Chemical Engineering Research Bulletin 23 (2023)
Available online at http://banglajol.info/index.php/CERB
DOI: https://doi.org/10.3329/cerb.v23i10.78498

Special Issue on the 7th International Conference on
Chemical Engineering (ICChE), 2023
ISSN: 2072-9510 (Open Access)

AN INVESTIGATION OF HYDROCOLLOIDS FILM FORMING ABILITY ON A VERTICALLY ROTATING DISC

Md Salim Miah*[,a,b], Alison McMillan[b] and Saphwan Al-Assaf[c]

[a]School of Physics, Engineering and Computer Science, University of Hertfordshire, Hatfield, AL10 9AB, UK
[b]Faculty of Arts, Science and Technology, Wrexham University, Wrexham, LL11 2AW, UK
[c] Hydrocolloids Research Centre, University of Chester, Chester, CH1 4BJ, UK

Abstract

Hydrocolloids are widely used in the food industry to perform variety of functions such as coatings, thickening, emulsifying, stabilizing and edible films. Their functionality for a given application are underpinned by the molecular weight, shape, and conformation in aqueous solution. The film forming ability of selected hydrocolloids, different in shape (rod, random coil and spherical) and/or conformation in aqueous solution were investigated experimentally and numerically on a vertically rotating disc. These include: xanthan, pectin, carboxymethyl cellulose (CMC) and gum arabic. The Laser scan method was used for the measurement of film thickness of the respective the hydrocolloids. The Volume of Fluid (VOF) Computational Fluid Dynamics (CFD) modelling approach was used in the numerical model. The variation in film formation at different concentrations has been observed to ascertain a trend. Both the experimental and simulation results revealed that the film formation depends on the molecular structure of the hydrocolloid while viscosity and rotating speed significantly influenced the film thickness. Xanthan showed higher film formation ability compared to the other hydrocolloids due to its higher viscosity. It was interesting to note that the film formation ability by CMC was significantly higher than pectin though pectin was five times more viscous than CMC. Gum arabic exhibited the lowest viscosity but formed almost the same film thickness on the disc as pectin despite being twenty times less viscous. Increasing CMC concentration from 0.5% to 1% resulted in increasing its viscosity and the film thickness. The film thickness increased at the disc rotating speed of 6 rpm as compared to 3 rpm. The simulation results were in good agreement with the experimental data.

Keywords: Hydrocolloids, CMC, Gum Arabic, Xanthan, Pectin, Rotating disc, Film thickness, CFD, Laser scan.

1. Introduction

Non-Newtonian fluid flow (such as that of hydrocolloids) has received much attention for multiple industrial applications, especially in the food processing industry. Hydrocolloids are mainly hydrophilic biopolymers with high molecular weight that act as thickeners, gelling agents, foam formation, stabilisers and emulsifiers. For example, carboxymethylcellulose, gum arabic, pectin, and xanthan gum are examples of hydrocolloids which differ in structure, shape and conformation. Their structure function relationship in aqueous solution have already been reviewed [1]. Briefly, hydrocolloids alter the physical properties of a solution by gel formation, or thickening, emulsifying, coating, and stabilizing. The thickness of edible films and coatings is an important parameter since it directly affects the biological properties and the shelf life of the coated food. The effectiveness of edible films and coatings for protection of food depends primarily on controlling the spreading of the coating solutions, which affect the thickness of the film [2]. In the present study, the film forming ability of these hydrocolloids are investigated experimentally as well as numerically.

2. Description of the Experiments

The accurate measurement of film thickness is vitally important. A number of film thickness measurement methods have been developed and trialed for practical and achievable precision and reliability [3]. Various techniques for film thickness measurement have previously been investigated and described, such as needle contact method [4], electrical conductance method [5], capacitance methods [6], optical method [7], ultrasonic pulse echo method [8], and the fluorescence method [9]. Optical techniques are usually preferred for measuring thin film thickness as they are more accurate, non-destructive and require little or no sample preparation [10]. Laser based

*Corresponding Author: *m.s.miah@herts.ac.uk*

techniques are more reliable and suitable in most cases [11,12].

