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Review Article

A Review on Solution Techniques and Application of Peristaltic Transport in Generalized Newtonian Fluid

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ABSTRACT

In this review, a quantitative research survey has been carried out on the peristaltic motion of Carreau fluid (CF), one of the most important generalized Newtonian fluids. This work primarily focuses on the fluid's diverse behavior as a result of the application of various methods and the broad overview of peristaltic Carreau fluids in a range of impacts such as Heat and Mass Transfer, Magnetohydrodynamic (MHD), stagnation point, stretching and shrinking sheet, porous medium and boundary layer. The various approaches that have been explored to depict this exquisite physiological transport system, which is frequently seen in nature, are summarized in this paper. The extensive study of biofluid peristaltic pumping pertaining to its importance in various fields, perspectives, and mathematical models is also discussed in depth. This analysis compares the major components and research results over the last 50 years and offers recommendations for future advancement. Researchers can use this analysis as a platform for building peristaltic transport for various applications.

1. Introduction

Mathematical modeling serves as a valuable tool in biomechanics, allowing researchers to investigate medical problems. Within biomechanics, biofluid mechanics specifically focuses on studying the movement and forces of body fluids in humans, animals, and plants. It encompasses the analysis of fluid flow in various physiological systems, including blood vessels, the respiratory system, the lymphatic system, the gastrointestinal system, the urinary system, and more.

Researchers can measure and analyze the dynamics and kinematics of fluid flow in these systems by employing mathematical models. This provides valuable insights into the behavior of body fluids, which in turn have significant implications for medical science. The findings obtained from biofluid mechanics research contribute to developing clinical applications such as artificial organ design, vascular vessel

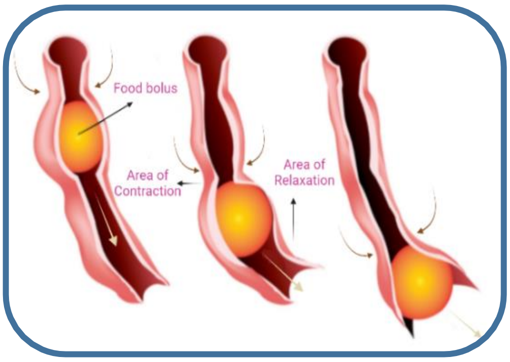

Fig 1. Peristaltic Motion

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development, medical tool design, fabrication of material membranes for orthopedics and numerous other areas.

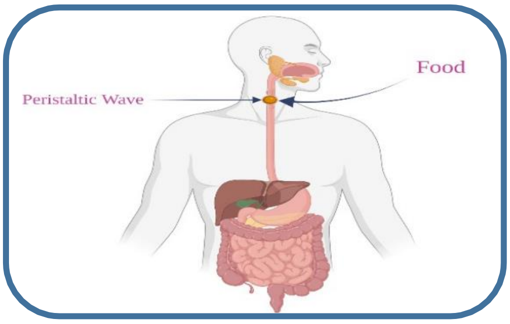

Fig 2. The food bolus through the digestive tract

Peristalsis is a remarkable mechanism of fluid transport that occurs in various parts of the human body and is characterized by the propagation of waves along the walls of tubular ducts. It is prominently observed in the digestive tract, where smooth muscle tissue contracts and relaxes sequentially, generating a peristaltic wave. This wave-like motion propels a ball of food, known as a 'bolus,' through the esophagus and upper gastrointestinal tract, facilitating its movement along the digestive system [Figs. 1-5].

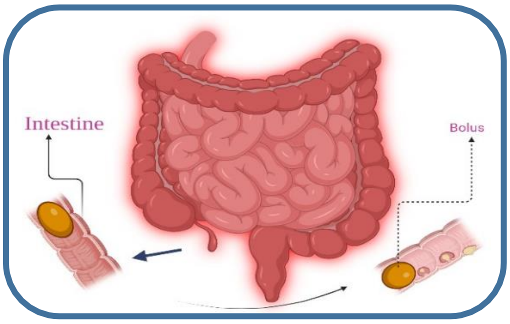

Fig. 3. Intestinal Peristalsis

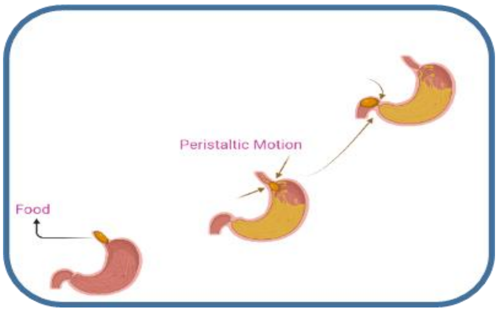

Fig. 4. Peristalsis in stomach

The coordinated contraction and relaxation of smooth muscles in peristalsis not only prevent the bolus from moving backward but also push it forward. This mechanism is not limited to humans; certain animals, like earthworms and insect larvae, employ peristaltic movements for locomotion. An intriguing feature of peristalsis is its ability to propel the bolus against gravity effectively, enabling the transport of food and other substances in an upward direction.

Inspired by this natural biomechanism, there are man-made devices and machines designed to mimic peristalsis to address specific everyday needs. Furthermore, peristalsis plays a crucial role in various physiological processes. Some notable applications of peristalsis include the movement of chyme (partially digested food) in the intestine, the transportation of eggs in the fallopian tube, the movement of spermatozoa through the cervical canal, the transport of bile in the bile duct, the circulation of blood in small blood vessels, and the transport of urine from the kidneys to the urinary bladder.

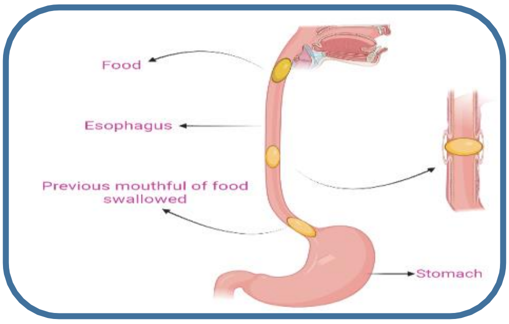

Fig. 5. Peristalsis in the digestive tract of human

A peristaltic pump (Fig. 6), also known as a roller pump, is a device that replicates peristalsis by employing multiple evenly spaced rollers to rotate and compress a flexible tube. This type of positive displacement pump is utilized for pumping various fluids. The pump comprises a circular casing that encloses a flexible tube, serving as a conduit for the fluid. Rollers, shoes, or wipers compress the flexible tube and are affixed to the outer circumference of a rotor. As the rotor rotates, the compressed portion of the tube occludes, propelling the fluid to flow through the tube. Additionally, when the cam passes, the tube returns to its natural state, inducing fluid flow into the pump through a process called restitution or resilience. This cyclic compression and tube relaxation enables the peristaltic pump to move fluids effectively.

