# iiSME Educational Transfer Plan

Leon Cox
Host Organization Shaqfeh Labs
Lesson Plan: Hands-on Lab Experiment
Physics
Grade 10-12
Coach Debra Dimas
22-06-2016

# Terminal Velocity of a Sphere in Liquid

## 0. Abstract

Quantifying the settling velocity (terminal velocity) of a spherical particle in a liquid is of importance because it relates to areas in industry that process and transport suspensions of particles. Typical applications include pharmaceutical manufacturing, wastewater treatment, semiconductor processing and oil and gas extraction. The objective of the experiment described is for students to perform a terminal velocity experiment to aid in their ability to understand that velocity is the slope of the change in position divided by change in time through graphing and plotting the free settling terminal velocity of spherical objects in a liquid using graphical techniques.

---

## I. Standards/Skills/Objectives/Assessment

### 1. Focal Standard or Skill:* Required

**HS-PS2-1. Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.**

---

### 2. Measurable Objective(s):

1. Each group of students will perform a lab experiment to determine the terminal velocity of a defined diameter and density sphere.
2. Students will develop as a class a class-graph of various terminal velocities with their sphere identified by sphere diameter and density.
3. The students will demonstrate understanding that the position-time slope of the line is velocity.
4. Students will correctly correctly state and utilize Newton's second law,: F=ma, Students will use Free Body Diagrams to identify forces and exhibit that when these forces sum to zero the terminal velocity will be reached because (mass is constant) acceleration will be zero.

## 3. Assessment:

Formative and summative assessment will be utilized.

Formative will entail teacher and students exchanging open dialogue as to the velocity results obtained and what they think:during Pre-lab and Lab-day and includes

1. a larger/smaller diameter sphere would show what relative to terminal velocity
2. a less/more dense sphere would show.what relative to terminal velocity
3. Out of ordinary densities or velocities and why they would be considered and outlier and what to do with the data from the outlier.

Summative will be graded based on

1. 30 pts. Pre-Lab in-class/HW (students follow defined steps answering vocabulary, sketching lab components, identifying forces, and developing procedure based on demo)
2. 30 pts Lab-day experiment (students follow defined steps to populate tables, perform calculations, sketch graph and participate in a class-graph. Discussion includes why group graphs varied based on properties of spheres)
3. 40 pts Post-lab based on rubric (provided with the Post-lab handout., Post-Lab Report is to based on a general lab format found here: Lab-Report-Template:. The rubric which is included with the post lab for the group report includes sections on:
   1] PURPOSE/HYPOTHESIS
   2] PROCEDURE
   3] DATA COLLECTION
   4] MATERIAL
   5] DISCUSSION/DATA ANALYSIS/CONCLUSION.

Each section will be rated as 1] BASIC, 2] PROGRESSING and 3] PROFICIENT

In addition to the general lab format this lab specifically includes:

1. In the Procedure followed (how did you measure and time the sphere).
2. Including tables of data and graph from Sheets and an accurate sketch of class combined data graph transcribed being careful to relate sphere properties to graphed lines.
3. Specific: (Research is necessary) to discuss (100-200 words) the findings of the terminal velocity as a relation between change in position versus change in time. Include:
   a. the calculations for your group
   b. The forces involved and how they affect acceleration
   c. what causes changes in the terminal velocity based on the results from the other groups findings.
   d. Do the measured velocities depend on the size of the sphere? Do you think it is area or mass or a combination?

## 4. Additional Standards

### Details of skills/standards addressed in this lesson include

1. **Free body diagram (FBD),**
2. **F=ma where F = force, m = Mass of sphere; a = acceleration due to gravity.**

3. **There are only forces in the vertical direction: positive forces of buoyancy and drag and negative force due to gravity.**
4. **Once balanced there will be no more acceleration and terminal velocity reached.**
5. **Terminal Velocity calculations: distance travelled divided by time**

---

# II. Fellowship Connections

## 1. 21st Century Skill(s):

Learning and Innovation Skills/Critical Thinking and Problem Solving Make Judgments and Decisions: Effectively analyze and evaluate evidence. Interpret information and draw conclusions based on the best analysis:

Students engage in problem solving in the pre-lab portion of the lab and it directly reinforces the Newton's 2nd Law concept (F=ma) utilized often in the course. Throughout the lab and experiment there is inquiry involving force and motion. Students are guided to discussions about what they learn from research and performing the lab.

## 2. 21st Century Skill(s) Application:

Students research, hypothesize, evaluate and draw conclusions from the experiment.

