1.1 PERISTALTIC TRANSPORT

A branch of biology that deals physical and chemical phenomena along with the functions and activities of life or of living matter (as organs, tissues, or cells), defined as physiology. In physiology, peristalsis is one of the mechanisms which propel or mix the contents in a vessels as in ureter, gastro-intestinal tract, bile duct and other glandular ducts. Some worms use peristalsis as a means of Locomotion. Some investigators have studied peristalsis with reference to water transport in trees. Most of the recent inventions and ongoing researchs are inspired by the nature. The peristaltic transport has most convincing and feasible solution for some important engineering and biological problems.

Figure 1.1 Peristaltic transport in distensible channel (a) local fluid transport due to single peristaltic expansion wave with static fluid (b) Trapped volume in peristaltic expansion wave.

Generally, physiological fluids are being transported from one part to another part by self-generated pumping (distinctive pattern of smooth muscle contractions) which is known as peristaltic pumping and this process is known as peristalsis. It was first
described by Bayliss and Starling (1902) as a type of motility in which there is contraction above and relaxation below a segment being stimulated. Peristaltic transport of fluid inside pipe of diameter \( d \) under single wave moving with velocity \( c \) within time interval \( \Delta t \) explained in Figure 1.1(a) and further trapping in Figure 1.1(b). It could be understood by motion of food bolus. Food bolus is swallowed and moved through the esophagus. Smooth muscles contract behind the bolus to prevent it from being squeezed back into the mouth. Then rhythmic, unidirectional waves of contractions work rapidly to force the food into the stomach. This process works in one direction only and its sole esophageal function is to move food from the mouth to the stomach. There is a primary peristaltic wave, which occurs when the bolus enters the esophagus during swallowing. The peristaltic wave forces the bolus down the esophagus and into the stomach in a wave lasting about 8–9 seconds. The wave travels down to the stomach even if the bolus of food descends at a greater rate than the wave itself, and continues even if for some reason the bolus gets stuck further up the esophagus. In the event that the bolus gets stuck or moves slower than the primary peristaltic wave (as can happen when it is poorly lubricated), stretch receptors in the esophageal lining are stimulated and a local reflex response causes a secondary peristaltic wave around the bolus, forcing it further down the esophagus, and these secondary waves continue indefinitely until the bolus enters the stomach.

Figure 1.2 Working of kidney dialysis machine.
From mechanical point of view, the peristaltic pumping is a pumping in which the transported medium does not come in direct contact with any moving parts such as valves, plungers, and rotors. Nowadays, peristaltic pumps are very applicable, and popular in industries & laboratories. This could be of great benefit in cases where the medium is either highly abrasive or decomposable under stress. This has led to the development of fingers and roller pumps which work according to the principle of peristalsis. Applications include dialysis machines (Figure 1.2), open-heart bypass pump machines and infusion pumps.

1.2 ELECTROKINETIC TRANSPORT

An electrokinetic phenomenon refers to relative motion between an electrolyte liquid and a charged solid, under the action of an applied or induced electric field. Electrokinetic flows removed the necessity of having moving parts in a microfluidic system. Electrokinetic flows offer an advantage when dealing with the flows in interconnected or branched channels. Such flows can be easily controlled by switching voltages without the need of valves. When a charged solid surface and a polar medium are in contact, the surface charge influences the distribution of the ions within the liquid near the solid surface. The counterions in the liquid are attracted toward the surface and coions are repelled from the surface. The electric double layer (EDL) is the region formed by the excess counterions in the liquid. The EDL consists of two regions: the Stern layer and diffuse (or Gouy–Chapman) layer (Figure 1.3). The Stern layer is a thin region in which counterions are adsorbed onto the charged surface. Although ions in the Stern layer are fixed in place, ions in the diffuse layer are free to migrate. The plane between the Stern layer and diffuse layer is called the ‘shear plane.’ The potential at this plane is called the ‘zeta potential,’ denoted by ‘ζ’.

Under an applied electric field, the diffuse layer positive ions move in the direction of the field, causing the ion drag on the liquid. The liquid motion in the diffuse layer is translated to the rest of the channel via viscous forces.

The motion of electrically charged molecules and particles due to an applied electric field in moving substances such as water is studied in electrokinetics. Further electrokinetics includes the phenomenon of electroosmosis, electrophoresis, streaming potential and sedimentation potential.
Electrokinetic transport happens to provide one of the most popular non-mechanical techniques that utilize favorable interfacial phenomena over small scales for flow actuation and control. Fluidic devices with mechanical pumps or valves have moving components, hence they are complicated to design, costly to fabricate and maintenance is not too easy. On the other hand, in electroosmosis, a fluid can be pumped and controlled by an external electric field, using the surface and electrokinetic properties of the system. At the same time, the velocity profiles for pressure-driven flow are parabolic; whereas, in case of electroosmotic flows the velocity profiles are almost uniform with uniform surface properties, which have significant consequences in species transport and dispersion in microfluidic applications. However, electrokinetic flows also have some disadvantages such as the flow is limited to polar solvents and Joule heating effect.

Figure 1.3 Electrokinetic phenomenon (a) EDL formation at solid-liquid interface (b) potential distribution from solid surface.