In the present study, the laser scan method was used to measure the liquid film thickness. The experimental measurements by laser scan method were made using FARO laser scanner as shown in figure 1. The experimental data were processed in the software package 'Geomagic Qualify 2012' that can process the 3D scanned images for dimensional analysis. The laser scan raw data were calibrated mechanically using a micrometre and a scaling factor was applied to get the accurate film thickness.

Fig.1: Faro laser scanner.

The experimental device designed and manufactured by Miah et. al. (2016) [13] was used in the current investigations. The experimental device consists of the main parts: like liquid bath, cylindrical shape experimental area, rotating disc, shaft and motor, as shown in Figure 2. The diameter of the disc is 54.46 mm, and the thickness is 3 mm. The disc is placed in the middle of the half-cylindrical experimental area of dimensions 40x80x40 mm shaped as semicircle. This experimental area is part of the bigger liquid bath (Bath container) where rest of the liquid is present. It is made on such a way to control the flow velocity of the liquid (into the limited area) from the liquid bath, so it can prevent any instability in the film formation caused by any kind of liquid velocity in the z- direction. The dimensions of the bath container are 100x100x40 mm.

This design ensures that enough liquid can be provided in the experimental area through the semi-circle hole while not interfering with the measurements. A high-quality DC motor ran the disc at rotating speed of 1 to 12 rpm with enough power to move the disc with the required accuracy and precision. The motor was attached to the disc through a metal shaft (stainless steel) of diameter of 6 mm. Also, the shaft and motor were placed on massive supports to maintain the rotating disc in the vertical position and to inhibit any unwanted vibration caused by the device.

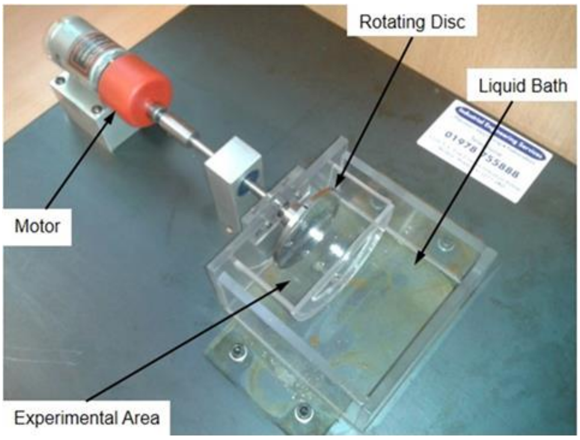

Fig.2: Small laboratory scale experimental rotating disc device for measuring the film thickness of aqueous hydrocolloid solution.

For the material of the rotating disc, stainless steel has been used to ensure the disc surface was smooth. The smooth surface of the rotating disc is important to achieve the accurate film thickness profile. The manufacturing company achieved the smooth surface of the disc by surface grinding. This machining process is mostly used to make any surface flat or smooth, and can achieve surface precision to within ±0.002 mm. The size of such remaining surface features is significantly smaller than the numerical grid size and would have a negligible effect on bulk flow. There could be some surface capillary effect on unwetted regions of the disc, but after flow stabilization, the effect should be minimal as the film thickness would be sufficiently greater than the channels formed by the surface features.

The liquid bath and the cylindrical shape were manufactured from clear polycarbonate material. The main reason for choosing this material is its easy machinability and cost effectiveness. Polycarbonate is a finished material, and it was used in both the liquid bath and cylindrical shape. All the components of the device were placed on a metal sheet with some rubber supports underneath to avoid the possible external vibrations during operation which may cause instabilities in film formation. During the experiments the device was kept on a sponge surface to avoid any extra vibration effect caused by the motor: the sponge surface used here was found pragmatically to have the capability to absorb the vibration effects experienced in this test set-up.

3. Experimental Results

Four different hydrocolloids with different viscosities but similar densities were studied. By changing the CMC concentration, it was possible to change its viscosity. This provided five different liquids to investigate experimentally. The properties are listed in Table 1, in decreasing order of viscosity.