## 3. Fellowship Description:

Information for studying particle suspensions for such things as delivering material to a particular position in piping and delivering specific drugs to cancerous tumors is necessary. A method for studying fluid flow is the utilization of a Taylor-Couette cell consisting of two concentric cylinders, one or both of which can rotate to develop a shear flow which can simulate flows during drilling or flow near walls in pipes, cracks or arteries. The Shaqfeh lab in the Chemical Engineering department at Stanford University is utilizing a Taylor-Couette experimental setup to study:

1. Boundary and elastic effects on particles under orthogonal shear in non-Newtonian fluids.
2. Effect of sphere size and density
3. Rheology of test fluids and suspensions
4. As well as validation of simulation code.

I helped run the experiment and since I have skills in operating lathes and milling machines for machining parts, I have built parts for the experiment utilizing the campus machine shop.

The research area I was associated with is studying how particles behave in a controlled shear flow. Specifically, the results will be utilized to enhance design and delivery of drilling muds and development of fluids for suspending particles. There are close to ten graduate students working on related projects who give weekly updates on their work in addition to going to class. Most of them have already co-authored papers that appear in scientific journals.

My association with the lab reinforced the importance of studying fluid dynamics and rheology (the study of flow of matter). Particles suspended in fluids react differently depending on what they are suspended in. As an example, ketchup behaves differently than water because it is a non-Newtonian shear thinning fluid which means it is thick until a force causes it to flow freely like a liquid, while water is a Newtonian liquid.

Students will be able to perform experiments which will be similar to this one carried out at the Shaqfeh lab. Interesting phenomena occur at the boundary of flow and most fluid-based research in chemical engineering is carried out examining laminar flow. Laminar flow can be visualized as lava flowing from a volcano, blood flowing in arteries or iced tea being poured from a pitcher . Determining the terminal velocity of a sphere in a liquid is one of the experiments utilized in the Shaqfeh lab and this is similar.

4. Fellowship Connection to School/Classroom:

Students will hear the story of the lab function. I will share with them what part the lab plays in helping industry, medicine and the environment through research. The research area I was associated with is in studying how particles behave during fluid flow. Specifically, the results are being utilized to enhance delivery of drilling muds and development of fluids for suspending particles. In addition I will share some other major items associated with this research, namely blood flow and the ability to use this knowledge to assist in delivering cancer fighting drugs and particles to affected areas.

My association with the lab taught me the importance of studying fluid dynamics and rheology (the study of flow of matter). Particles suspended in fluids react differently depending on what they are suspended in. Newtonian fluids versus non-Newtonian fluids affect fluid dynamics.

It is good to note that the students will be able to perform experiments which will be similar to this one carried out at the lab. An interesting phenomena occurs with viscous fluids that can be demonstrated with a Couette Cell: Three drops of coloring are inserted and slowly wound together, then upon unwinding return to their original shape upon insertion. This is shown to them at the end of the opening hook under the instruction plan. Another advanced experiment related will be used in an advanced physics class or suggesting a science fair project and it concerns side wall interaction at the boundary of flow. That is, the terminal velocity of a sphere in a liquid with a diameter greater than ½ the ratio of sphere diameter to wall spacing actually begins to slow and will approach zero as that ratio approaches 1 and students will be guided to discover this phenomenon.

---

# III. Instruction

## 1. Instructional Plan:

**Opening/Hook**

1. Open the (attachment 1-Terminal Velocity-Hook). Show the video (link found on slide) of the food coloring in a viscous fluid demonstration, Tell students that this is a fluid property and that knowing fluid properties is an important knowledge base. In the skydiving slide: Ask students to identify (1)-which of the two or both might be at terminal velocity (Teacher Note-1:).
2. Show slides 4(blood) and 5(drilling) Lead students in discussing how material flow in piping is not just the liquid but also includes particulates;-Lead them to particulates in suspension. (Teacher Note-2:)
3. Ask them if blood contains things in suspension, if an oil rig only pumps out, lead to what materials are pumped down and what happens things in blood don't reach destination and if coolant doesn't reach the drill bit. (Teacher Note-3:)
4. Have groups of four share what the similarities and differences are in the graphic relative to particulates sizing of slide 6 (wastewater) if they are solid materials in a liquid. (Teacher Note-4:)
5. Relate that particulates can react in a manner that can be modelled and thereby piping can be designed to carry it optimally or particulates sized to reach a particular destination (nano-particles to treat cancer)
6. Relate that my summer research centered on this modelling (see LDC Fellowship Narrative).