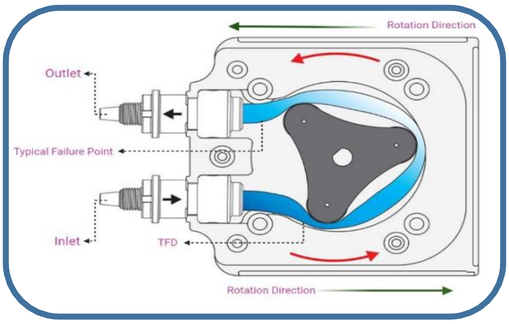

Fig. 6. Image of peristaltic pump

Peristaltic pumps have played a crucial role in the fight against COVID-19. They have been extensively used in various aspects of the pandemic response, including vaccine manufacturing, COVID-19 testing, treatment, and the production of personal protective equipment (PPE). For example, they have been instrumental in ensuring consistent and effective vaccine formulation, transporting patient samples and reagents during testing, delivering medications and fluids for patient treatment, and aiding in producing PPE.

The present work is organized as follows: Section 2. provides a literature review on peristaltic motion, covering Newtonian and non-Newtonian fluids, heat transfer, MHD, and porous media. Section 3. discusses the importance and basic equations of Carreau fluid. Section 4. examines the analytic and semi-analytic techniques used in the literature to analyze the peristaltic motion in Carreau fluids. Section 5. showcases the numerical techniques employed to study the peristaltic flow of Carreau fluids. Section 6. focuses on the peristaltic wave of Carreau fluid using the Multi-Step Differential Transformation Method. Section 7. presents the applications of the Carreau fluid peristaltic wave. Section 8. summarizes some notable results of various authors, and finally, Section 9. includes a conclusion and future direction based on this review.

2. Literature Review

Recent research has dedicated considerable efforts to investigating the characteristics of peristaltic motion in different types of fluids, including both Newtonian and non-Newtonian fluids. These studies have examined the influence of various factors such as MHD, heat transfer, porous medium, fluid viscosity, Reynolds number, and wave amplitude on the flow rate and pressure drop during peristaltic pumping. The findings thus have provided valuable insights into the behavior of peristaltic motion.

However, it is important to note that there is still much to be explored and understood regarding the peristaltic motion in diverse fluid types and under various conditions. Further research is necessary to deepen our understanding of the intricacies involved. This ongoing investigation can contribute to developing improved designs and enhanced efficiency of peristaltic devices in a wide range of applications.

2.1. Newtonian Fluid

The flow behavior of Newtonian fluids during peristaltic motion can be described by well-established mathematical models, either by using the lubrication theory or the Naiver-Stokes equations. These models take into account factors like fluid viscosity, tube geometry, and the applied peristaltic wave characteristics to analyze the flow rate, pressure distribution, and other flow parameters.

The study of peristaltic motion in Newtonian fluids has practical applications in fields such as gastroenterology, where it helps to understand and model the movement of food boluses in the digestive tract. It also plays a role in designing and optimizing peristaltic devices, such as peristaltic pumps, used for controlled fluid transport in various industries and medical applications.

Table 1. Review on Newtonian Fluid in Peristalsis

Authors	Year	Findings
Latham [1]	1966	"Investigated the flow of urine through the ureter."
Burns and Parkets[2]	1967	"Researched peristaltic motion without a pressure gradient and flow under pressure in a pipe or channel with constant walls and sinusoidally variable cross-section."
Fung and Yih [3]	1968	"Peristalsis may be involved in the vasomotion of tiny blood vessels that change diameter on a regular basis."
Barton and Raynor [4]	1968	"Peristaltic flow was initiated in the tubes".
Yin and Fung [5]	1969	"Researchers looked on peristaltic waves in circular cylindrical tubes."
Shapiro et al. [6]	1969	"Pumping was investigated using an infinite train of peristaltic waves across the cross-section, and theoretical findings for planar and axisymmetric geometries were presented."
Eckstein [7]	1970	"Finds a Theoretical Pressure Study of Peristaltic Pumping and Its Relationship to Ureteral Function."

Yin and Fung [8]	1971	"Look into the Peristaltic transport and mixing of chyme in the small intestine."
Shapiro and Jaffrin[9]	1971	"Examined Newtonian fluid peristaltic pumping."
Weinberg et al. [10]	1971	"Experimentally measuring mean flow, mean pressure increase, and pressure-time pulses at defined points from two-dimensional, infinite peristaltic waves pumping Newtonian fluids".
Brown and Hung [11]	1976	"When the Reynolds number is set to zero, they find solid particle motion in two-dimensional peristaltic flows."
Takabatake [12]	1982	"Peristalsis flow simulation in two dimensions."
Srivastava and Srivastava [13]	1983	"Investigated the issue of fluid peristaltic movement under zero Reynolds number and long wavelength approximation"
Pozrikidis [14]	1987	"An examination of peristaltic motion".
Siddiqui et al. [15]	1991	"Explained the Peristaltic pumping of a second-order fluid in a planar channel."
Tang and Rankin [16]	1993	"Explained the numerical and asymptotic solutions for the peristaltic motion of nonlinear viscous flows with elastic boundaries."
Meijing and Brasseur [17]	1993	“Non-steady peristaltic transport in limited length tubes was investigated.”
Das and Batra [18]	1993	"Investigated the secondary flow of a Casson fluid in a slightly curved tube."
Rathish Kumar and Naidu [19]	1995	Peristaltic flow has been numerically studied.
Mishra and Rao [20]	2003	“The peristaltic transport of a Newtonian fluid in an asymmetric conduit was discussed”.
Rachid and Ouzzani [21]	2008	“The influence of pulsatile flow on peristaltic output in Newtonian fluid was investigated”.
Hayat and Ali [22]	2008	“The effect of varying viscosity on the peristaltic transport of a Newtonian fluid in an asymmetric channel.”
Mekheimer et al. [23]	2008	"The effect of heat transfer and magnetic field on peristaltic transport of a Newtonian fluid in a vertical annulus was studied using an endoscope. "
Hayat et al. [24]	2011	"Explained the Peristaltic transport of a viscous fluid in a curved channel with compliant walls."
Suresh Goud et al. [25]	2017	“The peristaltic motion of a Bingham fluid in contact with a Newtonian fluid in a vertical channel was studied”.
Sivaiah et al. [26]	2017	“Evaluate the impact of suction and injection procedures on peristaltic motion through porous walls”.
Gangavathi et al. [27]	2020	“Analysed the impact of the Hall effect on the peristaltic motion of a Newtonian fluid in an inclined planar channel via a porous medium”.
Mccash et at. [28]	2022	“The existence of ciliated walls and the effects of heating on a Newtonian fluid were the focus of this study”.
Sushma et al. [29]	2023	“Investigated the influence of heat transfer mechanisms, including conduction, convection, and possibly radiation, on the peristaltic flow of the Newtonian fluid”.

2.2. Non-Newtonian Fluid

The Newtonian fluid flow on the peristalsis was carried out to comprehend the physiological behavior of biological fluids, such as the urine flow through the ureter. Yet, it neglects to clarify the complex rheological activity in the stomach, lymphatic vessels, and bloodstream. This underscores the use of non-Newtonian models to examine the physiological conduct of such frameworks. A few non-Newtonian fluid models are the Power-law fluid model, Rabinowitz fluid model, Herschel-Bulk-ley fluid model, Carreau fluid, Casson fluid model, and Jeffery fluid model.