Among various microfluidic techniques alternating current (AC) electrokinetics represents a promising approach towards the development of a fully integrated micro total analysis systems (μ-TAS). The advantages of AC electrokinetics include rigorous micro and nano manipulation methods, low power consumption, cost-effectiveness, simplicity in microelectrode fabrication and advancement in portable electronics. AC electrokinetic phenomena include dielectrophoresis (DEP), AC electroosmosis (ACEO), and AC electrothermal flow (ACEF). These techniques are capable of performing most fundamental microfluidic operations, such as sample
pumping, mixing, concentration, and separation, to develop automated biomedical analysis systems.

1.2.1 Electroosmosis
If a charged surface is in contact with a liquid and an electric field is applied parallel to the interface, movement of liquid adjacent to the wall occurs. If the surface is negatively charged, the net excess of positive ions in the EDL will draw the liquid along because of viscous interactions, which results in flow toward the cathode.

1.2.2 Electrophoresis
Electrophoresis is a common technique used to move ions and molecules in microfluidic and nanofluidic channels (Santiago et al. 2002). In simple way electrophoresis is defined as the converse of electro-osmosis; the liquid is regarded as fixed so that a molecule moves in the opposite direction relative to the solution.

One of the key applications of electrokinetics is in vitro diagnostics, the detection of biochemical species, such as proteins or nucleic acids that indicate a physiological condition or the presence of a disease. In many cases, the relevant analytes are present at such low concentrations that they cannot be detected using conventional methods. To overcome this, a specific electrokinetic separation and focusing technique called isotachophoresis (ITP) are used. ITP uses a discontinuous buffer system to separate and concentrate target analytes based on differences in their electrophoretic mobility. As illustrated (Figure 1.4) the discontinuous buffer system consists of a leading (LE) and a terminating (TE) electrolyte, which respectively have a higher and a lower electrophoretic mobility than the analyte(s) of interest. When an electric field is
applied, the analytes are focused at the continuously moving interface between the LE and TE. In this way, a “virtual vial” of several hundred picolitres is created, in which the concentration of analytes is enhanced by many orders of magnitude.

1.2.3 Streaming potential

When a liquid is forced to flow through a small channel under hydrostatic pressure, ions in the mobile part of the EDL are carried downstream. This creates an electric current, which is called the streaming current, flowing in the same direction as the liquid. The accumulation of ions downstream sets up an electric field, which causes a current to flow in the opposite direction through the liquid conduction current. When the conduction current is equal to the streaming current, steady state is achieved. The resultant electrostatic potential difference between the two ends of the channel is referred to as the streaming potential. One possible environmental and engineering application of self-potential method is to study subsurface water movement. Measurements of electro-filtration potentials or streaming potentials have been used in Russia to detect water leakage spots on the submerged slopes of earth dams. Method of self-potential (Figure 1.5) in addition to EC mapping and vertical electrical sounding or imaging (VES) can aid in archaeological and civil engineering projects (Pozdnyakova et al., 2001)

![Figure 1.5 Self potential map indicates places of water recharge (red) and discharge (blue)](image-url)
1.2.4 Sedimentation potential
Whenever an electrical double layer at an interface in an ionic liquid is sheared, a potential difference in the form of a streaming potential is established, which will tend to resist the flow of liquid Elton (1948). This potential will produce a backflow by electroosmosis, and the net effect is a diminished flow in the forward direction. The liquid appears to exhibit enhanced viscosity if its flow rate is compared to the flow without EDL effects. This phenomenon is electroviscous effect.

1.3 MAGNETOHYDRODYNAMICS (MHD)
Study of properties of electrically conducting fluids like plasma, liquid metal, salt water or other electrolytes includes the MHD flow. It was first observed by Faraday (1832) that due to motion of an electrically conducting fluid in the magnetic field the electric currents are induced in the fluid which produces their own magnetic field called induced magnetic field. This modifies the original magnetic field and original motion. The two basic effect of magnetohydrodynamics are (a) the motion of the fluid affects the magnetic field (b) the magnetic field affects the motion of the fluid. In MHD flow the fluid is taken as incompressible and the other fluid properties such as viscosity, thermal conductivity and electrical conductivity are regarded as constant. In general, the motion of the fluid slow down due to these electromagnetic forces, unless sufficiently large electrical field is applied, opposite to the induced electrical field to overcome its effect so that the net electromagnetic forces accelerate the fluid motion.

The motion of Newtonian and non-Newtonian fluids in the presence as well as in the absence of magnetic field have found several applications in different areas, including the flow of nuclear fuel slurries, liquid metals, alloys, plasma, mercury amalgams and blood etc. To study the MHD effect on peristaltic flow of biological fluids is very important in connection with certain problems of the movement of conductive physiological fluids, for example, the blood flow and the blood pump machines. Such analysis is of great value in medical research. Recently few investigations have been carried out to understand the interaction between heat transfer and peristaltic flow of non-Newtonian fluid under the influence of magnetic force. In fact, heat transfer analysis is also important in MHD fluid flow because of its industrial and biological applications like sanitary fluid transport, blood pump in heart lungs machine and transport of corrosive fluid with the machinery part. Magnetize drug targeting is one
of the emerging methods to transport medicines at affected organs of body. The effect of magnetic field on a Newtonian fluid has been reported for treatment of gastronomic pathologies, constipation, and hypertension.

