IITB-Monash Research Academy

Indian Institute of Technology Bombay | MONASH University

An Indian-Australian research partnership

Project Title:	**Rheological design of biopolymeric food thickeners to make swallowing easier**	
Project Number	**IMURA1076**	
Monash Main Supervisor (Name, Email Id, Phone)	Ravi Jagadeeshan, ravi.jagadeeshan@monash.edu,	*Full name, Email*
Monash Co-supervisor(s) (Name, Email Id, Phone)		
Monash Head of Dept/Centre (Name,Email)	Sankar Bhattacharya, sankar.bhattacharya@monash.edu	*Full name, email*
Monash Department:	Chemical and Biological Engineering	
Monash ADGR (Name,Email)	A/Professor Timothy Scott, timothy.scott@monash.edu	*Full name, email*
IITB Main Supervisor (Name, Email Id, Phone)	P. Sunthar, sunthar@che.iitb.ac.in,	*Full name, Email*
IITB Co-supervisor(s) (Name, Email Id, Phone)		*Full name, Email*
IITB Head of Dept (Name, Email, Phone)	Prof. Madhu Vinjamur, madhu@che.iitb.ac.in,	*Full name, email*
IITB Department:	Chemical Engineering	

Research Clusters: / Research Themes:

Highlight which of the Academy's CLUSTERS this project will address? *(Please nominate JUST **one.** For more information, see www.iitbmonash.org)*		**Highlight which of the Academy's Theme(s) this project will address?** *(Feel free to nominate more than one. For more information, see www.iitbmonash.org)*	
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The research problem

Many elderly people and patients with neurological diseases suffer from oropharyngeal dysphagia (OD) that makes it difficult for them to swallow liquids and chewed food. This often leads to aspiration and severe respiratory complications and pneumonia. A common procedure used to increase the safety of swallowing and avoiding aspiration is to increase the viscosity of the swallowed food by the addition of a thickening or “viscosifying” agent. Many studies have shown that this increases the ability of people suffering from dysphagia to swallow fluids and chewed food [1, 2]. Traditionally, starch-based thickeners have been used to increase the viscosity of consumed fluids [1]. However, these thickeners have been found to lead to a residual amount of food or beverage in the pharynx after swallowing (pharyngeal residue) leading to an increased risk of post-swallow aspirations. Moreover, starch-based thickeners are in general not well accepted by patients for textural reasons. More recently, thickeners based on xanthan gum have been developed that have improved therapeutic benefits and sensory attributes and are increasingly being used to thicken a wide range of liquids at different temperatures [2, 3]. Xanthan gum, produced by *Xanthomonas campestris*, is a polysaccharide with a negative charge that exhibits a high viscosity and also strong shear-thinning in aqueous solution. This makes the biopolymer useful in a wide variety of applications such as the food industry. Currently the specifications for OD thickeners are subjective, with very little empirical basis for their use. Effective treatment of swallowing disorders depends on being able to thicken drinks to a predetermined degree based on particular requirements. It is clearly important to understand the flow properties of drinks thickened with xanthan gum and be able to make quantitative predictions of the fluids’ viscosity based on the temperature and concentration of xanthan gum.

The effectiveness of xanthan gum as a thickener has its origins in the conformations adopted by xanthan molecules in solution. The structure of the xanthan monomer is shown in Fig. 1, with the charged side groups leading to a molecule that is rigid locally [4]. Images of the conformations of individual xanthan gum molecules have been obtained by AFM measurements [5], displayed at various salt concentrations in Fig. 2.