The hydrocolloids used in the current study have significant applications in food processing industry. Therefore, their behaviour becomes important in industrial applications. Based on the CFD simulation results by Miah et. al. (2016) [13], the film thickness equation is simplified to identify the dominant terms in film formation as

$$h' \propto \frac{\mu^{0.3}\Omega^{0.54}}{\sigma^{0.1}\rho^{0.2}g^{0.32}} \qquad (1)$$

Where h' is dimensionless film thickness, μ is viscosity, Ω is rotating speed of the disc, σ is surface tension force, ρ is density and g are gravitational force. Equation (1) shows that the film thickness is dependent on two dominant factors: the viscosity and the rotating speed of the disc. The density and the surface tension force of the fluids used in this study were very similar therefore will not influence the film thickness.

Table 1

Properties of the hydrocolloids used in the experiments

Liquids	**Solution Concentration**	**Maximum viscosity μ (Pa.s)**	**Density ρ (kg/m3)**
Xanthan	1%	90	1031.5
Pectin	1%	8	995.6
CMC	1%	1.6	1005.7
CMC	0.5%	1.15	1005.7
Gum Arabic (EM 10)	1%	0.4	1062.4

The film thickness profile on the rotating disc was obtained by FARO laser scanner and processed in the software package 'Geomagic Qualify 2012' as shown in Figure 2(a) and 2(b). The different colors represent the film thickness variation at different positions on the disc surface. The film thickness at the radial and angular positions was obtained from the numerical ranges for different colors.

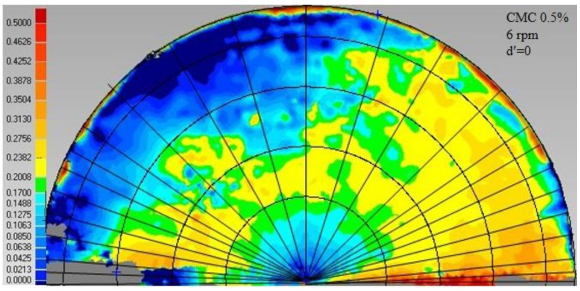

Fig.2(a): Film thickness distribution on the disc surface for CMC 0.5% concentration obtained from the laser scanner.

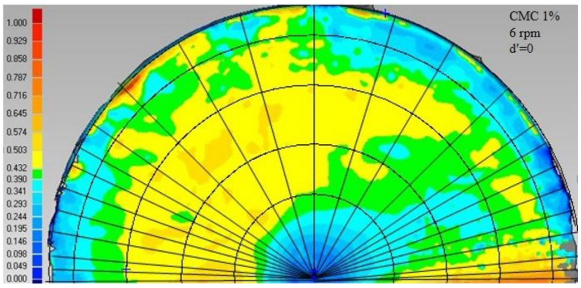

Fig.2(b): Film thickness distribution on the disc surface for CMC 1% concentration obtained from the laser scanner.

The graphical representation of the obtained film thickness profile can be seen in Figure 3 where the dimensionless film thickness (the film thickness was divided by the radius of the disc, and then multiplied by a factor of 10) is plotted in the x-axis against the angular positions in y-axis for a constant rotating speed. It is interesting to notice that the film formation trend and thickness are not similar for different hydrocolloids.

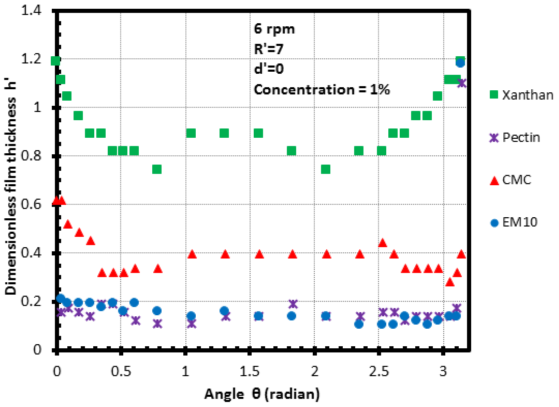

Fig.3: Film thickness profile for different hydrocolloids (xanthan, pectin, CMC and gum arabic (EM 10)) at 1% concentration.

The film thickness was higher at the beginning and started decreasing to a certain angular position then increased again. So, it was observed that the film formation was unstable at the drag out and drag in region of the rotating disc. A stable film formation was noticed at the angular position of 1-2.5 radian.