![Figure 1.6 Direction of magnetic force between two parallel plate in uniform magnetic field.](image)

1.4 FLOW THROUGH POROUS MEDIA

In recent years, flow through porous media has found applications in RO systems for water purification, fuel cell membranes and nuclear waste disposal. Traditionally, the study of underground oil and water transport has been investigated under this head. A porous medium is a matrix that contains void space occupied by one or more fluid phase and solid matrix. The properties of solid matrix are represented by porosity or permeability explained in (Figure 1.7). where \( \nu_\beta \), \( \nu_s \) are empty and solid volume, and \( A_s, A_\beta \) is surface area for phase interaction. Flow through porous media is usually very slow assumed to be incompressible and Newtonian. Such type of flow patterns are generally independent of flow rate and type of fluid. Solving such flow with stokes equation called direct modelling approach because the physics is directly solved without any assumption. The only input is geometry of solid Skelton and fluid properties are required. This approach is limited to small objects only. In another method, the control volumes are defined all over the domain and quantities averaged over these volumes are considered called Representative Elementary Volume (REV). This average quantity is governed by Darcy’s law called macro scaling modeling. Physiological passages used for fluid transport such as net of blood veins, bone structure, and urine filter system can be modeled as porous media once their wall flexibility is ignored.
1.5 NANOFLOUIDS

The nanoparticle-fluid suspensions are termed nanofluids, obtained by dispersing nanometer sized particles in a conventional base fluid like water, oil, ethylene glycol etc. A possible combination of base fluid with nanoparticlæ is summerised in Figure 1.8. Nanoparticles of materials such as metallic oxides (Al₂O₃, CuO), nitride ceramics (AlN, SiN), carbide ceramics (SiC, TiC), metals (Cu, Ag, Au), semiconductors (TiO₂, SiC), single, double or multi walled carbon nanotubes (SWCNT, DWCNT, MWCNT), alloyed nanoparticles (Al₇₀Cu₃₀) etc. have been used for the preparation of nanofluids. These nanofluids have been found to possess an enhanced thermal conductivity (Choi & Eastman 1995; Lee et al. 1999; Eastman et al. 2001) as well as improved heat transfer performance (Xuan & Li 2000; Yu & Choi 2003; Heris et al. 2006; Trisaksri & Wongwises 2007) at low concentrations of nanoparticles. Compared to micrometer sized particles, nanoparticles possess high surface area to volume ratio due to the occupancy of large number of atoms on the boundaries, which make them highly stable in suspensions. Due to the lower dimensions, the dispersed nanoparticles can behave like a base fluid molecule in a suspension, which helps us to reduce problems like particle clogging, sedimentation etc. found with micro particle suspensions. The combination of these two features; extra high stability and high conductivity of the dispersed nanospecies make them highly preferable for designing heat transfer fluids. The stable suspensions of small quantities of nanoparticles help to design lighter, high performance thermal management systems. Nanofluid flow also play a very important role in medical science, biology, biomedical and processing system engineering such as biological organisms on their primary cellular level, snapping shrimps and super-hydrophobic beetle wings, drug delivery, photodynamic therapy, use of charged polymers for lubrication, the lotus effect for self-cleaning
surfaces, molecular motors, neuro electronic interfaces, membranes for filtering on size or charge (e.g., for desalination) and nanoporous materials for size exclusion chromatography, cancer diagnosis and therapy, surgery, in vivo therapy, passive selective transport in aquaporin and active transport in the ion channels, neuro electronic interfaces, cell repair machines, protein engineering, shedding new light on cells molecular motors like kinesis and charge-based filtration in the kidney basal membrane etc.

**Figure 1.8** Various Nano particle and base fluids (Rashmi et al. 2014).

### 1.6 REVIEW OF LITERATURE

#### 1.6.1 Peristaltic transport with electroosmosis

Electroosmosis is a natural phenomenon in numerous medical and biological processes. It arises in botanical processes (Ginsburg 1972), canalicular fluid flow in bone functioning (Sansalone et al. 2013) (interstitial fluid rich in ions), porous membranes (Marshall 1977), transport in the human skin (Grimnes 1983), dialysis mechanisms (Eykamp 1990). This phenomenon has been exploited in industrial separation techniques in biotechnology (Orsat et al. 1996) and in particular in medical micropumps (Manz et al. 1994). Micropumps have become popular in microfluidics and electroosmotic designs which can generate significant pressures and flux without moving mechanical parts. In capillary electrophoresis devices, electroosmotic pumping can achieve high efficiencies in capillaries lower than 100 micrometeres and
this is beneficial to deployment in miniaturized chemical analysis systems. Electroosmotic pumps offer similar advantages to electrohydrodynamic (EHD) pumps and travelling wave pumps since the imposed electrical force generates the pumping effect without any mechanical parts and thereby maintenance and other part-replacement issues can be mitigated. The on-going refinement in electroosmotic pump design has stimulated great interest in both experimental prototype testing and also computational and mathematical modelling. These two approaches have proved to be extremely complimentary in accelerating the arrival of next-generation electroosmotic micropumps. Ngoma and Erchiqui (2005) studied the dynamics of two immiscible fluids in a microchannel incorporating interfacial viscous shear stress, pressure gradient and electroosmosis effects. They solved the Poisson–Boltzmann equation and modified Navier–Stokes equations for a steady fully-developed laminar flow and computed the electric potential, pressure difference, wall and interfacial zeta potentials. Zhao and Liao (2002) considered non-isothermal electroosmotic and pressure-driven flow behavior in a straight microchannel, evaluating via a numerical finite difference method, the charge distribution density based on the nonlinear two-dimensional Poisson–Boltzmann equation, and full Navier–Stokes equations with applied electrical potential field. They observed that maximum hydraulic head generated by the electroosmotic force corresponds to an optimal dimensionless parameter which is the product of the inverse Debye length and the channel size. Henry and chu (2012) studied analytically on electrohydrodynamic flows through a circular tube with longitudinal or transverse slip-stick stripes walls. Bhattacharyya and Bera (2013) simulated numerically the electrokinetics and mixing driven by an imposed pressure gradient and electric field in a charged modulated microchannel. Cho and Chen (2013) investigated numerically the flow characteristics of the electroosmotic flow induced within a microchannel with a complex-wavy surface by a time-varying periodic electric field. Sadeghi et al. (2016) analyzed the fully developed electroosmotic flow in hydrophobic microducts of general cross section under the Debye–Hückel approximation.

