

MIXING AND HEAT TRANSFER

INTRODUCTION AND SCOPE

Read: Geankopolis Sections 3.4, 3.5J, 4.1A, 4.1C 4.3D, 4.5, 4.13

Mixing and heat transfer in agitated vessels in both batch and continuous processes are fundamental operations for the chemical, biochemical and food processing industries. The mixing process, especially for liquids, is often complemented with a heating/cooling operation in order to reach the specifications required for a particular process or product. Sometimes the purpose of heat may be to assist with mixing (e.g. while dissolving a solid into a liquid). Other times the purpose of the mixing may be to assist with the heat transfer. One of the most common pieces of equipment is an agitated vessel supplied with a surrounding heating/cooling jacket that provides or removes heat by using either steam or a cooling fluid. Stirred vessels are ubiquitous equipment in industry and come in a variety of sizes, materials of construction and impellers design.

Agitation Vessels. Agitation refers to mechanically forcing a fluid to move around (e.g. in a circular pattern) in a tank or vessel. Mixing is a physical process used to reduce heterogeneity of fluids by eliminating gradients in concentration, temperature and other properties. Industrial processes commonly use agitation vessels to conduct mixing. The geometry of the tank/impeller, the agitation speed (how quickly the impeller rotates), and the physical properties of the fluid strongly influence how quickly mixing occurs (the mixing time) and how much power is required.

For this lab, we will use two different agitated vessels: Hamilton-kettle and Groen. Each group will use only one of the vessels. The main focus of the lab is to find a correlation between the heat transfer coefficient and the agitation speed for a non-Newtonian fluid (solution of 0.5% xanthan gum). Additionally, the relationships between power consumption, agitation speed, rheological properties of the fluid, and mixing time will be studied. This information would be important for design and operation of a vessel for bacterial fermentation.

AIMS

- Study the dependence of the viscosity of a xanthan gum (XG) solution on temperature and agitation speed.
- Develop a correlation between the power consumption of the mixer and the agitation speed.
- Analyze the relationship between mixing time and the different agitation speeds developed by the agitated mixer.
- Develop a correlation based in dimensionless analysis to predict the heat transfer coefficient at the jacketed well at different agitation velocities.

THEORY AND BACKGROUND

Mixing Time. The mixing time refers to the time for a heterogeneous material to become homogeneous during a particular mixing process. Empirically mixing time can be measured using a tracer and measuring its concentration along time until a steady state of the system is achieved. Some tracers widely used are acids, bases or highly concentrated salt solutions. In our case, mixing time will not be measured empirically; but rather calculated based on previously determined correlations reported in literature using

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different Reynolds numbers (Re) developed during mixing. Intuitively it makes sense that mixing time will depend on factors such as the geometry of the vessel, the viscosity of the fluid, and extent of agitation, which are accounted for in the Reynolds number.

Impeller Reynolds Numbers (3.4E, 3.5J). For Newtonian fluids, the Reynolds number for tank/impeller agitators is defined as.

$$N'_{Re} = \frac{D_a^2 N \rho}{\mu} \quad (1)$$

Where D_a is the diameter of the agitator impeller (m), N is the impeller rotational speed (revolutions per second), ρ is the density of the fluid (kg/m^3), and μ is the viscosity of the fluid (kg/m-s). For non-Newtonian fluids, such as XG, viscosity varies with shear rate and therefore agitation speed. For non-Newtonian fluids during agitation, then we will use the average apparent viscosity, μ_a , to calculate the Reynolds number of the impeller.

$$N'_{Re,n} = \frac{D_a^2 N \rho}{\mu_a} \quad (2)$$

Note that viscosity will also depend on the concentration of solution and temperature. We will be mixing and heating in this lab, so we will need to understand the average apparent viscosity at different temperatures as the temperature changes during the experiment.

Viscosity of Non-Newtonian Fluids Under Agitation (take special note of 3.5J).

When we apply a force (in this case with our impeller) to move a layer of liquid (such as the fluid layer nearest our impeller), we define the force per unit area as the shear stress (τ) in units of pressure. How fast that layer moves relative to adjacent layers is a velocity gradient (dv/dx), which we define as the shear rate ($\dot{\gamma}$) in units inverse time [$\text{m/s} / \text{m} = \text{s}^{-1}$]. Newton postulated that the velocity gradient would be proportional to the force applied. So we call materials for which this holds true, Newtonian fluids. This linear relationship between shear stress and shear rate breaks down for many biological and food materials. You will study these concepts in more detail during the Rheology lab.