Table 2. Review on Non-Newtonian Fluid in Peristalsis

Authors	Year	Findings
Raju and Devanatham [30]	1972	"Power-law model-based peristaltic transport in non-Newtonian fluids."
Jaffrin [31]	1973	"The effects of inertia and streamline curvature on peristaltic pumping were investigated."
Shukla and Gupta [32]	1982	"The peristaltic transport of a variable Power-law fluid was investigated."
Srivastava and Srivastava [33]	1984	"Casson fluid model II was used to investigate peristaltic transport of blood."
Siddiqui and Schwarz [34]	1993	"The peristaltic transport of a third-order fluid in a planner channel was examined."
Srivastana and Sexena [35]	1995	"Determine a two fluid non-Newtonian blood flow induced by peristaltic waves."
Misery et al. [36]	1996	"Peristaltic Motion of a Generalised Newtonian Incompressible Fluid in a Planar Channel."
Usha and Rao [37]	1997	"The peristaltic transport of a two-layered Power-law fluid was investigated."
Elshehawey [38]	1998	"Explained the Peristaltic motion of a generalised Newtonian fluid in a non-uniform channel."
Mernone et al. [39]	2002	"The peristaltic transport of a Casson fluid was mathematically investigated."
Mekheimer [40]	2002	"Peristaltic transport of a couple stress fluid in uniform and irregular channels."
Vajravelu et al. [41]	2005	"The peristaltic transport of a Herschel-Bulkley fluid in an inclined tube was investigated."
Hayat et al. [42]	2007	"Peristaltic transport for the flow of a Jeffrey fluid was studied."
Hariharan et al. [43]	2008	"The peristaltic transport of a non-Newtonian fluid in a diverging tube with a variety of wave shapes was investigated."
Hayat et al. [44]	2012	"The peristaltic transport of non-Newtonian fluid in a diverging tube with diverse wave shapes was investigated."
Hayat et al. [45]	2014	"Investigated the peristaltic transport of Casson fluid in a two-dimensional asymmetric channel with convective conditions."
Shehzad et al. [46]	2015	"Developed the Model and comparative study for peristaltic transport of water-based nanofluids".
Anum Tanveer et al. [47]	2019	"Developed the numerical simulation of electro osmosis-regulated peristaltic transport of Bingham nanofluid".
Asghar et al. [48]	2019	“Peristaltic flow of non-Newtonian Sisko fluid in undulating porous curved tube with heat and mass transfer effects have been studied”.
Anum Tanveer et al. [49]	2021	“The investigation of electroosmosis in the peristaltic activity of MHD non-Newtonian fluid discloses the generation of electroosmotic flow”.
Durga Priyadarsini et al. [50]	2023	“Examined the behaviour of non-Newtonian fluids in an angled conduit during peristaltic motion”.

2.3. Peristalsis involving Heat in a Tube/Channel

Thermal peristalsis is an emerging area of research that focuses on the movement of heat in a tube or channel through peristaltic motion. It has the potential to be applied in various fields, such as thermal management, fluid mixing, and heat transfer enhancement. Recent research in this area has gained significant attention due to the promising results. Studies have shown that thermal peristalsis can enhance heat transfer in both Newtonian and non-Newtonian fluids and can be influenced by factors such as wave amplitude, frequency, and thermal conductivity of the tube. The findings from this research can lead to improvements in the design and efficiency of devices that utilize thermal peristalsis, such as heat exchangers and Carreau fluid systems.

Table 3. Review on Heat Transfer in Peristalsis

Authors	Year	Findings
Vajravelu et al. [51]	2007	"The flow through a vertical porous tube with peristalsis and heat transfer were investigated."
Radhakrish and Srinivasalu [52]	2007	"The effect of wall characteristics on peristaltic transport with heat transfer was investigated."
Srinivas and Kothandapani [53]	2008	"A comment on peristaltic transport in an asymmetric channel with heat transfer."
Mekheimer and Elmaboud [54]	2008	"The effect of heat transfer and magnetic field on peristaltic transport of a Newtonian fluid in a vertical annulus was discussed using an endoscope."
Srinivas and Kothandapani [55]	2009	"The effect of heat and mass transfer on MHD peristaltic flow across a porous area with compliant walls was investigated".
Nadeem and Akbar [56]	2009	"The implications of heat transfer on the peristaltic transport of MHD Newtonian fluid with varying viscosity were discussed".
Nadeem and Akbar [57]	2010	"Heat transfer's effect on peristaltic transport of a Johnson - Segalman fluid in an inclined asymmetric channel".
Vasudev et. al. [58]	2010	"Williamson fluid peristaltic pumping through a porous material in a horizontal tube with heat transfer".
Nadeem and Akbar [59]	2012	"Endoscopic and heat transfer effects on the peristaltic flow of a third-order fluid with chemical reactions were discussed".
Saleem and Haider [60]	2014	"The heat and mass transfer on the peristaltic transport of Maxwell fluid with creeping flow were theoretically investigated".
Asghar and Ali [61]	2015	"The study of mixed convective heat and mass transfer on peristaltic flow of Fene-P fluid with chemical reaction was presented".
Hina [62]	2016	"The MHD peristaltic transport of Eyring Power fluid with heat and mass transfer, as well as wall characteristics and slip circumstances, was investigated".
Tanveer et al. [63]	2018	“Temperature distribution and heat transfer rates were impacted by the magnetic field's (MHD) presence on the curved channel's heat transfer properties”.
Akram et al. [64]	2020	“The work optimises heat transfer efficiency and fluid flow in peristaltic systems using Carreau fluids in rectangular ducts, including wave shapes and heating effects”.
Noreena et al. [65]	2020	“The heat transfer rate in the inclined asymmetric channel was found to be influenced by the peristaltic pumping action and the rheological properties of the Carreau fluid”.
Alsemiry et al. [66]	2022	“Mathematical analysis of Carreau fluid flow and heat transfer within an eccentric catheterized artery”.

2.4. MHD Peristalsis through Tube/Channel involving Newtonian/Non-Newtonian Fluids

Research on MHD peristalsis through tubes or channels involving both Newtonian and non-Newtonian fluids has the potential to bring out enhanced device designs in various applications. The results obtained from studies can advance the knowledge of MHD peristalsis, including its effect on fluid flow, pressure drop, and heat transfer under different conditions and fluid types. Such knowledge can contribute to more effective and efficient device designs in fields such as chemical engineering, medical diagnostics, and drug delivery.

