**Chapter 1: Viscosity**

1. Introduction
   1. Viscosity is a flow property of fluids.
      1. Resistance of fluid to flow.
         1. Low viscosity = flow easily, i.e. milk, juice
         2. High viscosity, i.e. honey, syrup
      2. Measurement characterizes flow behavior of food systems.
         1. Pumps supply energy to overcome frictional losses of fluid.
            1. Frictional losses are volumetric flow rate and magnitude of viscosity.
            2. As fluid viscosity increases, frictional losses increase, more energy required.
         2. Viscosity may determine choice of pump, heat exchanger, packaging equipment.
         3. Texture of food determined by viscosity.
2. Newton’s Law and Viscosity
   1. Fluid vs. Solid
      1. When subjected to a stress or applied force.
         1. Stress = force per unit area
         2. Elastic solid deforms by amount proportional to applied stress
         3. Fluid continues to deform, flows at velocity that increases with increasing stress.
      2. Fluid resists the stress with viscosity.
      3. Viscous forces due to intermolecular forces in fluid
      4. Similar to shear forces in solids.
   2. Parallel Plate example
      1. Bottom plate moves parallel to top plate with a constant velocity due to steady force applied.
         1. Force is viscous drag.
      2. Plates are y distance apart.
      3. Each layer of liquid moves in z direction.
         1. Layer immediately adjacent to plate moves at the same velocity as the plate.
         2. Layer above is slightly slower.
         3. Each layer slower and slower until top plate is reached.
      4. Velocity profile linear with y direction.
         1. Deck of playing cards sliding analogy.
   3. Experimental equation
      1. Equation 1: F/A = -μ dvz/dy
         1. μ is proportionality constant: viscosity, units Pa.s, or kg/m.s.
         2. F/A is shear stress (force per unit area)
         3. dvz/dy is rate of deformation, rate of change of distance between neighboring points moving with the fluid divided by the distance between the points
         4. Allow dy to approach 0 to get Equation 2
      2. Equation 2: τyz = -μ dvz/dy
         1. Τyz = F/A, shear stress, units N/m2
         2. Shear stress is proportional to rate of deformation (aka rate of strain), proportionality constant is viscosity.
   4. Units of viscosity
      1. SI: N.s.m-2
      2. Literature: Poise (P) or centipoise (cP)
         1. Water has viscosity of 1 cP at 20°C
   5. Viscosity of gases vs. liquids
      1. Gases
         1. Newtonian fluids
         2. Increases with temperature
         3. Independent of pressure up to 1000 kPa
      2. Liquids
         1. Decreases with increasing temperature
         2. Incompressible, independent of pressure
      3. Solutions
         1. Viscosity increases as solute concentration increases
         2. Proteins more effective than salts and minerals.
3. Effect of Temperature
   1. Liquids decrease in viscosity as temperature increases.
      1. 2% change in viscosity for each °C change in temperature
      2. Important to control temperature during experimental measurement of viscosity.
      3. Fit experimental data to account for variation of viscosity with temperature
         1. Equation 3: log(μ) = B/T + C
            1. T is absolute temperature
            2. B and C are constants for a fluid
4. Kinematic Viscosity
   1. **v** = ratio of viscosity and density of a fluid
      1. Dimensions: L2T-1
      2. Units: stoke (St)
5. Relative Specific and Intrinsic Viscosities
   1. Emulsions, Suspensions, and Solutions
      1. Viscosity measured in comparative terms (compared with the pure solvent)
      2. Example: Relative viscosity
         1. Equation 4: ηr = ηs/η0 = 1 + kՓ
            1. ηr is relative viscosity of suspension
            2. ηs is viscosity of suspension
            3. η0 is viscosity of solvent
            4. k is a constant
            5. Փ is volume fraction of the dispersed phase
         2. In dilute solutions, volume fraction proportional to solute concentration.
            1. Equation 5: ηr = 1 + kc

C is the concentration

* + 1. Specific viscosity: ηsp
       1. Increment due to addition of solute
       2. Equation 6: ηsp = ηr - 1 = kc
    2. Ratio of specific viscosity and concentration is reduced viscosity or viscosity number
    3. Intrinsic viscosity is limiting value of reduced viscosity as concentration approaches zero.
       1. Units = m3kg-1 or mlg-1
       2. For spherical particles in dilute solutions, reduced viscosity = 2.5 (Einstein).
    4. Effect of dispersed particles on viscosity
       1. Non-rotating particles slow down the liquid.
       2. Rotating particle keeps liquid flowing, but energy goes into rotation, slowing down the liquid.
       3. Viscosity of suspension:
          1. Equation 7: ηs = η0(1 + kՓ)

K = 2.5 for spheres)

* + - 1. Intrinsic viscosity [η]:
         1. Equation 8: [η] = kNvh/M

For rigid macromolecules:

Equation 9: vh = v2 + δv1

v2 and v1 are specific volumes of macromolecule and solvent respectively

δ is weight of solvent per unit weight of macromolecule

For flexible macromolecules:

Equation 10: [η] = KMs

Exponent s depends on shape of molecule (i.e. sphere = 0)

1. Intrinsic Viscosity as a Measure of Molecular Weight
   1. Finding molecular weight with intrinsic viscosity
      1. Equation 11: [η]ici = KMiaci
         1. [η]i is intrinsic viscosity of species of molecular weight Mi (see Equation 10)
         2. ci is concentration in gms per cc
      2. Equation 12: [η] = K∑Miaci/∑ci
         1. c = ∑ci
      3. Viscosity average: Equation 13: [η] = KMava
      4. Equation 14: Mav = (∑Miaci/∑ci)1/a
         1. Average viscosity = average molecular weight if a = 1
         2. For values of a < 1, falling between number and weight average molecular weights.