ENG H191: Hands on Labs
Transport Phenomena
Engineering Disciplines Explored: Chemical, Aeronautical, Biomedical

MOTIVATION
Engineering Applications
The movement and use of energy in various forms is of concern to all engineering disciplines at some level. It is the basis of an area of study known as thermodynamics in which one learns that in any process (except those involving nuclear fission) energy is neither created nor destroyed. However, keeping track of the various forms of energy in a process is a complicated task.

Chemical, civil, aerospace, biomedical, and mechanical engineers (and all others to some extent) are interested in the movement of energy, mass and momentum from place to place. The collective study of these movement processes is called “transport phenomena”. This term simply conveys the fact that many transport processes in science and engineering are caused by forces that can be described by the same general equations. For example, the same mathematical equations that describe how heat transfers away from an integrated circuit chip can be used to describe how temperature changes in a chemical reactor. In biomedical applications, the transport processes of the human body, ruled by the same relationships, dictate different treatments. Savvy engineers are able to recognize these similarities and study them as the related fields they truly are.

Objectives
- Demonstrate an understanding of fluid flow
- Describe a fluid based on observed or derived characteristics
- Demonstrate an understanding of the power of data acquisition systems
- Demonstrate an analytical perspective on acquired data

Basic Principles
This lab write-up will cover the following basic principles:
- Types of Transport Phenomena
- Rheology
- Fluid Classification
- Types of Flow

Lab Experience
The lab experience will include observation and experimentation with:
- Viscous Fluids
- Falling Ball viscometers
- Data Acquisition systems
- Excel

FUNDAMENTALS

Driving Forces of Transport Phenomena

One of the basic principles in all transport phenomena calculations is that the rate of transport is directly related to the measured driving force. For example, in transport of momentum (fluid flow), pressure is the driving force and a difference in pressure between two points causes fluid to flow. Similarly in transport of energy (heat transfer) the rate of movement of heat energy from a hot body to a cold body is related to the difference in temperatures between the bodies. The exact formulation of these equations is very complex and beyond the scope here, however it is useful to recognize the relationship.

Rheology

Rheology is the science of deformation and flow of matter. It describes the material properties of fluids (including gases) and semi-solid materials. Rheology is interdisciplinary and is used to describe interrelation between applied force (or stress), deformation, and time for a wide variety of materials such as oils, food, inks, polymers, clays, concrete etc. The common factor is that these materials exhibit some type of inelastic deformation or "flow" under stress and, therefore, cannot be treated as solids.

Fluid rheology is used to describe the consistency of different products, normally by the two components viscosity and elasticity. Viscosity describes resistance of a fluid to flow and can be thought of as its thickness. For example, the viscosity of molasses is higher than the viscosity of water. It can be measured in several ways. Elasticity describes the fluid's "memory" and results in a delay of the fluid's reaction to stress. Viscosity is often difficult to determine directly and must be calculated based on other observed characteristics of a fluid.

Shear Force and Shear Rate

A shear force is one that acts parallel to the plane in which is lies. For example, sliding a playing card across a table has a force component perpendicular to the table (from gravity) and a shear force parallel to the table (force from you pushing and friction between the table and the card.)

The shear rate is simply the rate of shear motion between two substances. For instance, sliding your hand across a table slowly creates bit of heat from friction while sliding your hand at a faster rate produces more heat.

Fluid Classifications

Based on flow behavior, fluids are normally divided into different groups.

- Newtonian fluids – viscosity is dependent only on temperature
  Examples: Water, milk, sugar solution, mineral oil

- Non-Newtonian fluids (time independent) – viscosity is dependent not only on temperature but also on shear rate. Depending on how viscosity changes with shear rate, the flow behavior is characterized as:
  - Shear thinning – viscosity decreases with increased shear rate
    Examples: Paint, shampoo, fruit juice concentrates, molten plastic

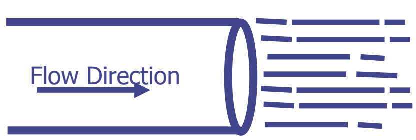
  - Shear thickening – viscosity increases with increased shear rate
    Examples: wet sand and concentrated starch suspensions

  - Plastic – exhibits a so-called yield value, *i.e.* a certain shear stress must be applied before flow occurs
    Examples: toothpaste, hand cream, grease