The above studies were generally confined to steady flows with rigid boundaries. However, most transport processes in physiology are transient e.g. pulsatile effects due to the beating of the heart. An important unsteady propagation mechanisms for transport is peristalsis which is a radially symmetrical contraction and relaxation of
muscles that propagates materials in a wave-like motion along a conduit utilizing deformable walls. The peristalsis is considered as an important type of fluid flow has gained the interest of researchers in recent year (Figure 1.9). Although documented for over a century in medical sciences, fundamental studies of peristaltic hydrodynamics only materialized in the 1960s. The premier researcher in biomechanics, Y.C. Fung with co-workers presented a seminal investigation on the subject (Fung & Yih 1969). This study considered peristaltic pumping generated via the imposition of an axisymmetric traveling sinusoidal wave of moderate amplitude on the wall of a flexible conduit. Further studies of Newtonian peristaltic propulsion considering different aspects including inertial, elastic wall and activation waves were communicated by Weinberg et al. (1971), Tang and Rankin (1993), Pedley (1997) and Tang and Shen (1989). This mechanism arises in an astonishing range of biological systems including pharyngeal physiology (De Loubens et al. 2010), vasomotion (periodic oscillations of blood vessels walls) in bat wing venules (Farina et al. 2016), pulmonary and perivascular space (PVS) dynamics (Bokka et al. 2015), bile migration in the gastric tract (Maiti & Misra 2011). Peristalsis has also been implemented in several bio-inspired medical devices including nano-scale pharmacological delivery systems (Costa & Furness 1976; Tripathi & Bég 2014a), fish locomotion for underwater robots (Rønnestad et al. 2000) and biomimetic worm soft peristaltic land crawling robots (Daltorio et al. 2013; Lock et al. 2013). The nonlinear convective acceleration terms in the Navier-Stokes equation were retained and perturbation solutions developed.

Figure 1.9 Number of research papers published on peristaltic transport in recent years.
LITREATURE TREE

Soundalgekar et al. (1977) MHD convection flow of polar fluids past a vertical moving porous plate

Srivastava et al. (1984) The problem of peristaltic transport of blood in a uniform and non-uniform tube

Rao et al. (1995) The formation and growth of the trapping zone in the core and the peripheral layer are explained

Soundalgekar et al. (1977) Two dimensional MHD flow past a semi-infinite plate taking into account viscous dissipative effect

El Shehawey et al. (2000) A sinusoidal traveling wave in the porous walls of a two dimensional channel

Crewe et al. (1997) An active membrane model for peristaltic pumping

Misra et al. (1999) Peristaltic flow of power law fluids with a peripheral layer through channel and cylindrical tube

Krzeminski et al. (2000) A generalised mathematical model describing the dynamics of magnetic field influence on a peristaltic flow

Affi et al. (2001) Incompressible fluid under the effect of a transverse magnetic field through a porous medium

Mekheimer et al. (2003) Electrically insulated walls

Mishra et al. (2003) The effects of phase difference, varying channel width and wave amplitudes on the pumping characteristics


Vajravelu et al. (2007) The interaction of peristalsis with heat transfer for the flow of a viscous fluid in a vertical porous annular region

Reddy et al. (2005) Influence of Lateral Walls on Peristaltic Flow in a Rectangular Duct

Vajravelu et al. (2005) Herschel-Bulkley fluid in an inclined tube is analyzed

T Hayat et al. (2006) (MHD) third grade fluid confined in a circular tube

Vajravelu et al. (2009) Peristaltic transport in a porous space with compliant walls

Hayat et al. (2007) The flow in the porous space, Hall effect

Tasawar Hayat et al. (2006) Peristaltic flow of a Jeffrey fluid through the gap between concentric uniform tubes

Muthu et al. (2008) Perturbation technique for small values of amplitude ratio

El-Shehawey et al. (2006) Viscosity as well as the compressibility of the liquid is taken into account

Srinivas et al. (2009) Peristaltic transport in a porous space with compliant walls

Jiménez-Lozano et al. (2009) Motion for a small rigid sphere in nonuniform flow taking Stokes drag

Nadeem et al. (2010b) Williamson model in an asymmetric channel

Reddy et al. (2010) The effects of phase shift and Hartmann number

Nadeem et al. (2010a) Effects of radially varying MHD

Vajravelu et al. (2011) A Jeffrey fluid in a vertical porous stratum with heat transfer