Xanthan has a higher film formation ability compared to the other hydrocolloids because of its higher viscosity. The film thickness formed by CMC was 90% higher than pectin despite pectin has five times more viscosity than CMC. Gum Arabic (EM10) had formed film of almost the same thickness on the disc, though pectin was twenty times more viscous than gum arabic (EM10).

When the concentration of CMC was changed from 1% to 0.5%, the film thickness reduced by 34% while the viscosity was decreased by 40% as shown in figure 4. All these results seem to be in conflict until one remembers that the fluid is non-Newtonian. Thus "viscosity" is only meaningful in terms of fluid flow rate. The rotating speeds were used in such way that the fluid flow persists a laminar flow.

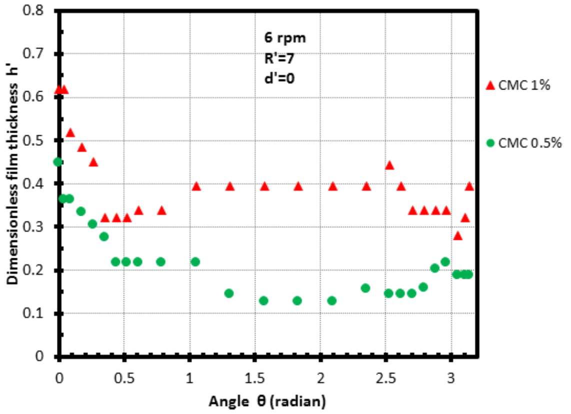

Fig.4: Film thickness profile for CMC 0.5% and CMC 1% concentrations.

The second dominant term in Equation (1) was the rotating speed. Its influence on the subsequent film thickness is shown in Figure 5. The film thickness increased by 56% at disc rotating speed of 6 rpm as compared to 3 rpm for CMC 1% concentration.

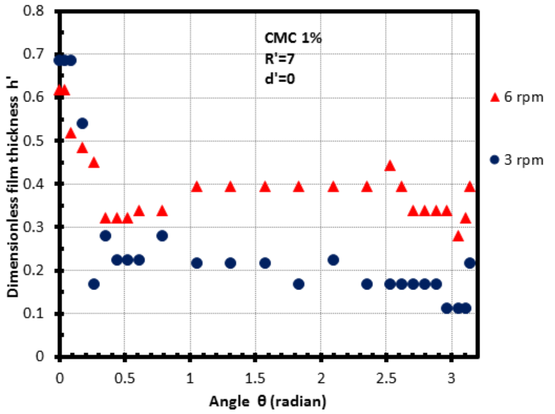

Fig.5: Film thickness variation with rotating speeds (3 and 6rpm).

The CFD model by Miah et. al. 2016, and Miah et. al. 2017 [13,14] has been used in the current investigation. The experimental results obtained by laser scan method are found to be consistent with those of the numerical simulation results using CFD method as shown in figure 6. The film thickness profile from the numerical results is slightly higher compared to the experimental results and this could be due to the numerical diffusions.

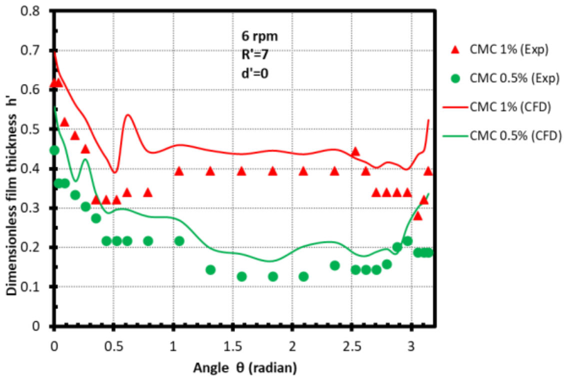

Fig.6: Film thickness comparisons of the experimental with CFD results at 0.5% and 1% CMC in water.