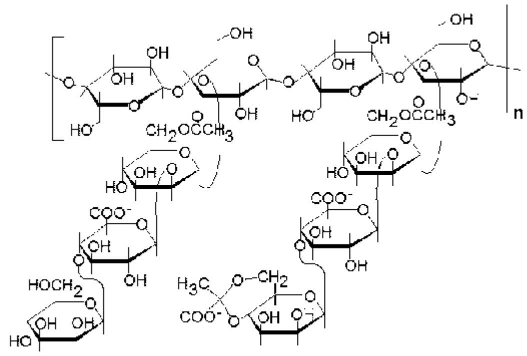

Fig. 1. Monomer structure of xanthan [4]

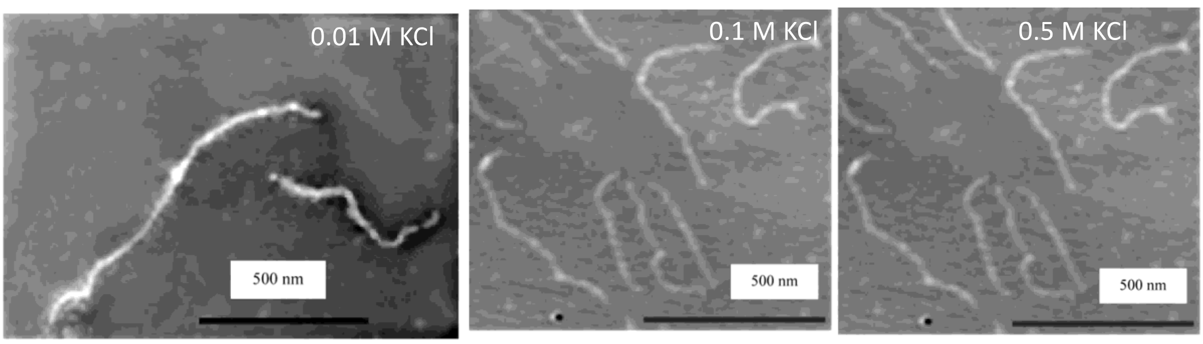

Fig. 2. Conformations of xanthan molecules at various salt concentrations. From [5].

In salt free solution, the xanthan molecule is highly extended because the charges on the side chains repel each other. With increasing salt ions in solution, the side chain charges are shielded from one another because of the presence of an ion cloud surrounding each charge, leading to the chain adopting a more flexible conformation, as can be seen in Fig. 2. In addition, xanthan molecules have a helical conformation that becomes coil-like at higher temperatures [6,7]. The degree of rigidity or semi-flexibility of a xanthan molecule can consequently be controlled by varying the concentration of salt ions or the temperature of the solution, or both. Thus, offering a very wide range of molecular rheology control in the laboratory.

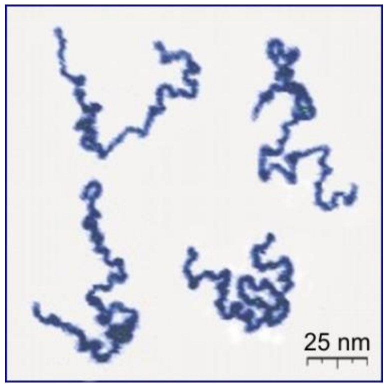

Fig. 3. A flexible polymer chain. From [8].

In contrast, an image of a flexible polymer (from Wikipedia [8]) is shown in Fig. 3. The significant difference between the conformations of a semi-flexible polymer like xanthan gum and a flexible polymer like polyethylene oxide (PEO) leads to an enormous difference in their shear viscosities, as can be seen from the flow curves displayed in Fig. 4. While a 1000 ppm PEO solution has a viscosity at very low shear rates of around 2.3 mPas, a 2000 ppm xanthan gum solution has a viscosity that is roughly 1870 mPas [9], an increase of nearly three orders of magnitude! This increase is essentially the reason for the suitability of xanthan gum as a liquid food modifier. Despite the large difference in zero shear-rate viscosities, both the xanthan gum solutions and solutions of flexible polymers exhibit shear-thinning at high shear rates, i.e., a decrease in viscosity to very similar values, which makes dispensing and actions such as swallowing very easy. On the other hand, there is a qualitative difference in the behaviour of these solutions in extensional flows.

