquid slurries in chemical and nuclear processing etc. Several industrial food processes involve flow of food suspension in which the knowledge of flow properties is essential for assessing pumping requirements.

Hung and Brown (1976) investigated various geometric and dynamic effects on peristaltic transport of suspended solid particles in a fluid in a two-dimensional channel. Drew (1979, 1983) presented a two-phase flow model that accounts for a mixture of dispersed small particles in a fluid. Srivastava and Srivastava (1989) applied Drew's model (1979) to a particle-fluid mixture flowing in a channel and obtained perturbation solution for small amplitude ratio. The flow of diseased urine modelled as particle-fluid suspension through the ureters was subsequently studied by Misra and Pandey (1994) who concluded that the mean flow induced by peristaltic motion is proportional to the square of the amplitude ratio and depends on the mean pressure gradient. Ureters are muscular ducts that propel urine from the kidneys to the bladder by peristalsis. Jimenez-Lozano et al. (2011) also presented a model for peristaltic flow in ureters due to a solitary wave with the objective of explaining the flow mechanics of a particle-fluid mixture. Mekheimer and Abdelmaboud (2008) theoretically analysed peristaltic flow through uniform and non-uniform annuli filled with particle-fluid suspension by long wavelength approximation. Popularity of the Drew's model is revealed through a series of recent publications in biomechanics involving peristalsis (Bhatti and Zeeshan, 2016; Zeeshan et al., 2017) and rheological flow of blood (Zeeshan et al., 2018). A model for heat transfer on solid particle motion of dusty Jeffrey fluid through a planar channel has been investigated by Bhatti and Zeeshan (2016). Pandey and Singh (2018a) investigated influence of suspended particles in oesophageal swallowing.

2.1.4 Multi-layered flows: application to intestinal flows

The analysis of Shapiro et al. (1969) was extended to include a Newtonian peripheral layer close to the wall to simulate the effect of a coating in physiological flows by Brasseur et al. (1987) who corrected a similar investigation for peripheral layer by Shukla et al. (1980). Similar corrections were then required in Shukla and Gupta (1982) and Srivastava and Srivastava (1984) whose models were meant for power-law and Casson fluids respectively. Rao and Usha (1995) presented a peripheral layer model for axisymmetric flows. Misra and Pandey (1999, 2001a) later reported corrected versions of power-law peripheral models for channel and tubular flows respectively. They further presented a peripheral Casson fluid model for blood flows. A three layered peripheral model was published by Elshehawey and Gharsseldien (2004) while porosity in the peripheral layer was introduced by Mishra and Rao (2005). Pandey et al. (2011) worked for intestinal flows and reported that an intermediate layer of viscosity lower than that of the mucus layer may overcome constipation. They (2015) further published similar reports for axisymmetric flows.

2.1.5 Flows in vessels of finite length: application to swallowing in oesophagus

Li and Brasseur (1993) theoretically developed a model for Newtonian fluids through oesophagus and focused the study on both the local and global dynamics. Unlike the consideration that the wall oscillates about the stationary boundary, they pointed out that the oesophageal wall undergoes contraction followed by relaxation. They also discussed the effect of integral and non-integral number of peristaltic waves. Nguyen et al. (1997) studied dynamics of oesophageal bolus transport in healthy subjects using multiple intraluminal impedancometry. Misra and Pandey (2001) modified the wall equation for oesophageal swallowing and considered the food bolus to follow the power law. Later on, several mathematical models (Pandey and Tripathi, 2010a, 2010b, 2010c, 2010d; 2011a, 2011b, 2011c, 2011d, 2012; Tripathi et al. 2011, 2013) were presented based on the modified model of oesophageal wall motion under the consideration of different fluids resembling the properties of different edible foods. Misra and Maiti (2012) developed a mathematical model with the specific aim of exploring some important information concerning the movement of food bolus through the oesophagus. The model was formulated and analysed for peristaltic transport of Ostwald-de Waele power law fluid for arbitrary wave shapes and tube lengths.