4. Conclusion

Hydrocolloids are the most widely used additive in the food industry that have a variety of properties and applications, including dietary fibre as well as gluten and fat substitutes. To keep the food product attractive for the consumers, the surface of edible films and coatings must appear uniform and without defects. The effectiveness of edible films and coatings for protection of food depends primarily on controlling the spreading of the coating solutions, which affect the thickness of the film. However, the classic methods such as dipping, spraying, solvent casting do not allow control of the film thickness. This study demonstrated that a uniform film thickness can be obtained using the rotating disc method. The experiments and simulations revealed that CMC has a very good film forming ability. A higher concentration of CMC can produce more stable film formation. The experimental and simulation results revealed that the film formation on the rotating disc is controlled by the main factors such as rotating speed, concentration, and molecular structure of the hydrocolloids. Thus, a stable and uniform film thickness is achievable by adjusting the main dominating factors.

Acknowledgement

The authors wish to acknowledge the experimental facilities provided by Wrexham University, Wrexham, UK, to the project.

References

[1] Al-Assaf, S.; Phillips, G. O. Hydrocolloids: Structure function relationships. *J Food Science and Technology*. **2009**, *23* (3), 17–20.

[2] Verma, A. k.; Hasan, M., Mangaraj, S.; Pravitha, M.; Verma, D. K.; Srivastav, P. P. Trends in Edible Packaging Films and its Prospective Future in Food: A Review. *Applied Food Research*. **2022**, 2, 100–118.

[3] Han, Y.; Shikazono, N. Measurement of liquid film thickness in micro square channel. *Int. J. of Multiphase Flow*. ***2009***, *35, 896–903.*

[4] Vijayraghvan, K.; Gupta, J. P. Thickness of the film on a vertically rotating disk partially immersed in a Newtonian liquid. *Industrial Eng. Chem. Fundamentals.* **1982**, 21, 333–336.

[5] Coney, M. The theory and application of conductance probes for the measurement of liquid film thickness in two phase flow. *J.Phys. E. Sci. Instrum.* **1973**, 6, 903–910.

[6] Thorncroft, G. E.; Klausner, J. F. A capacitance sensor for two-phase liquid film thickness in a square duct. *Trans. ASME, J. Fluids Eng.* **1997**, *119,* 164–169.

[7] Garapon, S. G.; Heid, G.; Lavergne, G.; Simonin, O. Thin wall liquid film thickness measurement: A video optical technique. *Proceedings of PSFVIP-4 June.* **2003**, 3–5.

[8] Park, J. R.; Chun, M. H.; Lee, S. K. Liquid film thickness measurement by an ultrasonic pulse echo method. *J. of the Korean Nuclear Soc*. **1985**, *17* (1), 25–33.

[9] Morton, C. E.; Baker, R. C.; Hutchings, I. M. Measurement of liquid film thickness by optical fluorescence and its application to an oscillating piston positive displacement flowmeter. *Measurement Science and Technology*. **2011**, 1–11.

[10] Sung, L.; Jasmin, J.; Gu, X., Nguyen, T.; Martin, J. W. Use of laser scanning confocal microscopy for characterizing changes in film thickness and local surface morphology of UV-exposed polymer coatings. *JCT Research.* **2004**, 1 (4), 267–276.

[11] Oliveira, F. S.; Yanagihara, J. I.; Pacifico, A. L. Film thickness and wave velocity measurement using reflected laser intensity. *J. Of the Braz. Soc. Of Mech. Sci. & Eng.* **2006**, *28* (1), 30–36.

[12] Wegener, J. L.; Drallmeier, J. A. Measurement of thin liquid film characteristics using laser focus displacement instruments for atomization applications. *ILASS-Americas 22nd Annual Conference on Liquid Atomization and Spray Systems, Cincinnati, OH.* **2010**, 1–14.

[13] Miah, M. S.; Assaf, S. A.; Yang, X., McMillan, A. Thin film flow on a vertically rotating disc of finite thickness partially immersed in a highly viscous liquid. *Chemical Engineering Science.* **2016**, 143, 226–239.

[14] Miah, M. S.; Hossain, M. S.; Ashraf, M. A.; Assaf, S. A.; McMillan, A. Numerical simulation of non-Newtonian polymer film flow on a rotating spoked annulus. *Journal of Applied Polymer Science*, **2017**, 134, 44943.