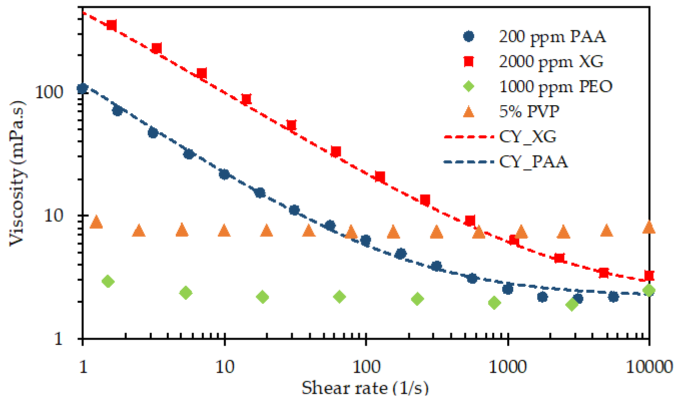

Fig. 4. Comparison of the flow curves for xanthan gum with polyethylene oxide (PEO), polyvinylpyrrolidone (PVP) and polyacrylamide (PAA) solutions. From [9].

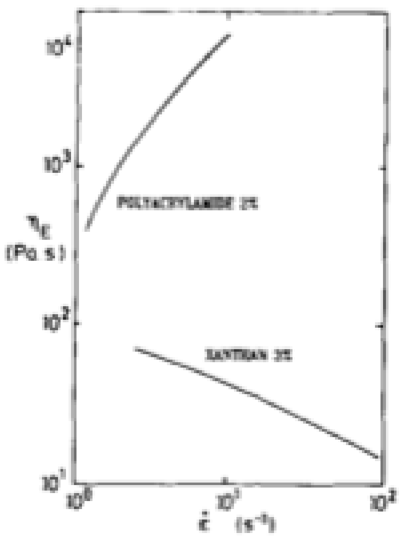

Fig. 5. Extensional viscosity of a 3% xanthan gum solution compared to a 2% polyacrylamide solution. From [10].

Figure 5 illustrates the differences in the dependence of the extensional viscosity on extension rate in a 2% PAA solution compared to a 3% xanthan gum solution [10]. The concentrations of the two solutions were chosen carefully to ensure that they had the same viscosity in shear flow. It is clear that while the PAA solution undergoes *extensional hardening*, the xanthan gum solution experiences *extensional thinning*. This is a direct consequence of the differences in the molecular conformations of the two systems. The flexible PAA chains are stretched and unravelled from their equilibrium coiled conformations and are able to withstand much greater stresses at comparable extension rates, in contrast to the semi-flexible xanthan gum molecules that align in the extensional flow but do not experience a significant change in their molecular conformation since they are already stretched at equilibrium.

To achieve the goal of using xanthan gum as a food additive and texture modifier, especially as a potential treatment for conditions such as dysphagia, it is clearly essential to understand how the coupling of flow strength and flow type affect the conformations of the xanthan molecules in solution and how this influences the macroscopic rheological properties of the fluid. Currently this is very poorly understood, and the use of xanthan gum is largely based on a heuristic approach. In order to be able to choose the appropriate temperature, concentration of salt ions and concentration of xanthan gum to achieve a desired solution viscosity, it is necessary to carry out systematic research that combines theoretical, computational and experimental approaches. This is the goal of the proposed research project, as outlined in the detailed project aims below.

References

[1] M. O'Leary, B. Hanson, and C. Smith, "Viscosity and Non-Newtonian Features of Thickened Fluids Used for Dysphagia Therapy," Journal of Food Science, 75, E330 – E338, 2010.

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[10] K. Walters, A.Q. Bhatti, N. Mori, The influence of polymer conformation on the rheological properties of aqueous polymer solutions, in: K.D. Dee, P.N. Kaloni, Pitman (Eds.), Recent Developments in Structured Continua, 1990.

Project aims

The project will focus on two complimentary aims. The first is to develop a constitutive model for xanthan gum solutions that can be used in flow solvers for polymer solutions and the second is to carry out Brownian dynamics simulations of coarse-grained bead-spring chain models that can validate the predictions of the closed-form constitutive model. Both these theoretical goals will be pursued in synergy with experimental measurements carried out in Professor Gareth McKinley's lab at MIT. Each of these goals in discussed in turn below.