2.1.6 Flows with dilating wave amplitude: application to sliding hiatus hernia

Kahrilas et al. (1995) made an experimental investigation and found a high pressure zone in the distal part of the oesophagus. The findings contradicted uniform pressure distribution along the entire length of the oesophagus reported by several researches. In the meantime, Xia et al. (2009) published the measurement of oesophageal wall thickness in contracted and dilated states. This paved the way for modification in the popular models describing oesophageal flow. Pandey et al. (2017) modified the oesophageal wall equations accordingly by considering exponentially increasing wave amplitude. The main inference drawn were that the pressure along the length of the oesophagus rises as the wave amplitude increases slightly down the oesophagus during the swallowing process. The pressure is largest where the wave propagation culminates. The cause of this natural rising of pressure ensures natural surety of delivery of food bolus into the stomach through the cardiac sphincter. This discovered knowledge was implemented to investigate peristaltic transport of Casson fluid through oesophagus by Pandey and Tiwari (2017). Pandey and Singh (2018b) further used this to investigate oesophageal flow affected by sliding hiatus hernia.

2.1.7 Heat transfer in peristaltic transport: application to cryosurgery

Radhakrishnamacharya and Murty (1993) presented a model for heat transfer and obtained closed form solutions for temperature, coefficient of heat transfer and velocity up to the second order by perturbation techniques. Vajravelu et al. (2007) discussed the interaction of peristalsis with heat transfer in a vertical porous annular region and formulated heat transfer at the wall and the pressure–flow relationship. Observations were that the heat transfer at the wall was affected significantly by the amplitude of the peristaltic wave but effect of pressure drop on flux was almost negligible for peristaltic waves of large amplitude. Mekheimer and Abdelmaboud (2008b) investigated heat transfer and magnetic field on peristaltic transport of a Newtonian fluids in a vertical annulus with application to endoscope. Srinivas et al. (2009) studied the effects of wall slip conditions and heat transfer both on peristaltic flow of MHD Newtonian fluids in a porous channel with elastic wall properties under the assumptions of long wavelength and low-Reynolds number approximations. Makinde and Chinyoka (2010) presented a model for transient heat transfer in channel flow and solved the governing nonlinear equations of momentum and energy transport numerically by finite difference methods. Sreenadh et al. (2012) presented a model for the effect of heat transfer and wall properties of flexible walls in oesophageal swallowing. Tripathi (2012) and Tripathi et al. (2013) investigated mathematical model for swallowing of food bolus under the influence of heat transfer and derived the expressions for temperature field, axial velocity, volume flow rate, pressure gradient, local wall shear stress, stream function and reflux limit under the assumptions of long wavelength and low Reynolds number approximations. Hayat et al. (2014) presented a study in order to show the effects of convective boundary conditions on peristaltic transport of a micropolar fluid in an asymmetric channel with heat source/sink. A model for heat transfer on solid particle motion of dusty Jeffrey fluid through a planar channel was constructed by Bhatti and Zeeshan (2016). Prakash et al. (2018) discussed a numerical simulation to study the heat and flow characteristics of blood flow altered by electro-osmosis through the tapered micro-vessels assuming blood as non-Newtonian (micro-polar) nano-fluids. This study explored the nano-fluid dynamics in peristaltic transport as symbolized by heat transport in biological flows and also in gastro-intestinal motility enhancement. Misra et al. (2018) formulated a mathematical model to analyse the peristaltic transport of magneto hydrodynamic fluid associated with heat and mass transfer in an asymmetric channel. On the basis of this study, the authors reported that fluid velocity and the distributions of concentration and temperature are considerably influenced by Grashof number.

2.1.8 Flows in asymmetric channels

Mishra and Rao (2003) investigated steady peristaltic transport of a Newtonian fluid through an asymmetric channel. It was followed by investigations of peristaltic transport through an asymmetric channel of Casson fluid by Rani and Sarojmma (2004), of a couple stress fluids by Ali et al. (2007) and of a power-law fluid by Reddy et al. (2007). Hayat et al. (2008) investigated peristaltic mechanism of in an asymmetric channel using a perturbation method in terms of the wave number. They (2008) explored the effects of various parameters on pressure rise per wavelength and the axial pressure gradient through numerical integration. Mekheimer and Ablelmaboud (2008b) investigated the influence of heat transfer and magnetic field on peristaltic transport of a Newtonian fluid in a vertical annulus with application to endoscope. Peristaltic flow of Sisko fluid in a symmestric or asymmetric channel was studied by Wang et al. (2009). They studied the shear-thickening and shear-thinning effects of the non-Newtonian fluid. Akbar et al. (2014) presented a numerical simulation of peristaltic flow of a Carreau nano-fluid in an asymmetric channel. The study of heat and mass transfer of an MHD fluid having temperature dependent properties in an asymmetric channel was explored by Misra et al. (2018).