Akbar et al. (2012) First article on the peristaltic flow in nanofluids

Bég et al. (2012) The peristaltic pumping with double-diffusive (thermal and concentration diffusive)

Tripathi et al. (2012) Transient magneto-fluid flow

Kothandapani et al. (2015a) Combine effect of thermal radiation and MHD flow

Kothandapani et al. (2015b) Combining effect of thermal radiation and MHD flow

Rathod et al. (2014) Peristaltic magneto-hydrodynamic (MHD) flow of a Bingham fluid through a porous medium

Tripathi (2013) Transient peristaltic heat flow through a finite length porous channel

Akbar (2014) Peristaltic flow of a Jeffrey nanofluid in a two-dimensional porous asymmetric channel

Tripathi et al. (2013b) A mathematical study on peristaltic flow of viscoelastic fluids (with the robust Jeffrey model)

Ellahi et al. (2014) Model of bioheat transfer in tissues

Akbar (2014) The first paper on the peristaltic flow with Maxwell carbon nanotubes (CNTs)

Abbas et al. (2015) Transport of copper-water nanofluid through an asymmetric channel

Kothandapani et al. (2015a) Combined effect of thermal radiation and MHD flow

Tripathi et al. (2013a) the movement of food bolus in the digestive system

Hina (2016) Combined influence of slip and magneto-hydrodynamics on the peristaltic motion of Eyring–Powell fluid

Tripathi et al. (2013b) A mathematical study on peristaltic flow of viscoelastic fluids (with the robust Jeffrey model)

Ellahi et al. (2014) Model of bioheat transfer in tissues

Akbar (2014) The first paper on the peristaltic flow with Maxwell carbon nanotubes (CNTs)

Abbas et al. (2015) Transport of copper-water nanofluid through an asymmetric channel

Kothandapani et al. (2015a) Combined effect of thermal radiation and MHD flow

Tripathi et al. (2013a) the movement of food bolus in the digestive system

Hina (2016) Combined influence of slip and magneto-hydrodynamics on the peristaltic motion of Eyring–Powell fluid

Figure 1.10 Tree of literature.
Biological mechanism, peristalsis, has also been exploited in the development of high-efficiency and low-maintenance pumps in medical engineering. Peristalsis arises in swallowing, digestive propulsion and phloem trans-location in plants, comprises an automatic periodic series of muscle contractions and relaxation which can efficiently pump fluids, generally, at low velocities (creeping flows). The literature on viscous peristaltic flows is extensive. Apparently, the first such investigation was communicated by Chakraborty (2006) who developed analytical solutions to demonstrate that axial electric field can significantly elevate microfluidic transport rates in peristaltic flows in microtubes. He further elaborated on the modes of interaction between the electroosmotic and peristaltic wave mechanisms, determining the pressure rise as a function of occlusion number, characteristic electroosmotic velocity and the peristaltic wave speed. Further Goswami et al. (2016a) extended this work for electrokinetically modulated peristaltic transport of power law fluids through a narrow deformable tube, observing that electroosmosis has a more dramatic effect on pressure rise at lower occlusion values and furthermore that trapping is efficiently controlled via electric field.

1.6.2 Peristaltic transport with magnetohydrodynamics

Magnetohydrodynamic effects provide an important control mechanism in fluid flow, for example biomagnetic micro-pumps and magnetic peristaltic pumps etc. It requires low maintenance and minimal damage. Kim et al. (2006) developed a peristaltic MF (magnetic fluid) medical micropump in which magnetic fluids are propelled via magnetic force via a concentric channel (silicone rubber diaphragm) with significantly better reliability and durability than other micro-pumps. The added advantage of reflux control was also highlighted in this study. Other examples of magnetohydrodynamic peristaltic pumps include the bi-directional linear peristaltic MHD pump developed by Neto et al. (2011). An interesting design has also been proposed by Al-Halhouli et al. (2010) which utilizes electromagnetic pumping magnets placed in an annular channel in opposing polarity through simultaneous energization of a set of solenoids. This design has been tested for Newtonian fluid (water) and partly has motivated the present investigation which considers non-Newtonian flow in a coaxial magnetic peristaltic flow.

In biomechanical and industrial fluid dynamics, the flow regime and boundary conditions play an important role. Endoscopy is a minimally invasive diagnostic
medical procedure. It is used to examine the interior surfaces of an organ or tissue. In view of wide application of this geometry, some researchers (El Naby & El Misiery 2002; El Naby et al. 2004; Hayat et al. 2006; Afsar & Ali 2008; Mekheimer 2008a; Tripathi 2011a; Tripathi 2011e; Tripathi 2011b; Tripathi 2011d; Tripathi & Bég 2012b) have studied the peristaltic flow of Newtonian and non-Newtonian fluids through the gap between two concentric tubes (inner tube is rigid and outer tube is flexible). Magnetic endoscopy is also a rapidly growing area of clinical biomechanics. This technology involves the interaction of coaxial non-Newtonian flows with static transverse magnetic fields.