**Model**: (previously covered topics that pertain to this lab)

1. Review/scaffold with students:
    a. Force = mass * acceleration
    b. Free Body Diagrams
    c. Acceleration is only when an unbalanced force acts on an object
    d. Velocity = (change in distance) / (change in time) (Teacher note-5:)
    e. If there are no unbalanced forces then velocity is constant
2. Compare-contrast Force due to gravity to
    a. Force due to buoyancy (Teacher note-6:)
    (Demo this with an object that floats by pushing it down and asking what happens when released. The buoyant force pushes it back to the surface. Relate that all objects in a liquid exhibit buoyant force, however with some the object will still sink because buoyant force was not able to overcome gravity force.)
    b. Force due to drag
    (Relate force of drag to sticking out your hand out the window in a moving car, that force is drag force and will be greater as the car increases speed.)
3. Review importance of units and significant digits

**Guided Pre-Lab (approx 45 min)**

1. Students will complete in class attachment (Velocity of Sphere in Liquid Pre-Lab) worksheet with teacher utilizing cue-do-review. ( Answer-key).

2. Cue: Observe the drawing showing a sphere in a liquid with free body forces of Fg, Fb, Fd. Do: Students reproduce the drawing on their lab sheet and identify Force due to gravity, buoyancy and drag. Teacher reviews: Solving for the students the Net Resultant Force =- Fg +Fb +Fd and lead them to understand that the buoyancy force is fixed as is Fg and that drag force increases with increase in velocity and when it becomes sufficient it will net out to zero the resultant Force which means acceleration becomes zero)
3. Students should be cued that a constant velocity will be a steady velocity. Using corn syrup based on teacher demonstration, students will see a steady -i.e. terminal velocity (Teacher Note-7:)
4. Students and teacher discuss the aspects of terminal velocity (Teacher Note-8:) **FA**
5. Students in their group discuss and hypothesize/answer the question whether size/mass of different sized spheres will affect the terminal velocity? Teacher reviews **FA**.
6. Students develop "Hypotheses" regarding terminal velocity regarding sphere diameter in a cylinder filled with corn syrup. (Teacher note-9:) Remind students understanding that they will be timing only one size sphere but will be looking for information from other groups as to terminal velocity for other sized spheres.
7. Students and teacher co-develop method for determining terminal velocity from equipment and supplies available. (Teacher note-10:).

**Lab Exercise (approx 80 min) (**Velocity of sphere in Liquid Lab-Experiment)
1. Students mark cylinder total 10 cm at intervals of 1 cm for measurement of y dimension and will time the sphere crossing each interval as a lap time on a stopwatch and later evaluate times from camera frames. They will enter the data in Data Table.
2. Students with teacher assistance determine density of their sphere. (on the lab handout attachment and change units to centimeters and cubic centimeters) (Teacher note-11:)
   Discuss and model how to find density of a sphere (Teacher Note: V=4/3(Pi*r**3)
   a. Students use the calculator found here to calcuate volume using diameter: http://www.handymath.com/cgi-bin/solidsphere.cgi?submit=Entry (Teacher note: change units to centimeters and cubic centimeters.)
   b. Use the calculator found here to find density: Density=mass/volume http://www.calculator.net/density-calculator.html
   c. Students determine density of their corn syrup (Teacher note-12:)
   d. Extra credit applied to post lab report: Research and find how the force due to drag and buoyancy are evaluated and calculate.
   e. Based on results, the sphere will sink because:_________________________________
3. Students set-up and run 1 trial for their assigned sphere diameter: (Note: there are 1/16 in., ⅛ in. and 3/16 in., ¼ in. and 5/16 in. and ⅜ in. diameter spheres, dropping in a 1 inch diameter 100 ml graduated cylinder). Using the given table on the Lab handout students record each time the sphere passed a graduated mark. (Teacher Note-13:).
4. From the data for each group which was entered on Table provided (Data Table of Velocity of sphere in Liquid Lab-Experiment-2), students plot individual distance-time marking points on graph provided Graph page (Graph Page), this slope is velocity in cm/sec (Teacher Note-14:).

5. After the individual experiments, a class graph is made. (There will be up to six separate sloped lines, one for each diameter, each group plots their graphed data as estimated best fit line). Data table and Graph page are discussed as a class to find commonality in data and graph. (Teacher Note-15:).

**Post Lab-Report (finished outside of lab time)**- Inquiry
Students answer Post lab questions (Post Lab: Velocity of sphere in Liquid-Post Lab includes grading rubric) Students are cued to note that the rubric found in the lab will be used to grade their overall report

# TOTAL Summative Assessment value

A total lab grade consists of

1. Pre lab in-class group participation in the completion of questions (30 points)
2. Lab Experiment (30 points)
3. Assembling and writing post lab report such that each category is addressed (40 points) The general Lab-Report-Template is used with lab specific items added for this particular lab..
4. Extra Credit for exceptional work (5 points)

