Handling Shear-Sensitive Fluids

by James F. Steffe (Michigan State University)

and Christopher R. Daubert (North Carolina State University)

Shear-sensitive fluids have a structure that may be altered when subjected to mechanical energy inputs. Many biological fluids are shear-sensitive; hence, it's important for engineers to have quantitative methods to evaluate this phenomenon for process design and scale-up. The issue is addressed here by presenting the concepts of shear work and shear power intensity.

Emulsions provide a good example of shear-sensitive fluid behavior. A stable emulsion may be created by homogenization which is a very high energy input process. On the other hand, excessive energy input during the handling of a fluid such as mayonnaise may destroy the emulsion by causing oil droplets to coalesce. Fluids containing fragile particles also require careful consideration of energy inputs as well as an analysis of the maximum shear rates (not covered in this article) found in the process.

Let's consider two processing example problems: gentle mixing of cream in a 132 liter tank (500 gal tank: a cylinder approximately 5 feet in diameter and 3.5 feet tall) during batch pasteurization, and the homogenization of milk. We'll calculate the shear work and shear power intensity of these processes that fall on opposite ends of the energy input spectrum.

132 liters (with a mass of 1817 kg) of cream were held in a steam-jacketed tank equipped with an anchor impeller turning at 20 revolutions per minute. The fluid was pasteurized (heated, held at the pasteurization temperature, and cooled) over a total

process time of 165 minutes or 9900 seconds. An average power input of 200 Watts was determined using an established relationship between the impeller Reynolds number and the power number for this type of mixing system. The shear work imparted to the cream during the process was found using this information:

$$\text{Shear Work} = \frac{(\text{power})(\text{time})}{\text{mass}} = \frac{(200\text{ W})(9900\text{ s})}{1817\text{ kg}} = 1090\text{ J/kg}$$

This means that tank agitation (irrespective of thermal inputs from pasteurization) contributed 1090 J of energy to each kg of cream. The energy is dissipated as frictional heat.

Shear power intensity depends on the power dissipated per unit volume of fluid. Recognizing that a 190 liter tank has a volume of 1.89 cubic meters, shear power intensity is easily calculated:

$$\text{Shear Power Intensity} = \frac{\text{power}}{\text{volume}} = \frac{200\text{ W}}{1.89\text{ m}^3} = 106\text{ W/m}^3$$

Shear power intensity is the rate of energy input (recall that a watt is energy per unit time, i.e., a joule per second) per cubic meter of fluid. Tank agitation with an anchor impeller is very gentle process resulting in low values of shear work and shear power intensity. Fat globules in the cream would not be damaged in this bioprocessing operation. This example would apply equally well to a fermentation vessel where adequate agitation is needed for the distribution of nutrients, but energy inputs must low enough to avoid damage or stress to the fermentation organisms.

Homogenization is designed to create an emulsion. Fat globules in raw milk typically vary from 1 micron to 10 microns in diameter. Most fat particles in homogenized milk are less than 1 micron in diameter. This reduction in particle size creates a tremendous increase in surface area resulting in a stable emulsion. Homogenizers work by forcing fluid through a very small space at a very high velocity. The Michigan State University Dairy Plant has a homogenizer that operates at 159 liters/hr (600 gph) and generates a pressure drop of 10,343 kPa (1500 psi) over the first stage of the unit (It's a two stage homogenizer and we will only consider the first stage.). The spatial volume between the valve and the valve seat is approximately 1.9 x 10^-8 cubic meters. This is very small – about 1/18 the volume of a US penny – and has a shape resembling a compressed torus. Milk travels through this region at velocities exceeding 110 m/s, and stays in the gap for about 24 microseconds!

The shear work imparted to the milk during homogenization is calculated from the pressure drop across the valve and the density of the milk:

$$\text{Shear Work} = \frac{\text{pressure drop}}{\text{density}} = \frac{10{,}343{,}000\ \text{Pa}}{1020\ \text{kg/m}^3} = 10{,}140\ \text{J/kg}$$

The mass flow rate (0.644 kg/s) is needed to determine the power dissipation in the valve:

$$\text{Power Dissipation} = \frac{(\text{pressure drop})(\text{mass flow})}{\text{density}} = \frac{(10{,}343{,}000\ \text{Pa})(0.644\ \text{kg/s})}{1020\ \text{kg/m}^3} = 6530\ \text{W}$$

Using the above figure and the volume, the shear power intensity is calculated:

$$\text{Shear Power Intensity} = \frac{\text{power}}{\text{volume}} = \frac{6530\ \text{W}}{1.9\ \text{x}\ 10^{-8}\text{m}^3} = 3.4\ \text{x}\ 10^{11}\ \text{W/m}^3$$

Results show the enormous energy per unit volume necessary to ensure proper fat globule break-up for emulsion formation in homogenized milk. Shear power intensity in the first stage of the homogenizer is 9 orders of magnitude greater than the value found for tank mixing!

Gentle mixing and homogenization are at opposite ends of the mechanical input spectrum. To thoroughly evaluate the handling of a shear-sensitive fluid, all equipment is a processing system must be evaluated. Shear intensity can be very high in pneumatic valves and contractions but low in magnetic flow meters and long sweep elbows. Centrifugal pumps, which operate by converting kinetic energy to pressure energy, may severely damage shear-sensitive fluids. Other pumps, such as a diaphragm pumps or a progressing cavity pump, effectively transport biological fluids with little mechanical damage.

Shear work and shear power intensity can be calculated for any component of a fluid handling system. Rheological properties, equipment characterization, and sound analytical methods are needed for the successful evaluation of an overall process. For complete details and example problems, consult the authors recently published book: Steffe, J.F., and C.R. Daubert. 2006. ***Bioprocessing Pipelines: Rheology and Analysis***. Freeman Press. East Lansing, MI