In recent years, many researchers have examined peristaltic magnetohydrodynamic flows from a theoretical standpoint where magnetic body force is present and the pumping fluid is electrically-conducting. Representative works in this regard are Tripathi and Bég (2013), who also considered couple stress non-Newtonian effects. Kothandapani and Prakash (2015) studied magnetized nanofluid peristalsis with radiative heat transfer. Akbar et al. (2015) who considered magnetic induction and heat transfer effects in peristaltic pumping of carbon nanotube suspensions. Tripathi (2011c) numerically discussed the peristaltic flow of viscoelastic fluids through circular tube with fractional Burgers’ model. Other works have rigorously explored magnetohydrodynamic peristaltic pumping and identified certain advantages and disadvantages of this mechanism. These include the studies of Kumari and Radhakrishnamacharya (2012) and Ramesh and Devakar (2015) which have also incorporated slip effects and couple stress rheological effects. Other researchers have explored magnetohydrodynamic transport with a range of different formulations including Lorentz body forces (Ellahi et al. 2015b), streamwise magnetic field (Rashidi et al. 2015), ferrohydrodynamics (Kandelousi & Ellahi 2015), magnetic nanofluids (Ellahi et al. 2015a), magnetic induction and mesoscopic hydromagnetic heat transfer (Sheikholeslami & Ellahi 2015). Furthermore, magnetohydrodynamic micropumps (which propel conductive liquids which are subjected to perpendicular applied electric and magnetic fields across a microchannel via the Lorentz force) suffer from bubble formation problems associated with electrolysis which can seriously inhibit flow and reduce efficiency and the range of applications, especially in medicine.
1.6.3 Electroosmotic flow through Porous media

Electroosmotic flows in porous media are also of significance and arise in both biological systems and industrial systems and have been shown to markedly influence transport rates (Pengra et al. 1994). Brož and Epstein (1976) examined experimentally the electrokinetic flow through fine cylindrical capillaries with electrolyte comprising a dilute solution of potassium iodide in purified water. They considered non-Darcy porous media effects and quantified the electroviscous retardation effect for high electrokinetic radius (low double layer thickness). She and Liu (2003) used a computational finite volume method to simulate the electroosmotic flow in porous media with the solid phase approximated by cylinders of equal diameters arranged in a regular pattern in response to a given porosity. Al Quddus et al. (2005) investigated the influence of surface waviness of walls on electrokinetic flows in a cylindrical microchannel of finite length, with two reservoirs at the ends, noting that waviness i.e. irregularity in channel wall generates higher concentration and potential gradients across the channel. Gupta et al. (2007) analysed the electrokinetic flow in porous media micro-channels with Stern layer effects, computing expressions for surface charge density, electrical conductivity, and electroosmotic coupling coefficient for various porous structures and physico-chemical boundary conditions. Chai et al. (2007) have also investigated with a Darcy model, the electrokinetic dynamics in micro-channels containing variable porosity media. The classical approach to simulating transport in porous media is the Darcy model which is valid for viscous-dominated, low Reynolds number flows. It has been implemented extensively in electrokinetic modelling for porous media and such studies provide a very important complement to laboratory-based investigations (Maier et al. 2016). Gupta et al. (2008) derived approximate mathematical relations for electrokinetic flow in porous media, valid for general geometries, zeta potentials and electrolyte concentrations and also elongated pores, enabling a robust derivation of the electroosmotic coefficient. Tang et al. (2010) utilized the representative elementary volume scale porous media model and a lattice Boltzmann algorithm to simulate the combined pressure-driven and electroosmotic flow of Herschel–Bulkley rheological electrolytes in porous media. They evaluated the effects of porosity, solid particle diameter, power law exponent, yield stress and also electric parameters on flow characteristics. Wu and Keh (2012) mathematically studied the steady electrokinetic flow of electrolyte solutions in fibrous porous media, deriving explicit expressions for flow rate,
electroosmotic velocity, electric current, effective electric conductivity, and streaming potential as functions of the porosity of the fiber matrix and other electrokinetic characteristics. Li et al. (2013) studied both experimentally and computationally (with a Lattice Boltzmann method) the electroosmotic flow (EOF) in micro-porous media, showing that under constant external DC electric field, there is a reduction in flow resistance inside the pores decreases with influx of water into the electroosmosis pumping section. Obliger et al. (2014) used a Pore Network Model (PNM) to investigate numerically the influence of pressure, salt concentration, and electric potential gradients on steady-state response of complex charged porous media in a cylindrical channel. Yang et al. (2015) have reviewed many applications of electroosmotic pumping in porous media, considering dewatering of toxic sludges and extraction of poisonous heavy metal ions from contaminated soils. Fraia et al. (2016) used a finite element method with a characteristic-based split algorithm to investigate the electroosmotic flow (EOF) in microchannels containing porous media including the influence of electrical charge of solid particles. They solved the combined Laplace, Poisson-Boltzmann and Navier-Stokes equations and also considered heat transfer due to electroosmosis. The above studies have generally considered rigid boundaries for the conduit i.e. micro-channel. However recent progress has been made regarding wavy boundaries and also peristaltic propulsion mechanism in electroosmotic systems, which can enhance performance and may offer greater efficiencies (Piwowar 2012).