2.1.9 Flows in non-uniform vessels: application to vas deferens and uterine cavity

The mechanism of peristaltic transport in non-uniform tubes or channels that may exist in physiological conduits like uterus, vas deferens and blood vessels has been the objective of scientific research for long. Several researchers have made attempts to investigate peristaltic motion in non-uniform tubes or channels. Manton (1975) presented a model for peristaltic flow in an axisymmetric tube of varying radius whose wall was subjected to arbitrary wave propagation under Stokes approximation. Peristalsis in male reproductive system was observed experimentally and numerically by Batra (1974), Guha et al. (1975), Gupta and Seshadri (1976) and Srivastava and Srivastava (1985). Guha et al. (1975) studied the transport of the spermatic fluid in the vas deferens of monkey and reported that the transportation during ejaculation is mainly due to contraction of the ampulla and filling during the non-ejaculatory phase is due to peristalsis and epididymal pressure. Srivastava and Srivastava investigated peristaltic flows in the vas deferens by considering it a diverging tube and channel (1982) for Newtonian fluids and later (1985) for non-Newtonian fluids. The models were more realistic model investigating power-law fluid flow in a non-uniform tube and blood as a Casson fluid flowing inside small capillaries and blood vessels. Misra and Pandey (1995) modeled axisymmetric peristaltic motion of a Newtonian viscous incompressible fluid through a flexible tube of changing cross section, by retaining nonlinear convective acceleration terms. Their reports were more ascribable than the previous reports for spermatic flows reported by Guha et al. (1975) as their results were closer to experimental observations. Eytan and Elad (1999) and Eytan et al. (2001) investigated the effect of peristalsis in embryo transport within the uterine cavity. They discussed in detail the phenomenon of trapping and how the particle reflux impedes the embryo implantation at the fundus. Hariharan et al. (2008) studied peristaltic transport of non-Newtonian fluid in a diverging tube with different waveforms and concluded that square wave has the best pumping characteristics of all the wave forms and triangular wave has the worst characteristics. Pandey and Chaube (2010) modified the results of Misra and Pandey (1995) for Maxwell viscoelastic fluids. The same authors (2011b) investigated the peristaltic transport of Maxwell viscoelastic fluid in a channel of varying cross sections.

2.1.10 Flows of nano-fluids

Nowadays nano-science and nano-technology have emerged as a substantial development due to the vital role of non-Newtonian nano-fluids in bio rheology, medical nano-scale electro-osmotic devices and some other engineering applications. Nano fluids are produced by suspended nanoparticles which are generally 1–100 nm in dimension, in the base fluids. Kumar et al. (2010) analysed nano-fluid flow using a single phase thermal dispersion model and explained that the nano-fluid is a two-phase mixture in which the solid phase consists of nano-sized particles. Chakraborty and Roy (2008) developed electroosmotic transport of nano fluids in microchannels. Abbasi et al. (2014) simulated peristaltic transport of copper–water nano-fluid in an inclined channel. The presence of Grashoff number and inclination of the channel enhance the temperature of nano-fluid. Akbar et al. (2014) presented a numerical simulation of peristaltic flow of a Carreau nano fluid in an asymmetric channel. A theoretical analysis of the slip and joule heating effects in mixed convection peristaltic transport of nano-fluid was presented by Hayat et al. (2014a). Shehzad et al. (2015) incorporated an analytical model of peristaltic transport of water based nano-fluids in their comparative study. The influence of magnetic field on peristaltic transport of nano Eyring-Powell fluid in an asymmetric channel was investigated by Akbar (2015). Abbasi et al. (2016) analysed peristaltic transport of copper-water nano-fluid with temperature-dependent effective viscosity. Mathematical analyses for peristaltic flow of nano fluids were presented recently by several researchers (Kothandapani and Prakash, 2015; Reddy and Makinde, 2016; Hayat et al. 2016; Ding et al. 2017; Bhatti et al. 2017a). Tripathi et al. (2017) studied theoretically the electro kinetic pumping of nano fluids with heat and mass transfer in a micro-channel under peristaltic waves. They incorporated Soret and Dufour cross-diffusion effects and also thermal and species buoyancy effects. A numerical simulation was presented for heat and flow characteristics of micro polar nano fluids altered by electroosmosis through the tapered micro-vessels by Prakash et al. (2018). They examined thermal radiation effects on nano particle volume fraction and thermal characteristics. Prakash and Tripathi (2018) analysed the electroosmotic flow of non-Newtonian Williamson's fluid model for nano-liquids in presence of peristaltic propulsion through tapered channel. They employed perturbation method to find solutions for axial velocity, pressure rise, volumetric flow rate, temperature field and nano particle volume fraction.