As described above, xanthan gum is a semi-flexible molecule, whose rigidity depends on the concentration of salt ions and the temperature. Most constitutive models in the literature are designed to describe the flow of either perfectly flexible or rigid rodlike polymer molecules [11]. In particular, to our knowledge, there is no constitutive model that specifically describes the flow of semi-flexible polymer solutions. Recently, Prakash and co-workers have developed a coarse-grained bead-spring chain model that is based on a FENE-Fraenkel spring (FFS), with a bending potential between springs that characterizes the degree of semi-flexibility in the polymer chain [12, 13]. The FENE-Fraenkel spring is nonlinear when subjected to both compression and extension, and even the simple limit of a dumbbell model with an FFS is capable of describing (at a coarse-grained level) the response of a semiflexible polymer chain since it captures the orientation and relatively weak fluctuations in the end-to-end vector of the chain. The aim of the first part of this project is to develop a closed form constitutive model for a FFS dumbbell using the principles of Polymer Kinetic Theory [14]. Since the FFS spring is nonlinear, approximations along the lines of the Peterlin closure for FENE springs [14] will be required to achieve closure (i.e. to generate an explicit model of analytic form). Predictions of the model in shear and extensional flow will be obtained and compared with experimental measurements on xanthan gum solutions published by McKinley and co-workers [15, 16].

In the second part of the project, Brownian dynamics simulations of the coarse-grained model developed by Pincus et al., with the strength of the bending potential tuned to match the persistence length of xanthan gum, will be carried out to validate the predictions of the constitutive model developed in the first project goal (which will be based on a simple dumbbell model that involves closure approximations and a simplification in the transient dynamical response). Subsequently, simulations will be carried out at finite concentration using the multi-particle simulation algorithm developed in the Prakash group [17] and the code will be extended to describe polyelectrolyte solutions by including long-ranged Coulomb interactions between the individual beads.

The successful completion of these projects will lead to an unprecedented understanding of the rheology of semi-flexible polymer solutions such as xanthan gum as well as other food gums and a range of biopolymeric rheology modifiers. In turn, this will have a lasting impact on our capacity to use a semi-flexible polyelectrolyte such xanthan gum as a food modifier that leads to thickened fluids with the desired flow properties and ‘mouthfeel’.

References

[11] R. B. Bird, R. C. Armstrong, and O. Hassager, Dynamics of Polymeric Liquids - Volume 1: Fluid Mechanics, 2nd ed. (John Wiley, New York, 1987).
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What is expected of the student when at IITB and when at Monash?

Expected work at IITB

At IITB, the student would complete his/her course work and will start working on the project. The course work will be designed to obtain a working knowledge of Statistical Mechanics, Polymer Physics, Molecular Dynamics and the appropriate background in Mathematics. This will make the student ready for the next stage where he/she actually starts working on the specific project. Early work will involve understanding the different currently existing constitutive models for polymer solutions based on Polymer Kinetic Theory. Following this, the student will start developing a constitutive model for a FFS dumbbell. At an early stage in the PhD, the student will visit Monash to carry out simulations, which would be continued in IITB after he/she comes back from Monash.

Contributions and supervision responsibilities of IITB supervisor

IITB supervisor will take care of the student's course work at IITB. With the mutual consent of the supervisor at Monash, he/she will chalk out the courses to be taken by the student. In addition, it is the IITB supervisor's responsibility to connect the student with the research problem and start training the student with simple representative problems. The long-term task would be to supervise and guide the student towards the completion of his/her project after he/she comes back from Monash.

Expected work at Monash

In the first stages, the student will get familiar with the multi-particle Brownian dynamics simulation algorithm that has been developed in Jagadeeshan's group. Subsequently, the code will need to be modified to account for chain stiffness through the incorporation of bending potentials. Some benchmark problems will be examined to ensure the developed code is valid. Once these tasks are completed, the work on the actual research problem will begin. Early work will focus on comparing simulation predictions with those of the FFS constitutive model for simple shear and extensional flows. Based on the progress achieved, the student will continue to work on the project after returning to IITB.