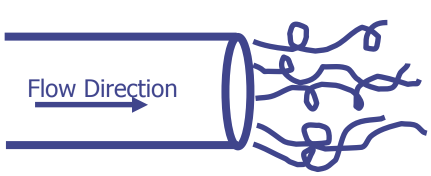
- Non-Newtonian fluids (time dependent) – viscosity is dependent on temperature, shear rate and time. Depending on how viscosity changes with time the flow behavior is characterized as:
  - Time thinning - viscosity decreases with time
  Examples: yogurt, paint
  - Time thickening - viscosity increases with time (rare)
  Example: gypsum paste, printers ink

Fluid Flow

Fluid flow deals with transport of momentum. A flow occurs when there is a difference in pressure between two areas, and the flow is from a higher pressure point to a lower pressure area. Fluid flow is typically described as being laminar (streamlined with layers of similarly moving molecules) or turbulent (chaotic movement). See Figure 1. The equations that will be used in this lab assume laminar flow, although a means of confirming whether flow is laminar or turbulent is provided using Reynold's number.



LAMINAR FLOW (MOLECULAR)
If pressure drop is small
- flow will be relatively small and laminar
- fluid motion is smooth (ordered fashion) and transfer of momentum is molecular



TURBULENT FLOW (EDDY)
If pressure drop is large
- flow will be relatively large
- fluid motion is chaotic and transfer of momentum occurs through blocks of molecules (called eddies) moving in all directions

Terminal Velocity

The terminal velocity of a falling object is the speed at which all forces are equal and the object ceases to accelerate. Skydivers reach a terminal velocity when the force of wind resistance slowing their descent exactly counters the force of gravity.

Newtonian Fluid Properties and Relationships

These equations should be used to find Reynolds' number and the viscosity of the fluid, based on the terminal velocity. Many needed constants are provided on the next page, or on the worksheet. A sample calculation is done later in the write-up.

Stokes Theorem

Ideally, Stokes theorem states $\mu_f = \frac{d_s^2}{18V_t}(\rho_s - \rho_f)g$, but this is only valid when the fall is in an infinite environment without inertial effects. The lab is not an infinite environment without inertial effects, so we must approach the viscosity using a different method. The following equations can find the viscosity by correcting for the finite environment.

Reynold's number (dimensionless, must be <<1 to indicate laminar fluid flow around an object such as a sphere for the remaining relationships to hold true)

$$R_e = \frac{d_s V_t \rho_f}{\mu_f}$$

Terminal velocity

$$V_{t,theoretical} = \frac{2r_s^2(\rho_s - \rho_f)g}{9\mu_f}$$

Ratio of experimental velocity to theoretical velocity (wall effects correction)

$$\frac{V_{t,theoretical}}{V_{t,\exp erimental}} = 1 + 2.1044\frac{d_s}{d_c}$$

Volume of Sphere:

$$v_s = \frac{4\pi r_s^3}{3}$$

Density of sphere

$$\rho_s = \frac{M_s}{v_s}$$

Constants used for the Lab Experience

NOTE: In this lab, all units should be converted to meters (m), kilograms (kg), seconds (s), kilograms per meter-second^2 (kg/m-s^2) for pressure, and kilograms per meter-second (kg/m-s) for viscosity.

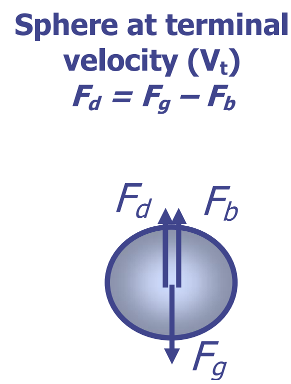
1" = 2.54 cm.
1 cm^3 = 1mL.
Pressure: 1 Pa = 1 N/m^2 = 1 (kg/m^2)(m/s^2) = 1 (kg/m-s^2).
Viscosity: 1 Pa-s = 1 N-s/m^2 = 1 (kg-s/m^2)(m/s^2) = 1 (kg/m-s).

Symbol	**Name**	**Constant Given**	**Preferred Units**
R_e	Reynold's number	TBD	unitless
d_s	Diameter of sphere	1/8"	m
V_t	Terminal velocity	TBD	m/s
ρ_f	Density of fluid		kg/m^3
	Corn syrup	1360 kg/m^3	
	Glycerin	1258 kg/m^3	
	Castor Oil	970 kg/m^3	
μ_f	Viscosity of fluid	TBD	kg/m-s
r_s	Radius of sphere	1/16"	m
v_s	Volume of sphere	$v_s = \frac{4\pi r_s^3}{3}$	m^3
M_s	Mass of sphere	0.000131 kg	kg
ρ_s	Density of sphere	$\rho_s = \frac{M_s}{v_s}$	kg/m^3
g	Acceleration of gravity	9.81 m/s^2	m/s^2
d_c	Diameter of cylinder	1.50"	m

Sample Calculation:

If a sphere with radius of 0.1 cm and mass of 0.01 g is falling through a cylinder of fluid with width of 6 cm reaches a terminal velocity of 0.01 m/s, what is the viscosity of the fluid assuming the fluid has a density of 1000 kg/m^3 and is Newtonian and the flow of fluid around the sphere is laminar? Confirm that the flow of fluid around the sphere is laminar.