Table 4. Review on MHD in Peristalsis

Authors	Year	Findings
Siddiqui and Schwarz [67]	1993	"A third order fluid's peristaltic transport in a planar channel has been studied."
Sud et al. [68]	1997	"Magnetohydrodynamic (MHD) peristaltic flows have been investigated."
Hayat et al. [69]	2002	"The discoveries about the axisymmetric tube were looked into".
Hakeem et al. [70]	2006	"An investigation on the hydromagnetic flow of a standard Newtonian fluid through a uniform tube with peristalsis was carried out".
Hayat et al. [71]	2007	"A magnetic field's effect on the peristaltic transport of a third-order fluid has been investigated."
Subba Reddy and Gangadhar [72]	2010	"The nonlinear peristaltic motion of a Carreau fluid in an inclined planar channel under the influence of a magnetic field is shown".
Hayat et al. [73]	2010	"Influence of magnetic field and endoscope on peristaltic transport: an accurate solution has been discussed"
Reddy and Raju [74]	2011	"Deborah number and phase difference influence the peristaltic MHD flow of a fourth grade fluid in an inclined asymmetric channel."
Rathod and Pallavi Kulkarni [75]	2011	"The effect of wall characteristics on the MHD peristaltic transport of dusty fluid was investigated."
Gangavati et al. [76]	2011	"The influence of a magnetic field on the peristaltic motion of third-grade fluid through porous media in an asymmetric channel was investigated."
Habibi et al. [77]	2012	"Magnetic particles enhance medication absorption while impeding uniform drug distribution in the circulatory system."
Akbar and Nadeem [78]	2013	"Studied the Newtonian - heated mixed convective MHD peristaltic flow of a Jeffrey nanofluid."
Gnaneswara reddy and OD Makinde [79]	2016	"Investigated the MHD peristaltic transport of Jeffrey nanofluid in an asymmetric channel"
Lakshminarayana et al. [80]	2017	"Looks into the effects of joule heating and wall flexibility on the peristaltic flow of MHD nanofluid."
Akbar et al. [81]	2018	"Developed the shape of nanoparticles on peristaltic transport of nanofluids in the presence of MHD."
Ellahi et al. [82]	2019	"Examines the effects of different nano particle shapes on the peristaltic flow of MHD nanofluids filled in an asymmetric channel."
Anum Tanveer et al. [83]	2020	“Theoretical investigation of peristaltic activity in MHD based blood flow of non-Newtonian material”.
Vaidya et al. [84]	2020	“Influence of transport properties on the peristaltic MHD Jeffrey fluid flow through a porous asymmetric tapered channel”.
Rafaqat et al. [85]	2022	“Magneto-hydrodynamics second-grade compressible fluid flow in a wavy channel under peristalsis: Thermal energy application”.
Mahendra et al. [86]	2023	“Entropy investigation of gyrotactic microorganisms in Eyring-Powell nanofluid flowing via an asymmetric channel during bioconvective peristaltic flow”.

2.5. Peristalsis in Porous Tube/Channel

Research on MHD peristalsis through tubes or channels involving both Newtonian and non-Newtonian fluids has the potential to bring out enhanced device designs in various applications. The results obtained from studies can advance the knowledge of MHD peristalsis, including its effect on fluid flow, pressure drop, and heat transfer under different conditions and fluid types. Such knowledge can contribute to more effective and efficient device designs in fields such as chemical engineering, medical diagnostics, and drug delivery.

Table 5. Review on Porous medium in Peristalsis

Authors	Year	Findings
Elsheshwey et al. [87]	1999	"The first porous media peristaltic flow investigation is given."
Elsheshwey et. [88]	2000	"Studied generalised Newtonian fluid peristaltic motion across a porous medium of peristaltic motion"
Mekheimer [89]	2003	" Peristaltic transport with a non-linear component in an inclined planar channel."
Sobh [90]	2004	"The peristaltic movement of a magnetoNewtonian fluid across a porous media has been considered."
Manoranjan and Ramachandra [91]	2005	"A flow model in the gastrointestinal system was established after studying peristaltic transport in a conduit with a porous peripheral layer."
Elsheshwey [92]	2006	"The peristaltic flow of Newtonian fluid in an asymmetric channel through porous media was investigated."
Hayat and Ali [93]	2006	"The peristaltic motion of MHD third-grade fluid in a deformable tube has been investigated."
Hayat et al. [94]	2007	"The effects of Hall on peristaltic motion of a Maxwell fluid in a porous media were investigated."
Sobh and Mady [95]	2008	"Peristaltic flow through a porous media in a non-uniform channel"
Subba Reddy [96]	2011	"The peristaltic transport of a Johnson-Segalman fluid in a channel across a porous material was investigated."
Ravikumar et al. [97]	2011	"The peristaltic transport of a power-law fluid in an asymmetric channel with permeable walls was investigated."
Hemadri et al. [98]	2011	"Presented the effect of porous material thickness on peristaltic pumping when the tube wall is provided with non-erodible porous lining."
Rathod and Pallalvi Kulkarni [99]	2011	"Discussed the influence of wall properties on the peristaltic transport of dusty fluid through porous medium."
Rathod and sridhar [100]	2012	"Considered the couple stress fluid to study the peristaltic transport in uniform and non-uniform annulus through porous medium."
Rathod and Laxmi Devindrappa [101]	2014	"Studied the effect of heat transfer on the peristaltic MHD flow of a non-Newtonian Bingham type fluid through a porous medium in a channel."
K.Ramesh, and Devakar [102]	2015	"The MHD peristaltic transport of a pair stress fluid through a porous material in an inclined asymmetric channel with heat transfer is investigated."
FM Abbasi [103]	2015	"The peristaltic transport of a copper-water nanofluid saturating a porous media has been discovered."
Ramesh and K Devakar [104]	2017	"The MHD peristaltic flow of a pseudoplastic fluid in a vertical asymmetric channel through porous media with heat and mass transfer is investigated."
AN S Ramesh babu et al. [105]	2018	"The peristaltic transport of a viscous fluid in a porous channel with suction and injection was explained."
G Manjunadha et al. [106]	2019	"The effect of heat and mass transfer on the peristaltic mechanism of Jeffrey fluid was examined in a non-uniform porous channel with variable velocity and thermal conductivity".
Balachandra et al. [107]	2021	“Peristalsis of Bingham fluid with different fluid characteristics through a porous channel showed homogenous and heterogeneous responses, demonstrating how fluid parameters affect peristaltic flow behaviour”.
Mohammed Obayes Kadhim et al. [108]	2023	“The combined effects of rotation and inclined magnetic field on peristaltic slip flow of a Bingham fluid with heat transfer in an asymmetric channel and porous material altered flow properties and heat transfer”.
Gudekote et al. [109]	2023	“The porous effect modulates heat and mass transfer effects on peristaltic transport of Eyring-Powell fluid through an inclined non-uniform channel”.

3. Background

From the literature review, the Carreau fluid model is a non-Newtonian fluid model that has been shown to accurately describe the behavior of a wide range of fluids, including shear-thinning fluids like blood. The model is widely used in numerous investigations because it accounts for the nonlinear connection between shear stress and shear rate in non-Newtonian fluids.

The Carreau fluid model was developed to investigate the behavior of peristaltic flow in non-Newtonian fluids under peristaltic motion. Nadeem et al. [110] investigated the influence of non-Newtonian behavior on peristaltic flow through a tube using the Carreau fluid model and discovered that the rheological features of the fluid have a substantial impact on peristalsis behaviour and that the Carreau fluid model gives a more realistic depiction of flow behavior than other non-Newtonian models. In a study by Ali et al. [111], the Carreau fluid model has been used to investigate the behavior of peristaltic flow of blood in a channel with stenosis. This study found that the Carreau fluid model accurately predicts the behavior of peristaltic flow in the blood and that the presence of stenosis significantly affects the flow behavior.