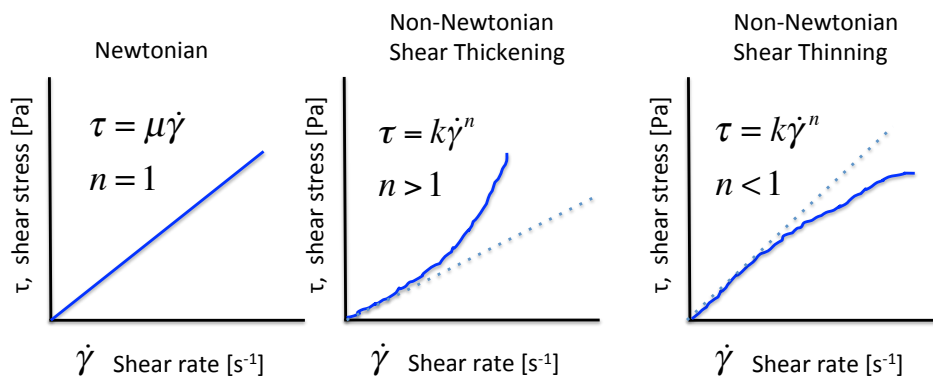


Figure 1. Typical shear stress versus shear rate curves for a Newtonian (left), Non-Newtonian shear thickening (middle), and Non-Newtonian shear thinning fluids.

In this lab you will use xanthan gum, which is a non-Newtonian (shear thickening) fluid. The relationship between shear stress and shear rate follows a power law form:

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$$\tau = K(\dot{\gamma})^n \quad (3)$$

*(*note that the shear rate sign is relative to the frame of reference, therefore you may see this relationship with or without the minus sign depending on how the shear rate is defined)*

The viscosity decreases as the shear rate increases. We can find an average apparent viscosity of the fluid by the relationship:

$$\mu_a = K(\dot{\gamma})_{ave}^{n-1} \quad (4)$$

Researchers have experimentally determined relationships between shear rate and the rotational speed of the agitator. For an agitator mixer, the shear rate, has been shown to be directly proportional to the shaft rotation speed (N, in revolution per s). The non-dimensional constant, known as the shear rate coefficient (Ks), has been measured for a wide variety of tanks and impellers, and generally varies between 2 and 14 are typical (Wu, 2006). For the vessel and impellers used in this lab, we will assume a $K_s = 11$. In this lab you will vary the agitator speed and can therefore estimate the shear rate from this relationship.

$$(\dot{\gamma})_{ave} = 11N \quad (5)$$

The average apparent viscosity (μ_a) can therefore be found from in Equation 6 (see pg 170 in Geankopolis).

$$\mu_a = K(11N)^{n-1} \quad (6)$$

If we determine K and n for our fluid without rotation using Equation 2, we can estimate the average apparent viscosity by the empirical relationship in Equation 6 for a given agitation rate. In addition the viscosity of a fluid and therefore the rheological parameters, K and n, will vary with temperature.

Power Consumption of Agitation. The energy cost of agitation and mixing is an important factor to consider in industrial operations. Frequently, electrical power is used to drive impellers in agitated vessels. The power required depends on the resistance of the fluid to the rotation of the impeller. Therefore the fluid properties (viscosity, density), the rate of impeller rotation, and the impeller geometry will again influence the power just as they do for mixing time. During this lab, you will experimentally measure the relationship between the power consumed and the velocity of the agitator for a certain impeller diameter and geometry. This relationship will be expressed as a power curve, relating the dimensionless power number, N_p , as a function of the impeller Reynolds number, N'_{Re} . The power number is a dimensionless number, which is a ratio of the power consumption (P), which you will measure, and fluid/impeller properties. You can find the equation for power number in agitation and example power curves for Newtonian and non-Newtonian fluids in your reading.

Heat Transfer (4.1A). You will be using a steam-jacketed kettle to heat the XG solution during the experiment. An energy balance for heat transfer in an agitated vessel (without a chemical reaction) is represented by:

$$q_{in} = q_{out} + q_{loss} + q_{accum} \quad (7)$$

where q_{in} is the rate of heat transfer from the steam to the fluid, q_{out} is energy of the water that leaves the vessel and q_{accum} is thermal energy that is accumulated by the fluid into the vessel.

The q_{in} for our system can be described as:

$$q_{in} = UA(T_s - T_f) \quad (8)$$

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Where T_s is the temperature for the steam, and T_f is the temperature at a specific point in the fluid being mixed. Note that T_s will be constant as you are using saturated steam at a constant pressure, while T_f will vary with time.

The overall heat transfer, U , represents the inverse of the sum of thermal resistances of the system and is a function of the heat transfer coefficient from the fluid to the tank (among others).

Heat transfer in an agitated vessel is complex and varies depending on the system. Due to this complexity it is necessary to use an empirical approach based on dimensionless analysis to find a correlation and predict the heat transfer coefficient at the jacketed wall given the agitation velocity. Empirical heat transfer coefficients have been developed for jacketed vessels. One widely used dimensionless number is the Nusselt number (Nu), depicted in Equation 9. The Nusselt number is a dimensionless number that relates the convective to conductive heat transfer across a boundary. Equation 8 relates the Nusselt number to the Prandtl number, Reynolds number and viscosity ratio.

$$Nu = a * Re^b * Pr^c * Vi^d \quad (9)$$

Where Pr is the Prandtl number and Vi is the viscosity ratio of the bulk fluid viscosity to the fluid viscosity at the interface (e.g. the tank wall). The Prandtl number relates the ability of a fluid for momentum transportation to the ability of that fluid for energy transportation. The relation of viscosities (Vi) accounts for the differences of viscosity with the temperature. For instance, the viscosity of the fluid near a hot wall will be different to the viscosity of the same liquid at the bulk of the mixer where the temperature is lower.