$F_g = mg = ((4/3)\pi(r_s)^3 \rho_s g)$
$F_b = ((4/3)\pi(r_s)^3 \rho_f g)$
$F_d = 6\mu\pi r_s V_{theoretical}$



Since $F_d = F_g - F_b$, equating, we find:
Fluid viscosity;
$\mu = (2(r_s)^2 (\rho_s - \rho_f) g)/(9V_{theoretical})$

From falling ball data, we calculate (*given in this case*):
$V_t \equiv V_{experimental}$ = **0.01** m/s

Correction factor for wall effects:
$V_{theoretical} = (1 + 2.1044 (d_s/d_t)) * V_{experimental}$ = **0.01035** m/s

Insert into fluid viscosity equation:
$\mu = (2(R_s)^2 (\rho_s - \rho_f) g)/(9V_{theoretical})$ = **1.896** kg/m.s

Calculate Re:
$Re = d_s V_{theoretical} \rho_f / \mu$ = **0.0109** < 1 (Therefore flow is laminar; Re has no units)

Note: PAY VERY CLOSE ATTENTION TO **UNITS** IN THESE CALCULATIONS.

LAB EXPERIENCE

The lab will be performed in groups of two students, with up to two groups at each lab table. Students will use an application built in LabVIEW to acquire data on a ball falling through a known viscous fluid. This data will be used to later determine the viscosity of the fluid.

There are 3 liquids to be tested (castor oil, glycerin, and corn syrup). Each group will test two liquids provided at their tables at least 3 times, following the instructions provided on the lab table. For each test, students will save a .csv file with overall data from the test. After each run, preliminary analysis should be done on the data according to the Data Analysis section of the instructions and the results posted to the Class Data Sheet on the instructor computer.

Students should follow the instructions provided on the lab table, also found on the website. Be sure all required data is collected, **and all .csv files are saved**. Three data sets for the one untested liquid should be obtained from the sample data on the lab website to complete the 9 data sets for analysis. The Class Data Sheet will be emailed to you.

Questions

Based on the objectives listed at the beginning of this laboratory write-up, answer the following in your report (in the appropriate sections):

- For the position data recorded through LabVIEW, create three separate plots in Excel, 1 per fluid, each with 3 data sets. Try to plot the absolute position, not just one component (think!). Note: Include trendlines for the datasets to find the velocities. These can be Excel-generated trendlines (usually least-squares), a moving average trendline, developed by the student, or another type. Justify (in words) why you chose that type of trendline.

- As a follow-up to the previous exercise, create three separate plots showing a trend of the total data collected in class in Excel using the data from the entire class. Prior to graphing, group the data points and then find the frequency at each grouping. In Excel, plot this data as was done in the Spot Speed Study. As before, the standard deviation and average should be given (these can easily be calculated using Excel's built-in functions).

- For the two fluids you tested and the downloaded data set, describe the consistency of the results. Note why it was or was not consistent. Additionally, comment on the consistency of the class data set. How do your teams' numbers measure up? It may be helpful to use the statistical measures calculated previously to answer this question.

- Following the example calculation, present, in tabular form, the terminal velocity and explain the method used to find it. Why was this an accurate method? (e.g. averaging all data points for a given fluid, determining most likely value, using only personal data, etc.). You must tell what method you chose and briefly defend your answer.

- Discuss the viscosities and Reynolds's numbers of all three fluids. Based on the Reynolds's number, is the calculation used to find the viscosity accurate? (e.g. Does the equation you used apply? Generally, did the ball experience laminar flow?)

Note: It is important to reflect on the following in your conclusions:

- Accuracy of the data acquisition system
- The calculated terminal velocity
- The spread of the data
- Viscosities found from the data

LAB REPORT

- Two-person Group Report, with Team Agreement
- Use standard lab report format as described in the FEH Lab Document
- Be sure to answer all questions given in the write-up.