Overall, the Carreau fluid model has been shown to be a useful tool for studying the behaviour of peristaltic flow in non-Newtonian fluids, and it has been used in several research in this field. As a result, using the Carreau fluid model to study peristaltic motion makes sense since it has a solid basis in the literature and is generally regarded as an appropriate model for understanding the behaviour of many kinds of non-Newtonian fluids.

The constitutive equation for a Carreau rheological model (CF) is ([112]).

$$\tau = -\mathrm{p}\varpi + \xi \qquad (1)$$

with,

$$\xi = \left[\xi_\infty + \left(\xi_0 - \xi_\infty \right) \left(1 + (\lambda\dot{\gamma})^2 \right)^{\frac{n-1}{2}} \right] \gamma \qquad (2)$$

since, it describes the slope of $(\xi - \xi_0)(\xi_0 - \xi_\infty)$ in the power law region.

We consider the most practical cases where in $\xi_0 \gg \xi_\infty$. Hence, $\xi_\infty = 0$ is taken and consequently equation (1) becomes,

$$\tau = -pI + \left[(\xi_0) \left(1 + (\lambda\dot{\gamma})^2 \right)^{\frac{n-1}{2}} \right] A_1 \qquad (3)$$

Applied mathematicians are distinguished from pure mathematicians, physicists, and engineers by their ability to make exact approximations for the purpose of solving equations. Analytical methods and numerical techniques are the two approaches that may be used to discover exact approximations. According to Nayfeh (1973, 1979) and Rand and Armbruster (1987), analytical and Numerical methods do not compete with one another but rather complement one another.

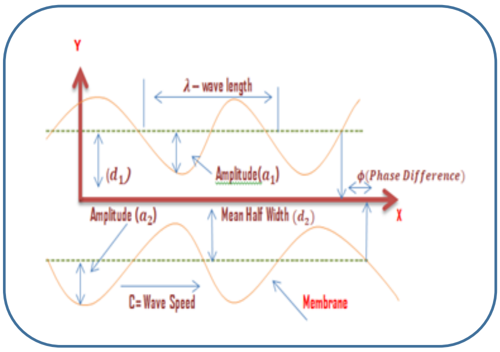

Fig. 7. Schematic diagram of Peristaltic channel

4. Analytical Technique

4.1. Exact Solution

Exact solutions, also known as closed-form solutions, are highly valuable in various fields of natural sciences as they accurately capture the qualitative properties of events and processes. In the context of fluid dynamics, a precise analytical solution to the flow equations involves a set of functions that describe the velocity components and fluid pressure. These solutions are obtained by considering all possible values of the independent variables and parameters that affect the fluid flow, such as thermal conductivity, elongation, elasticity, viscosity, specific heat, and temporal dilation.

Wang [113] identified two important factors that contribute to the significance of exact solutions:

1. Consistency with fundamental fluid-dynamic principles: The exact solutions align with the true underlying fluxes and enable a deeper understanding of the fundamental phenomena described by the flow equations.
2. Evaluation of approximation methods: The exact solutions serve as benchmarks to assess the accuracy of various approximation techniques, including numerical, asymptotic, and empirical approaches.

Several papers have explored the exact solutions for the peristaltic motion of Carreau fluids. A study by Abdul Hakeem et al. [114] focused on exact analytical solutions for Carreau fluid flow in a channel subjected to peristaltic waves. The authors provide closed-form expressions for velocity and pressure profiles, elucidating the behavior of the fluid during peristaltic motion. Kiran et al. [115] also found an accurate analytical solution for velocity and pressure distributions by investigating the Carreau fluid flow in channels driven by peristaltic transport, which shed light on the fluid behavior under peristaltic motion. Furthermore, Kiran [116] concentrated on obtaining an analytical solution for velocity and pressure profiles of the Carreau fluid peristaltic flow in inclined asymmetric channels by considering channel inclination and asymmetry.

In summary, these papers contribute to understanding Carreau fluid flow by developing exact solutions that characterize the velocity, pressure, and behavior of the fluid during peristaltic motion.

4.2. Perturbation Method

The perturbation techniques are effective when a certain parameter is very big or small, whereas the numerical methods work best when all parameters are of order one. When doing research, an agreement between the two methodologies is reassuring the accuracy of techniques. Perturbation approaches often provide greater physical immediacy. Finding approximations for perturbations requires more of an artistic approach than a scientific one. It is impossible to provide regulations; all that can be provided are recommendations. The techniques that are used in numerical analysis are very closely connected to perturbation theory. Methods that fall under the category of "perturbation" are those that rely on the presence of a dimensionless parameter in the issue at hand that is of a manageable size: $\epsilon \ll 1$

The general form of the perturbation series expansion is,

$$\mathrm{F} = \mathrm{F}_0 + \epsilon\mathrm{F}_1 + \epsilon^2\mathrm{F}_2 + \epsilon^3\mathrm{F}_3 + \cdots \quad (4)$$

Here, F_0 is the known solution to the initial problem that is precisely solvable and F_1, F_2, F_3 are the higher order terms. For small ε these higher order terms are smaller and smaller. By truncating the series, mostly by retaining the first two terms, a "perturbation solution" can be approximated.

Peristaltic motion studies have incorporated both singular perturbation methods and regular perturbation methods, as demonstrated in the following papers: the peristaltic motion of a Carreau fluid with properties of compliant walls and nanoparticles in a tending curved channel has been addressed by Nadeem et al. [117].

The geometry of the wall surfaces ([99]) is taken as,

$$\mathrm{z} = \mathrm{h}(\mathrm{x},\mathrm{t}) = \pm\mathrm{a} \pm \mathrm{b}\cos\left[\frac{2\pi}{\lambda}(\mathrm{X} - \mathrm{ct})\right] \quad (5)$$

The peristaltic motion of a Carreau fluid in an unbalanced canal with partial slip is investigated by Rajanikanth [118] using low Reynolds number and long wavelength assumptions.

It is noteworthy to point out that until now, no one has discussed the peristaltic motion of Newtonian or non-Newtonian fluid in a rectangular duct with complacent walls. The peristaltic wave of Carreau fluid in a canal with convective conditions has been studied by Hayat [119], incorporating the channel asymmetry and Hall effects.

The Hall parameter used ([119]) is as follows:

$$m = \frac{\sigma^* B_0}{en} \quad (6)$$

Akram [120] was the first to focus on the peristaltic motion of a Carreau fluid in a vertical unbalanced canal with slip condition. Analytically, the issue is solved under the hypotheses of a long wavelength and a low Reynolds number {LW & LR}. The majority of the peristalsis literature has been designed for fluid movement in a straight channel, but manufacturing and biological applications contain curved frames. Hence, Hayat et al. [121] investigated the convective heat flow and radial electromagnetic field reaction on the peristaltic motion of Carreau fluid in a curved canal. Srinivas [122] studied the peristaltic motion of a Newtonian fluid in generalized form in an elastic tube. Noreen et al. [123] investigated the flow of Carreau fluid in an inclined unbalanced tube caused by peristaltic motion.