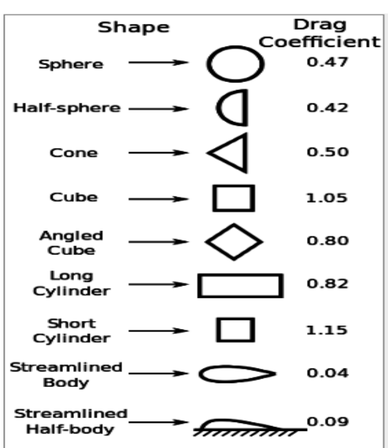
## 2. Additional Instructional Context: (*Optional)*

Wiki…

Mathematically, terminal velocity—without considering buoyancy effects

$$V_t = \sqrt{\frac{2mg}{\rho A C_d}}$$

$V_t$ is terminal velocity,
m is the mass of the falling object,
g is the acceleration due to gravity,
$C_d$ is the drag coefficient,
rho is the density of the fluid through which the object is falling, and
A is the projected area of the object.



Measured Drag Coefficients

Note: This is
In fluid dynamics, the drag coefficient (commonly denoted as: Cd is a dimensionless quantity that is used to quantify the drag or resistance of an object in a fluid environment, such as air or water. It is used in the drag equation in which a lower drag coefficient indicates the object will have less aerodynamic or hydrodynamic drag. The drag coefficient is always associated with a particular surface area.[1]

Force of buoyancy can be found weighing out of fluid and weighing in fluid, then only the Force of drag will be left to slow the object and is dependent on viscosity of the fluid and relative to the area looking at from below its fall direction.

1. Students might hear the terms Newtonian and Non-Newtonian fluids as well as Viscosity and Reynolds Number. They are an important set of concepts in the study of fluids but the differences in terminal velocity for them are not introduced because the purpose of the lab is to be able to visualize terminal velocity and use graphing techniques to find velocity. That said, the enterprising student who shows interest in fluids could be directed to further study for the discerning students in need of a challenge;
2. If students need a project the capability to build a viscometer exists (Krauser et all). This is a potential science fair project and would be applicable in AP Physics-2.
3. Another challenge would be to have students discover that velocity begins to go down as the ratio of sphere/cylinder diameter becomes greater than 0.5 (C. H. ATAÍDE et all) and will reach zero as it approaches 1; they could research why it affects terminal velocity.

## 3. Supply List:

Assuming 24 students groups of 4
6 ea-100 ml graduated cylinders 1 in or greater diameter which are on hand in most chemistry labs.
2 ea- 500 ml bottles of corn syrup
6- sets of spherical aluminum balls (1/16 in., ⅛ in. and 3/16 in., ¼ in. and 5/16 in. and ⅜ in. diameter) they can be ordered from McMaster-Carr
6-sets of Lab Handouts (Pre-lab, Lab and Post Lab) includes table and graph page.
6 ea- stopwatch with lap count (the typical smartphone will have a timer to do this)
6 ea - Dial calipers (one for each lab station to measure diameter of spheres. +/- 0.001 in)

## 4. Bibliography:

C. H. ATAÍDE, F. A. R. PEREIRA and M. A. S. BARROZO. “Wall effects on the terminal velocity of spherical particles in Newtonian and non-Newtonian fluids” Brazilian Journal of Chemical Engineering September 1999.
http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0104-66321999000400007&lng=en&nrm=iso&tlng=en

Matthieu Brizard, Mohamed Megharfi, Claude Verdier, Eric Mah. “Design of a High Precision Falling Ball Viscometer” Review of Scientific Instruments, American Institute of Physics (AIP), 2005, 76 (2), pp.025109.
https://hal.archives-ouvertes.fr/hal-00197586/document

John DeMoss and Kevin Cahill,
https://commons.wikimedia.org/wiki/File:Couette_Cell_for_Displaying_the_Properties_of_Laminar_Flow_(2)_-_UNM_Physics_and_Astronomy.webm

Leigh Krauser, Julia Mayer Adrienne Remener. "Creating a Falling Ball Viscometer" Kanbar College of Design, September 2013.
http://faculty.philau.edu/masoodir/PDF/Projects/Fluid/Falling%20Ball%20Viscometer.pdf

5. Keywords:
Terminal velocity, Newton's 2nd Law, Force of gravity, Drag force, Buoyancy force, Mass, Volume

---

## IV. Attachments

Attachment-1 Terminal Velocity-Hook "Graphic Hook"
Attachment-2 Velocity of Sphere in Liquid Pre-Lab
Attachment-3 Velocity of Sphere in Liquid Lab-Experiment
Attachment-4 Velocity of Sphere in Liquid Post-Lab includes grading Rubric
Attachment-5 Summary-Terminal Velocity Lesson
Attachment-6 LDC-Fellowship Narrative
Attachment-7 Teacher Notes
Attachment-8 Lab Report Template
Attachment-9 Answer Key for Velocity of Sphere in Liquid Pre-Lab