1.6.4 Peristaltic flow through Porous media

Peristalsis is an important biophysical mechanism arising in many natural systems including reptile locomotion, physiological transport, trans-location of phloem in plants etc. Peristaltic flows involve moving boundary fluid mechanics and are generally analysed with low wavelength and negligible inertial effects. Several mathematical studies of peristaltic hydrodynamics in porous media have been communicated, largely aimed at elucidating impeded flow in the digestive system. El Shehawey et al. (2000) used a Newtonian viscous flow model to compute perturbation solutions for stream function and pressure gradient in peristaltic propulsion in a tube containing a Darcian porous medium. Hayat et al. (2007) derived analytical solutions for small amplitude ratio in peristaltic hydromagnetic flow of viscoelastic fluids in porous medium with a modified Darcian model. Vajravelu et al.
(2007) computed perturbation solutions for peristalsis pumping and heat transfer in a vertical porous annular region between two concentric tubes. Vasudev et al. (2011) computed Darcy number effects in peristaltic flow and heat diffusion in a porous medium channel saturated with Jefferys viscoelastic fluid. Tripathi and Bég (2012a) who considered rheological peristaltic pumping in porous media conduits using Maxwell’s viscoelastic model and a generalized Darcy formulation. Bég et al. (2012) used a variational finite element method to investigate species diffusion in pulsating blood flow in non-Darcy porous media, considering different wave forms. Several researchers have also investigated electrokinetic peristaltic flows. Cho and Chen (2013) studied computationally the electroosmotic flow in a microchannel with a complex-wavy surface under the influence of a time-varying periodic electric field, observing that the phases of the electric field and electroosmotic velocity close to the channel wall are almost identical, whereas they differ in the central region of the channel and this difference is greater at higher Strouhal number.

1.6.5 Peristaltic transport of nanofluids

Nano-science and nano-technology have also stimulated great attention in recent years, largely propelled by the continuous miniaturization of existing technologies and improvement in performance of medical devices at smaller scales. A subsection of nanomechanics is nanofluid mechanics, pioneered by Choi (1995) which addresses the intelligent modification of macro-fluids using carefully designed nano-particles. This has had a diverse impact in medical engineering, to the extent that a Journal of Nanofluids has been launched in the USA (Prasad et al. 2015), and one of many with a large focus on nano-technological fluid mechanics including ASME Journal of Nanotechnology in Engineering Medicine (Lu et al. 2013). Important applications of these medical nanofluids which are revolutionizing clinical care include anti-bacterial wound treatment suspensions (Bég et al. 2013a), respiratory tracking mechanisms (Tombácz et al. 2008), magnetic biopolymers for drug coating to enable faster tracking to cancerous zones (Bég et al. 2014), pharmaco-dynamics (drug delivery) (De Jong & Borm 2008; Bég & Tripathi 2012; Tripathi & Bég 2014b) and protein identifications (Nam et al. 2003). Fluid dynamics models for nanofluid transport have been developed by a variety of groups worldwide, notably by Buongiorno (2006) at MIT. This model emphasizes the thermophoresis and Brownian motion mechanisms for nano-enhanced performance and is robust for adoption in peristaltic flows.
Progress has continued in nanofluid dynamic simulation. For example, mathematical models for thermal instability in a porous medium saturated by a nanofluid and convection of nanofluids with single and double diffusion have been reported by Nield and Kuznetsov (2009; 2010; 2011). In other developments, a predictor homotopy analysis for nanofluid flow through flexible permeable walls and unsteady MHD free convective flow from a permeable stretching vertical surface in a nanofluid have been considered by Freidoonimehr et al. (2015a; 2015b). An analytical approach for entropy generation for Casson rheological nanofluids induced by a stretching surface has been presented by Abolbashari et al. (2015).

Relatively sparse studies of peristaltic transport of nanofluids have been communicated. In the mathematical studies conducted so far, vast majority have addressed infinite straight or curved channels including Akbar and Nadeem (2012), Ebaid and Aly (2013) for slip flows, Mustafa et al. (2012), Akbar et al. (2012) Aly and Ebaid (2014). While mathematically rigorous, these studies have neglected a serious interpretation of the nanofluid characteristics on real performance in peristaltic systems.

1.6.6 Peristaltic transport of couple-stress fluids

The couple-stress fluid is a special type of a non-Newtonian fluid, for which particle sizes are taken into account. A micro-continuum theory was developed by Stokes (1966) to accurately simulate particle size effects. Srivastava (1986) studied the peristaltic transport of couple stress fluid and compared the results of couple stress fluids with those of the Newtonian fluids. Srivastava model was extended in subsequent investigations (El Shehawey & Mekheimer 1994; Mekheimer 2002; Pandey & Tripathi 2011; Tripathi 2012b). In certain modern applications of clinical biomagnetism, non-Newtonian fluid flows (blood flow) interact with magnetic fields to generate beneficial medical effects, in particular during extra-corporeal blood flow control during surgical procedures. This practical clinical application has stimulated with much interest in terms of developing more realistic mathematical models. Some of these models suggested by Bhargava et al. (2007), Bég et al. (2008), Bhargava et al. (2010) and Rashidi et al. (2011) include the coupled stress effect. Magnetohydrodynamic (MHD) couple-stress flows involve the interaction of electrically-conducting rheological couple-stress fluids with applied magnetic fields. As such magnetohydrodynamic effects provide an important control mechanism in
biomagnetic micro-pumps and magnetic peristaltic pumps etc, with minimal damage and maintenance.