Contributions and supervision responsibilities of Monash supervisor

Jagadeeshan brings expertise in molecular modelling and Brownian dynamics simulations. The protocol for the development of Brownian dynamics simulations algorithms is well established in his group, and consequently, the analytical and numerical tools for tackling the proposed problems are readily available. His role is to provide the technical expertise, to guide the student, to coordinate the various activities of the project, to manage the budget, and to ensure that the aims and objectives of the project are met.

Expected outcomes

The key outcomes of the PhD work will include:

1) A coarse-grained molecular model of semiflexible charged polymers that captures the experimentally observed macroscopic behaviour of xanthan gum solutions.
2) Elucidation of the general principles relating the structure of semiflexible charged polymers to the macroscopic rheological properties of the solution.
3) Prediction of the observed shear- and extension-rate dependence of the rheology of xanthan gum solutions in shear and extensional deformations, respectively.

These outcomes will result in high quality journal publications within the fields of polymer dynamics and soft matter, with exemplar outputs demonstrated in recent publications from the participating academics.

How will the project address the Goals of the above Themes?

Using theory and simulation we ultimately aim at understanding the dynamics of xanthan gum solutions, which is a problem of fundamental importance in the field of developing food thickeners for the treatment of dysphagia. Only a combination of computer simulation, theoretical techniques and experimental measurements can shed light on such complex dynamical processes. This project will accelerate the development of appropriate food thickeners based on xanthan gum. The outcome of this project will directly contribute to the Academy's research theme of "Health Sciences" to tackle the challenge of providing high quality health care to those who need it most.

Potential RPCs from IITB and Monash

Dr Prabhakar Ranganathan (Monash) - expert in soft matter and computer simulations.
Dr Sushil Dhital (Monash) – expert in Food Engineering
Dr Rajarshi Chakrabarti (IITB) - expert in polymer physics.
Dr Ranjith Padinhateeri (IITB) - expert in biophysics.

Capabilities and Degrees Required

The following capabilities are essential:

1. Excellent training in mathematics and numerical methods (biology knowledge is not mandatory)
2. Proven experience with computer programming in high level languages
3. Ability to write and communicate fluently
4. Strong background in Engineering/Physics/Applied Mathematics (Either MSc in Physics/Applied Mathematics or BTech/BE in Mechanical/Chemical Engineering).

While the topic has a biological context, students **without a background in physics or engineering will not be considered**.

Necessary Courses

The student will need to do courses in advanced mathematical methods, statistical mechanics, soft matter and computational methods. There are several courses offered at IITB that meet these requirements. For instance, the following are examples of courses that IITB-Monash Academy students of Jagadeeshan have completed previously:

CH 814 Fundamentals of Molecular Energetics and Dynamics
CH 576 Statistical Mechanics
CL 613 Special Topics in Complex Fluids
CL 602 Mathematical and Statistical Methods in Chemical Engineering
CL 651 Rheology of Complex Fluids
PH 550 Soft Matter Physics
CL 701 Computational Methods in Chemical Engineering
PH 543 Advanced Statistical Mechanics

The student will be advised to take similar courses in order to pick up the required background.

Potential Collaborators

This project will be carried out in close collaboration with Professor Gareth McKinley of MIT, USA (https://meche.mit.edu/people/faculty/GARETH@MIT.EDU). Professor McKinley has an ongoing interest in Xanthan Gum rheology for liquid food applications, and experiments carried out by his group will be used to validate the analytical and simulation approaches developed in the current project.

Select up to **(4)** keywords from the Academy's approved keyword list **(available at http://www.iitbmonash.org/becoming-a-research-supervisor/)** relating to this project to make it easier for the students to apply.

BioScience, Bio Medical Engineering; Food Innovation; Modelling and Simulation