PROCEDURE

For all the experiments a solution of 0.5% w/w of xanthan gum in water will be used.

Rheological analysis: Data of shear rate and shear stress for xanthan gum solution at different temperatures (ranging from 30°C to 80°C) is provided to determine the viscosity of the solution at different temperatures. This data will be needed to develop the dimensionless analysis).

Power consumption- Heat transfer & agitation:

1. Document your kettle/impeller type and make measurements of key dimensions. Sketch a diagram of the apparatus in your lab notebook.
2. Connect the outlet plug from the vessel in the wattmeter and then the wattmeter to an electrical outlet. Be careful to maintain all the electrical connections protected and away from the floor in case there is a spill.
3. Turn the agitation system on and check that the wattmeter is recording the power consumption.
For power consumption, Hamilton-kettle and Groen jacketed vessels will be used. The vessels possess a stirring system with adjustable velocity. Agitation velocity will be set up manually and the actual speed (in rpm's) of the agitator will be measured using a tachometer.
4. Fill the vessels with the XG solution keeping track of the total volume of solution you are adding into the vessel. Do not overfill the vessel (1/2 to 2/3 of total height is a good estimate).
5. Check that the thermometer is working (at this point should be measuring room temperature)
6. Close the vessel.

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7. At this point you might start the heating-cooling process with agitation. Remember all the precautions to work with steam.
 - a. You will measure agitation speed, power consumption and temperature vs. time starting at 30°C to 80°C. The heating process is very fast so have the timer ready.
8. Start the agitation and measure the agitation speed (before opening the steam), record the power consumption.
9. Turn the agitation off to purge the steam line.

PURGE STEAM LINE:

1. Open the outlet of the jacket, let all the liquid inside drain and close it. Open the steam valve and adjust it to have a constant pressure of 20 psi, let the steam flow until you see steam in the steam trap. Assume that the steam is saturated; hence the pressure will need to be constant to have a constant heating temperature.
 2. Turn the agitation on and start recording time vs. temperature starting at 30°C to 80°C at 10°C increments.
 3. Close the steam valve at 80°C and reset the timer.
 4. Open the cooling water and let the system reach a temperature below 30°C. Note that this process will be slow. At the end of the experiment, close the cooling water valves and if needed drain the water remaining in the cooling jacket.
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Adjust other agitation speed and record heating and cooling time as stated before. Five different agitation speeds will be needed for the correlation.

DATA ANALYSIS

Rheology

- Use the provided rheological properties of the fluid to determine K and n at different temperatures. Analyze the trend obtained to confirm that XG behaves like a non-Newtonian fluid.
- With the constants calculated at different temperatures (K and n), find the average apparent viscosity for the different agitation velocities. Analyze how average apparent viscosity changes with agitation speed and temperature.

Reynolds Number

- Calculate the impeller Reynolds number using the apparent viscosity (at 30°C) formerly found using Equations 2 and 3 at different agitation speeds.

Power Number

- Calculate the power number and generate a plot of N_p vs $N'_{Re,n}$. Contrast and analyze your results to what is reported in Geankopolis. Find and cite the original literature paper for this curve. Does your curve make sense? Why or why not?

Mixing time

- Use the previously calculated Reynolds number to determine the mixing time using the method and charts described in Geankopolis. Find and cite any relevant original work.
- How does mixing time vary with agitation and temperature?

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Heat transfer

After the heat transfer balance (and simplifications) from the background section (and prelab) you will have an equation as a function of the variables dT/dt and other known constants.

The resulting equation will be integrated taking as temperature limits T_{steam} and T_o (initial).

The resulting integrated equation will be a function of time (t) and $\ln[(T_s - T_o)/(T_s - T_f)]$, being time the recorded time and T_f the fluid temperature from your experimental data. The other parameters required (such as C_p) will be evaluated at initial T_o to simplify the calculations. The vessel area also required can be roughly calculated assuming a perfect half sphere.

Plot the experimental results as $\ln[(T_s - T_o)/(T_s - T_f)]$ against time, to obtain U from the slope of the best-fit line. The collected values of T and t for different agitation speeds will be used generate different values for h_i .

With the data of agitation speed vs. h_i , you will generate your own coefficients (a and b) for the dimensionless equation for the Nusselt number, shown by Equation 9.

To calculate Re and Pr and Vi use the values of the liquid properties $T_o(30^\circ\text{C})$, for the viscosity use the value found the lowest agitation speed. Additionally, for the Vi term use the viscosity at 75°C as the fluid viscosity at the heat transfer surface.

$$Nu = a * Re^b * Pr^c * Vi^d \quad (9)$$

Assume $c=1/3$ and $d=0.21$. Plot Nu (which is function of h_i) vs. $Re*Vi*Pr$ (Re is function of agitation speed) to obtain a and b from the best-fit regression line. Compare the results with the coefficients reported in literature for similar agitated vessels.