4.2.1. Regular Perturbation Theory

Regular perturbation methods are powerful tools for solving problems with small parameters, allowing researchers to gain valuable insights into the behavior of complex systems and obtain approximate solutions that would otherwise be challenging to obtain directly.

The study of the peristaltic motion of a Carreau fluid in an asymmetric channel can indeed be approached using regular perturbation methods. In 1996, Misery et al. [124] pursued using a perturbation incursion in the form of the Weissenberg number (We), the peristaltic wave in a two-dimensional medium with a sinusoidal signal. The long wavelength approximation by Elshehawey et al. [125] has been used to study the issue of a peristaltic wave of a Carreau fluid in a unidirectional channel with zero Reynolds number.

The channel wall equation ([125]) considered is,

$$Y = H_1(X,t) = a_1 + b_1\cos\left[\frac{2\pi}{\lambda}(X - ct)\right] \quad (7)$$

Naby and Misery [126] investigated the clear and specific forms of the velocity distribution, a relationship between the pressure gradient and rate of flow, and a connection between the friction factor using a perturbation expansion with the help of the inner and outer tubes. The tube equation ([126]) of Carreau fluid peristaltic flow is given below,

$$Y = H_1(\bar{Z},\bar{t}) = a_1 + b_1 sin\left[\frac{2\pi}{\lambda}(\bar{Z} - c\,\bar{t})\right] \quad (8)$$

Several researchers have investigated the separated flow (getting trapped) occurrence at the tunnel's center line in spherical and Cartesian coordinate system. In particular, Naby [127] has explained more about the separated flow. Nasir Ali and Hayat [128] were the pioneers in considering the flow of a non-compressible Carreau fluid in a sinusoidally varying unbalanced channel.

The geometry of the wall surfaces ([128]) is given below,

$$Y = H_1(X,t) = a_1 + b_1 cos\left[\frac{2\pi}{\lambda}(X - ct)\right] \quad (9)$$

$$Y = H_1(X,t) = a_1 + b_1 cos\left[\frac{2\pi}{\lambda}(X - ct) + \phi\right] \quad (10)$$

where b_1 and b_2 are the amplitudes of the waves, λ denotes the wave length, c refers wave speed, $\phi(0 \le \phi \le \pi)$ is the phase difference and $\bar{X}$ and $\bar{Y}$ are the rectangular coordinates. Hayat et al. [129] analyzed five different wave types of sinusoidal: sine wave (s), multi-sine wave (Ms), triangular wave (t), square wave (sq.), and trapezoid shape (tr) waves, defined in a planar channel. The peristaltic movement of CF in an unbalanced platform with boundary conditions caused by convection was addressed by Hayat [130].

4.2.2. Singular Perturbation Method

The singular perturbation method is valuable in analyzing peristaltic Carreau fluids near sharp transition regions, offering insights into their complex dynamics. It is a powerful tool for understanding the behavior of these fluids in critical areas. By employing this method, researchers can gain valuable insights into the intricate dynamics of peristaltic Carreau fluids. In summary, the singular perturbation method is an effective tool for analyzing the complex behavior of peristaltic Carreau fluids near regions of sharp transitions. Despite the fact there is always some slippage in real systems, the majority of the experiments were conducted with no-slip flow. The theoretical peristaltic wave of a Carreau fluid in an asymmetric channel is investigated by Ayman Sobh [131] with slip and no-slip effects.

4.3. Homotopy Analysis Method (HAM)

The presence of a minor variable limits popular perturbation techniques. Numerous methods for eliminating the tiny parameter have recently been introduced, one of which is known as the "Homotopy Analysis Method" (HAM). Because of its flexibility and ability to produce sufficiently accurate results with minimal effort, HAM has piqued the interest of researchers. In 1992, Liao was the first to introduce this method. Many authors have recently used HAM to solve different kinds of difference calculus, including non-linear and linear homogeneous and non-homogeneous equations, in a wide range of scientific and engineering applications.

To illustrate the basic idea of the Homotopy Perturbation Method (HPM), consider the following nonlinear differential equation,

$$L(u) + N(u) = f(r),\ r \in \Omega \quad (11)$$

with boundary conditions

$$\bar{B}\left(u, \frac{\partial u}{\partial s}\right) = 0,\ r \in \bar{\pi} \quad (12)$$

where L and N represent the linear and the non-linear operators respectively, $\bar{B}$ represents the boundary operator, $\bar{\pi}$ is represents the boundary of the domain Ω, and f(r) denotes a well-known analytic function.

According to the theme of Homotopy process, He (1999) suggests the Homotopy $\bar{u}(r,q) : \Omega \to \Omega \times [0,1] \to \Re$

$$\bar{H}(\bar{u},q) = (1-q)[L(\overline{u}) - L(u_0)] + q[L(\bar{u}) + N(\bar{u}) - f(r)] = 0 \quad (13)$$

in which q∈ [0,1] stands for embedding parameter and u_0 is an initial approximation which obey the defined boundary conditions. Now from Eq. (13), we can simply describe that for q→0,

$$\bar{H}(u,0) = L(\bar{u}) - L(u_0) = 0$$

and for $q \to 1$

$$\bar{H}(\bar{u},1) = L(\bar{u}) + N(\bar{u}) - f(r) = 0$$

From above two expressions, we can obviously mention that by changing q from 0 to 1, $\bar{u}(r,q)$ is converted from $u_0(r)$ to u(r) and this process is recognized as deformation in topology. The best approximation implies that the solution of Eq. (13) can be composed in a power series of the embedding parameter q. i.e.,

$$\bar{u} = \bar{u}_0 + q\,\bar{u}_1 + q^2\,\bar{u}_2 + \cdots \quad (14)$$

Now setting q=1, one gets the final approximate solution of Eq. (14) in the form,

$$u = \lim \bar{u} = \bar{u}_0 + \bar{u}_1 + \bar{u}_2 + \cdots$$

Akbar and Nadeem [132] investigated the effect of heat and mass transfer on the peristaltic motion of a Carreau fluid in a deviating tube. Furthermore, two different types of analytical solutions for velocity, temperature, and concentration field have indeed been evaluated using the perturbation method and HAM.

5. Numerical Technique

Numerical techniques play a vital role in understanding the complex behavior of the peristaltic flow of Carreau fluid in various channel types and boundary conditions. These techniques use mathematical models and computational algorithms to approximate the solution of the fluid flow equations. The selection of the appropriate numerical technique depends on the specific problem being studied, such as geometry, boundary conditions, and computational resources available. Some methods may be more suitable for nonlinear or time-dependent behavior, whereas others may be more efficient for specific boundary conditions or geometries. Researchers must choose the right numerical technique to model and analyze the peristaltic flow of Carreau fluid accurately, which can enhance understanding and open up potential applications in fields like biomedical engineering and microfluidics.

The aforementioned statement does not mention the peristaltic motion and heat transfer. Hayat et al. [133] focused on how heat exchange and slide simultaneously affect a peristaltic motion in an unbalanced channel. Furthermore, technicians, scientists, and developers are eager to focus on the peristaltic waves of non-Newtonian fluids in 3D tubes. Hence, Arshad Riaz et al. [134] presented a paper on the peristaltic motion of Carreau fluid in a rectangular tube with adaptable walls.