2.1.11 Flows in elastic tubes

Study of viscous flow in elastic tubes is a requirement for learning the true mechanisms of various phenomena (e.g., atherosclerosis, artery replacement by a graft, bolus transport in oesophagus, etc.) in medicine, biology, biomedical technology and also in industry. The information on the mechanisms of oesophageal and intestinal transport of food and liquids is of immense importance for the treatment of patients suffering from transport disorders. Initial investigation on wall properties on peristaltic transport of Newtonian fluids in a channel with flexible (elastic or viscoelastic) walls was carried out by Mittra and Prasad (1973). Srivastava and Srivastava (1997) extended their work from single-phase Newtonian fluid analysis to a two-phase flow. Carew and Pedley (1997) studied pumping phenomenon of peristaltic flow in the ureter by using lubrication theory by taking into account wall deformation. Rubinow and Keller (1972) and Fung (1997) considered the Poiseuille's flow locally, and found that the radius of a tube can be determined by the balance between the transmural pressure (i.e. the difference between the inside and outside pressure) and the tension in the tube wall. Takagi and Balmforth (2011) modelled tube wall deformation using linear elasticity and the internal flow assuming the lubrication approximation.

Waters and Guiot (2001) investigated flow in an elastic tube subject to a prescribed force. They considered blood as homogeneous Newtonian fluid and the vein an isotropic thin walled elastic tube. Muthu et al. (2001, 2003) respectively developed mathematical models for peristaltic flow of Newtonian fluid through an axisymmetric tube and that of micro-polar fluid through a channel with flexible walls. They observed that the mean axial velocity decreases with micro-polar parameter and flow reversal takes place at the wall of the tube for non-zero viscous damping. Sreenadh et al. (2012)

presented a model to study the effect of heat transfer and wall properties of flexible walls in oesophageal swallowing. Sochi (2014) investigated the flow of Newtonian and power law fluids in elastic tubes considering the lubrication approximation theory. He demonstrated qualitative similarity in general and asymptotic reduction of the flow equations to limiting cases. Uddin et al. (2018) investigated peristaltic transport of a nano-fluid via elastic sheets. Selvi et al. (2018) analysed the flow of blood in elastic arteries by considering blood as a power-law fluid. Pulsatile flow of a conducting Jeffrey fluid through a porous elastic tube with variable cross section was investigated by Selvi and Srinivas (2018). An analysis was carried out to study magneto hydrodynamics peristaltic flow of Prandtl fluid in a channel with flexible walls by Hayat et al. (2018).

2.1.12 Flows in porous media

Peristaltic transport in a porous medium has attracted researchers due to its pathological applications. It plays a key role to explore the transport process in bio-fluid mechanics, industrial mechanics and engineering fields. Best biological examples of porous medium are the intestine and pathological situation of gallstones falling into the bile ducts and closing them completely or partially. Miyamoto et al. (1983) investigated the laminar flow in a porous tube and considered a small water absorption or secretion in the intestinal perfusion experiment. Elshehawey and Husseny (2002) developed a model for peristaltic transport of a magneto-fluid with porous boundaries. The flow fields generated by peristaltic reflex in isolated guinea pig ileum were discussed by Jeffrey et al. (2003). Mishra and Rao (2004) investigated peristaltic transport of power-law fluids in a porous tube. Elshehawey et al. (2006) presented a mathematical model for peristaltic transport through an asymmetric porous channel and focused the application to intra uterine fluid motion in uterus. Vajravelu et al. (2007) discussed the interaction of peristalsis with heat transfer in a vertical porous annular region and derived expressions for pressure–flow relationship and heat transfer at the wall. Observations were that the heat transfer at the wall was affected significantly by the amplitude of the peristaltic wave but effect of pressure drop on flux was almost negligible for peristaltic waves of large amplitude. Srinivas et al. (2009) studied the effects of both of wall slip conditions and heat transfer on peristaltic flow of MHD Newtonian fluid in a porous channel with elastic wall properties under the lubrication approximations. Maiti and Misra (2011) investigated peristaltic flow of a fluid in a porous channel for studying flow of bile within ducts in pathological state. They concluded that due to the presence of gallstones, the critical pressure for reflux decreases as porosity increases. Maiti and Misra (2012) also developed theoretically a model to study the peristaltic transport of couple stress fluids in a porous channel. This study was motivated towards investigating physiological flow of blood in the micro-circulatory system. Tripathi et al. (2015) investigated peristaltic viscoelastic bio-fluid flow in symmetric porous media. Magneto-hydrodynamic peristaltic transport of couple stress fluid through porous medium in an inclined asymmetric channel with heat transfer was studied by Ramesh and Devakar (2015). Sheikholeslami et al. (2017) simulated transport of magneto hydrodynamic nano-fluid in a porous media.