1.6.7 Peristaltic transport of non-Newtonian fluids
For more biorheological applications, peristalsis is also studied for various type of non-Newtonian fluids. An incompressible non-Newtonian bio-fluid (Maxwell model) in the annular region between two coaxial tubes was considered by Husseny and Mekheimer (2014). Heat transfer characteristics of Burgers fluid (falls under the category of non-Newtonian fluids and is the subclass of rate type fluids which is used to describe the motion of the earth’s mantle) was studied by Javed et al. (2014). The effects of magnetohydrodynamics on the peristaltic flow of Jeffrey fluid in a rectangular duct was modeled by Ellahi et al. (2014). The model for peristaltic literature for Casson fluid is modelled first time by Akber (2015). A fractional second grade fluid confined in a cylindrical tube was considered by Hameed et al. (2015). The effects of magnetic field in the presence of heat transfer are taken into account and it was found that an increase in constant of fractional second grade fluid results in the decrease of velocity profile for the case of fractional second grade fluids. A power law fluid in asymmetric channel has been considered (Hayat et al. 2015), to examine heat transfer through convective conditions of channel walls. The effects of the Biot numbers and the power-law nature of the fluid on the longitudinal velocity, temperature and pumping characteristics are studied in detail. The pumping characteristics and the trapping of the fluid bolus fluids through a narrow confinement in the form of a deformable tube is investigated by considering the effect of fluid viscosities, power-law index and electroosmosis by Goswami et al. (2016a). The effects of Darcy number and yield stress on the pumping characteristics were obtained and discussed. Their results have shown that the presence of the endoscope (catheter) tube in the artery increases the pressure gradient and shear stress. It is observed that the net flow rate is positive for larger values of dimensionless relaxation time (Abbasi et al. 2016). Numerical integration was used to analyze the novel features of volumetric flow rate, average volume flow rate, instantaneous flux, and the pressure gradient for Williamson fluid in inclined channel by Hayat et al. (2016a). They observed temperature and concentration have similar effect qualitatively for the Schmidt, Soret and Dufour numbers. Bingham plastic fluid under the influence of magnetic force, space dependent viscosity is considered by Hayat et al. (2017a).
Novel Soret and Dufour effects were retained in the mathematical model. Special attention was given to role of embedded parameters on the axial velocity, temperature, concentration and pressure distributions. The review of literature revealed that the non-Newtonian nature of the fluids cannot be ignored while we model the biological flows.

1.7 AIM OF THE THESIS

Study of peristaltic transport has many applications in biomedical science and engineering to develop many biomedical devices like artificial esophagus, peristaltic pumps, finger pumps, heart-lung machine, blood pump machine, and dialysis machine. Study of electrokinetic transport has also wide range of applications in biomedical engineering and science to design microfluidics devices like lab on a chip (LOC) device which could provide rapid diagnosis. The combined studies will definitely increase the range of applications in biomedical engineering and science where biomedical engineers can develop the peristalsis-on-chip devices which control most of the physiological transport phenomena.

Owing to the very uneven structures of the organs and the complicated mechanism of physiology, still there is a strong need for in-depth study of various unknown aspects to a greater accuracy and develop new technology to use in biomedical science and engineering. It is, therefore, intended to develop some mathematical models on physiological fluids flow with various physiological conditions. The thesis presents six theoretical models to study the peristaltic transport and electrokinetic transport. The objectives of this thesis are:

- To develop the mathematical models to analyze the peristaltic transport under the influence of electrokinetics for following cases:
  - Channel flow,
  - Capillary flow,
  - MHD flow,
  - Channel flow in porous medium.
- To develop the mathematical model to examine the nanoparticle dispersion by peristaltic transport
- To develop the mathematical model to study the peristaltic transport of couple stress fluid in concentric channels
OUTLINE OF THE THESIS

- To provide a benchmark for combine study of electrokinetic transport and peristaltic transport which can explore biomicrofluidics applications.

1.8 OUTLINE OF THE THESIS

The remaining part of the thesis is organized as follows:

- Chapter 2 and Chapter 3 analytically investigate the unsteady viscous flow driven by the combined effects of peristalsis and electroosmosis through microchannel and cylindrical vessels respectively. An integral number of waves propagation and single wave propagation are considered to study the transportation of fluid bolus along the length of micro channel and capillary.

- In Chapter 4, the influence of transverse magnetic field on time-dependent peristaltic transport of electrically-conducting fluids through a microchannel under an applied external electric field is studied.

- Chapter 5, simulates the electrokinetic transport of aqueous solution through a micro-channel containing porous media. The micro-channel walls are considered as complex wavy surface and are modelled by superimposing the three wave functions of different amplitudes but the same wavelength. The micro-channel contains an isotropic, homogeneous porous medium, which is analysed with a generalized Darcy law.

- In Chapter 6, an investigation on time-dependent peristaltic flow of nanofluids with diffusive effects through a finite non-uniform channel has been done. The geometry is chosen due to its much closed similarity with real peristaltic-pumps.

- Chapter 7 deals the hydromagnetic wavy (sinusoidal) flow of a couple-stress fluid in the annular gap between flexible and rigid channels. Such systems can be used to control the flow effectively with applied magnetic fields which generate a Lorentzian drag force in the flow.

- Finally in Chapter 8, the concluding remarks of relevant findings of this thesis are given chapter wise. Thereafter future scope of this thesis work is also addressed.