The controlling equation for the flexible walls ([134]) takes the form,

$$L(\eta) = p - p_0 \tag{15}$$

The numerical techniques have been employed by various authors and researchers in order to obtain the flow velocity, pressure, density, and temperature. Nadeem and Akbar [135] studied the peristaltic movement in the context of mixed convection mass and heat transmission and presented the analytical and numerical solutions (ND Solve) for the velocity distribution. Noreen et al. [136] was the pioneer to use the Runge-Kutta 4th and 5th order (RK45) on the peristaltic motion of a Carreau fluid in an unbalanced tube. Abbasi [137] investigated the Hall effects on the MHD peristaltic motion of Carreau-Yasuda fluid through a rounded tube and obtained a solution using the Shooting method (Mathematica). The peristaltic motion of a Carreau fluid with mass and heat transfer through a porous medium in an unbalanced tube was studied by Eldabe [138] using the ND solve package. The heat convective and zero nanomaterial volume flow conditions have been used by Hayat [139] to solve the non-linear equations numerically using Mathematica. Safia Akram et al. [140] defined the thermal convective and zero nanoparticle mass flux conditions using a numerical method and discussed the significance of partial slip on double-diffusive convection on magnetic properties of Carreau nanofluid.

6. Multi-Step Differential Transformation Method (MS-DTM)

The Multi-Step Differential Transformation Method (MS-DTM) is a reliable semi-analytical technique that improves the traditional differential transformation method. As more nonlinear terms were introduced, the continuity motion equations became more difficult to deal with. As a result, analytical solutions to such problems are nearly impossible to find. Hence, one can employ novel techniques such as the Differential Transform Method (DTM), a semi-analytical technique. The MS-DTM method accelerates series solution convergence over a large region. However, this series will be cut short due to the required precision of solutions. Odibat et al. [141] validate this modified technique with exemplifications of non-chaotic or chaotic systems.

The differential transformation of the function u(z) [141] is considered as,

$$U(K) = \frac{1}{k!}\left[\frac{d^k u(z)}{dz^k}\right]_{z=z_0} \tag{16}$$

Eldabe [142] described the continuity equations of movement and used MS-DTM to obtain the velocity, temperature, and concentration distributions. The Darcy-Brinkman- Forchheimer channel stuffed with non-Newtonian Carreau fluid under the heat transport effect was computed for the first time by Bhatti et al. [143]. The impact of Joule conditions of heat and MHD on the PM of Carreau nanoparticles in a sloped unbalanced tube was studied by Asha and Joonabi Beleri [144] under long wavelength and low Reynolds number conditions (LW & LR). Asha [145] used the MS-DTM to find solutions for natural convection with triple diffusion on peristaltic pumping under the assumptions of LW & LR of a Carreau nanoparticle in an unbalanced tube.

Recent work by Asghar ([146]-[155]) focused on numerically based investigations of peristaltic motion, which leads one to believe that the researchers are using mathematical models and computer simulations in order to get a deeper comprehension of how fluids behave in peristaltic systems. This method may be highly helpful for anticipating fluid flow patterns, locating the processes that cause peristaltic motion, and optimizing the design of systems that depend on peristaltic motion, such as industrial pumping systems and biomedical devices.

7. Applications

- The use of peristaltic Carreau fluids is common in several sectors, including food processing, chemical manufacture, biomedical engineering, and environmental engineering.
- In wastewater treatment operations, peristaltic Carreau fluids are employed. They may be used to transport and measure viscous fluids like sludge and other pollutants.
- Carreau fluid models, which are widely used in various flow conditions, such as flow in plasma bloodstream through porous media, as well as type occurs measurement techniques. Thus, it is popular in many physiological, technical, and manufacturing fields of study, such as biological sciences and engineering, hydraulic fracturing, and food manufacturing.
- Carreau fluid's most important applications are fluid flow separator, liquid leakage in rivers ban groundwater and animal fat motion, granite, rye bread, natural materials, the living thing lung, biliary tubing, gallbladder with rocks, and tiny blood vessels.
- It is evident that the perturbation technique on Weissenberg number (We) limited us in selecting the variables for the CF when the value of We is lower than one, but the estimate used for the solution limited us in selecting the value of flow speed, frequency, and canal length such that the wave number and Reynolds number were ignored.
- In technology (MHD pumps) and biology (blood flow), the impact of MHD on peristaltic flow is significant; such analysis is highly important in medical research.
- Peristaltic motion with heat transfer, with industrial applications including properly sanitized fluid transport, blood pumping systems in cardiac machines, and harmful fluid transmission where fluid interaction with mechanical components is prohibited.
- The HAM approach can handle nonlinearity and include extra effects, making it useful for analyzing Carreau fluid peristaltic motion. It accommodates different boundary conditions. This approach helps researchers to study the Carreau fluid dynamics and characteristics during peristaltic motion.
- The importance of blood thermal effects in processes such as oxygen delivery and peritoneal dialysis necessitates research into heat transfer efficiency in peristaltic movement.
- Perturbation approaches have helped us to comprehend peristaltic motion in Carreau fluids by establishing approximate analytical solutions, examining flow instabilities, and analyzing external influences. They help us to understand peristaltic fluid movement by complementing numerical models and experimentation.
- MS-DTM is a technique used to solve the nonlinear differential equations accurately and to study how channel shape and Carreau fluid rheology affect the flow behavior. Due to the efficiency of this method, more researchers got attracted and used this technique to examine the peristaltic motion dynamics and Carreau fluid system fluid transport phenomena.

8. Compendium

- According to research on the peristaltic movement of Carreau fluid in a circular tube with compliant walls, [117] found that the channel's curvature significantly affects fluid velocity, temperature profile, and concentration profile. Increasing curvature led to a notable decrease in velocity. This decrease was rapid until a curvature parameter value of 5, beyond which the velocity decrease became invariant. These findings underscore the importance of considering channel curvature in designing and analyzing systems involving peristaltic flow in curved channels with compliant walls.
- In the study of the peristaltic wave of Carreau fluid in a tube with convective boundary conditions [118], the longitudinal velocity of a Newtonian fluid surpasses that of a Carreau fluid at the channel's center, while Carreau fluid exhibits lower velocities near the walls. Moreover, the heat transfer coefficient is

higher for a Newtonian fluid than a Carreau fluid, increasing with higher Biot numbers at the upper wall.