2.1.13 Electro-osmosis/electric double layer/ electro-kinetic flows

Siddiqui and Lakhtakia (2009) analysed the electro-osmotic flow of micro-polar fluids in micro channels and noted that the decay time of the fluid velocity is lesser for micro-polar fluid than that for Newtonian fluid under applied uniform electric fields. Tang et al. (2010) presented the Herschel-Bulkley model to analyse electro-osmotic flow in porous media. This model simulates actual biological fluids for which a critical value of yield stress must be achieved before flow is initiated. Casson model for electro-osmotic flow in a micro channel was discussed by Ng (2013). He noted that the yield surface describes the regime into sheared and unsheared zones and that the opposing effect of yield stress on time averaged-volume flow rate may be compensated via pressure gradient. Schit et al. (2016) presented the electro-osmotic flow of power-law bio-fluids in a micro-channel. They considered the scenario wherein the channel depth is substantially greater than the thickness of electrical double layer. Tripathi et al. (2017) studied theoretically the electro-kinetic pumping of nano fluids with heat and mass transfer in a micro-channel under peristaltic waves. They incorporated Soret and Dufour cross-diffusion effects and also thermal and species buoyancy effects. Chaube et al. (2018) carried out a theoretical model to analyse the effects of electric double layer and applied external electric field on peristaltic flow of non-Newtonian aqueous solution in a micro channel. Prakash et al. (2018) discussed a numerical simulation to study the heat and flow characteristics of blood flow altered by electro-osmosis through tapered micro-vessels assuming blood as a non-Newtonian (micro-polar) nano-fluid. This study explored the nano-fluid dynamics in peristaltic transport as symbolized by heat transport in biological flows and also in gastro-intestinal motility enhancement. Tripathi et al. (2018) presented a model to study the electro-kinetic flow in a finite length micro-channel. They observed that cooling occurs in the micro-channel electro-kinetic flow with positive joule heating effect and heating occurs with negative joule heating effect.

2.2 Objective of the thesis

Of concern in the present thesis is the flow dynamics of oesophageal swallowing. Oesophageal flow is governed by transverse and progressive peristaltic waves. Flow dynamics of oesophageal swallowing is affected by pathological states of oesophagus, different types of ingested food and various types of waves generated in the mussels of the oesophagus. Attempts are made to formulate some mathematical models of peristaltic transport in the oesophagus, which were not properly taken care of in previous investigations. The main objective is to examine the various factors affecting swallowing in the oesophagus. The reasons for various considerations are as follows:

- Unlike water most of the edible substances are of non-Newtonian nature. The Herschel-Bulkley model is very much versatile in nature. This can help us learn the properties of various fluids as special cases of this fluid. For this reason, Herschel-Bulkley fluid is being considered in the first two chapters.
- Fluids with particulate suspension is another practical type of food stuff but different from Herschel-Bulkley fluid.
- Dilation of wave amplitude for oesophageal swallowing is a natural phenomenon reported in the literature.
- Elastic properties of the vessels deserve due consideration but are often ignored.
- Study of heat propagation during swallowing in the oesophagus may be useful in cryosurgery.

This thesis deals with different classes of food stuffs transported peristaltically in normal or pathological states of oesophagus. A variety of theoretical approaches have been considered in various chapters of the thesis dealing with different oesophageal flow problems. The models presented in this thesis have potential applications to the physiology of oesophageal swallowing and biomedical engineering.