- The mathematical analysis of Carreau fluid of peristaltic motion in a compliant rectangular duct [119] found that as the velocity profile decreases, the quantitative values of the non-dimensional elasticity parameters n, E1, and E2 increase. However, the opposite trend is observed for the non-dimensional parameters E3 and We, which decrease as the velocity profile decreases. The analysis highlights the influence of the velocity profile on the various non-dimensional elasticity parameters in the study of CF behavior in a compliant rectangular duct.
- In the research of non-linear peristaltic motion of a Carreau fluid in the presence of Hall effect and heat conduction, it was concluded that as the flow rate (α) increases for both Newtonian and Carreau fluids, the number of streamlines and the size of the bolus also increase [123]. This suggests that higher flow rates result in a greater number of fluid particles being transported and a larger volume of fluid being carried within the peristaltic wave. These findings contribute to understanding the complex behavior of Carreau fluids in peristaltic motion and highlight the impact of flow rate on the flow characteristics.
- The impact of slip and heat transmission on the peristaltic motion of a Carreau fluid in a vertical unbalanced canal reveals that the velocity field exhibits different behaviors near the left and right canals. Specifically, the velocity field increases with increasing slip length (L) near the left canal, while it decreases with increasing slip length near the right canal. This variation in the velocity field is attributed to the utilization of partial slip conditions, where the velocity value on the boundary varies for different values of L. The findings emphasize the influence of slip and heat transmission on the velocity distribution in Carreau fluid flow within a vertical asymmetric channel. [129]
- In a study examining the effects of MHD and Joule heat transmission on the peristaltic motion of a Carreau fluid in a mixed convection circular pipe, it was observed that the velocity behavior for the We in the lower and upper halves of the channel is opposite. Furthermore, the characteristics of the circular M on the velocity profile were found to be qualitatively similar [132]. These findings highlight MHD and heat transmission's complex and contrasting influences on the velocity distribution in CF flows within a circular pipe under mixed convection conditions.
- In a study investigating the mass and heat transfer of blood flow as a Carreau fluid with peristaltic motion conveying gold nanomaterial in an unbalanced tube, the authors [143] concluded that gold, with its high atomic number, exhibits a velocity profile behavior similar to that of the Weissenberg and Forchheimer numbers. Additionally, the presence of gold particles generates beneficial heat, potentially aiding in treating tumor glands. These findings highlight the potential applications of gold nanomaterials in enhancing mass and heat transfer properties for medical treatments involving Carreau fluid flows, particularly in the context of tumor treatment.

9. Conclusion

This work comprehensively explores the application of peristaltic Carreau fluids in various fields, such as heat transfer, magnetohydrodynamics (MHD), stagnation point flow, and porous media. The study also investigates the influence of boundary conditions on these fields. Future directions and concluding remarks include:

- Exploring the analysis of more complex rheological fluids, such as Casson Fluid, Maxwell Fluid, Walters' B Fluid, Transverse Fluid, Power Law Fluid, Jeffery Fluid, and Bingham Fluid, using peristaltic motion and other techniques.
- Investigating the behavior of pressure difference, stream function, and temperature profile for small Weissenberg numbers and exploring their characteristics for large Weissenberg numbers.
- Identifying peristaltic Carreau hybrid nanofluid flow as an attractive topic for future research, considering the limited number of studies in this area.
- The study provides a comprehensive review of relevant literature, with appropriate references incorporated.

- To add more value to the present study, a mathematical discussion is conducted using MATLAB to evaluate oesophagus morphology over various time periods, as shown in Fig .8.

Overall, this research highlights the potential of peristaltic Carreau fluids in various applications and suggests directions for further investigation and analysis in the future.

Nomenclature

φ	Phase difference or phase angle(rad)
ε	Amplitude ratio(rad)
a	Amplitude of the symmetric wall(m)
a_1	Amplitude of the wall H1(m)
a_2	Amplitude of the wall H2(m)
c	Speed of wave(m/s)
D	Half width of the channel(m)
d1+d2	Width of the asymmetric channel(m)
H1, H2	Boundaries of the channel(m)
λ	Wavelength of the channel(m)
τ	Shear stress(N/m2)
Γ	Time constant (s)
ρ	Density(kg/m3)
$\tau_{xx}, \tau_{xy}, \tau_{yy}$	Extra stress components. (N/m2)
p	Pressure(N/m2)
ξ_0	Zero shear rate viscosity (kg/ (m. s))
ξ_∞	Infinite shear rate viscosity (kg/ (m. s))
b_1 & b_2	The amplitudes of the waves(m)

Dimensionless Parameters:

$(\bar{X}, \bar{Y})$	Stationary co-ordinates
$(\bar{x}, \bar{y})$	Moving co-ordinates
$(\bar{U}, \bar{V})$	Velocity components in moving frames
m, m´	Non - uniform parameter
$(\bar{u}, \bar{v})$	Velocity components in fixed frames
t´	Dimensional time
X, Y	The axial and transverse directions
x	Dimensionless axial coordinate
y	Dimensionless normal coordinate
$\dot{\gamma}$	Rate of shear stress
n	Power law index
We	Weissenberg number
ϖ	Identity tensor

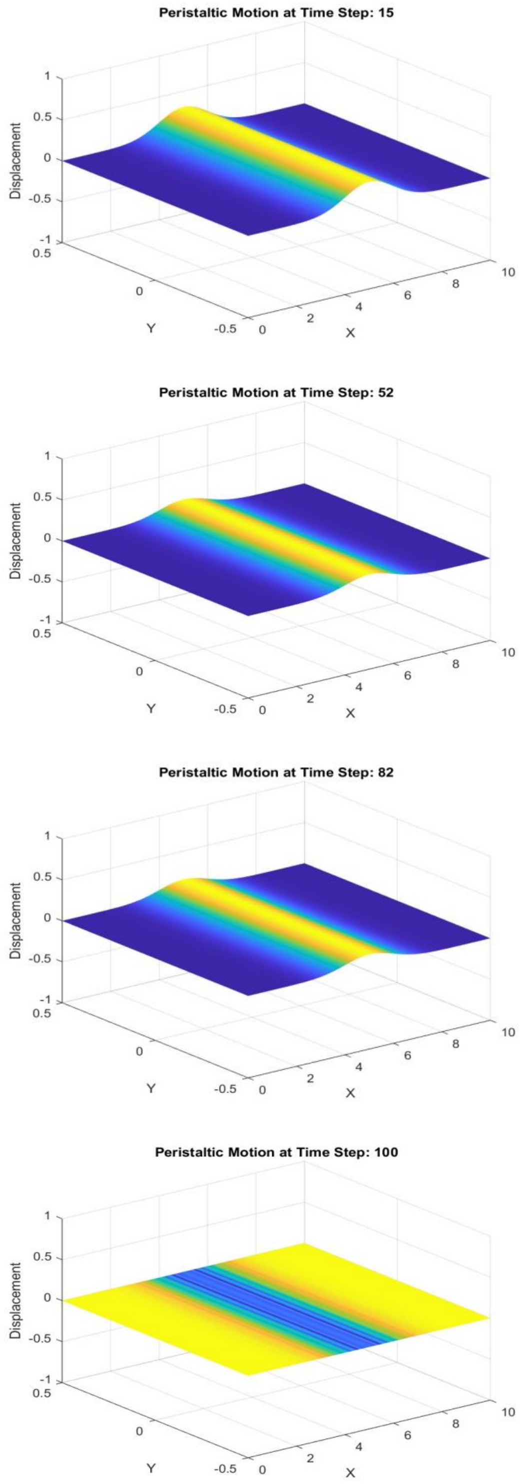

Figure 8. Peristaltic Motion at Different Time

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article. In addition, the authors have entirely observed the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

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