TWO SIMPLE EXPERIMENTS

For The Fluid-Mechanics and Heat-Transfer Laboratory Class

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Fluid mechanics and heat transfer are important subjects in undergraduate courses in chemical engineering, and surely there is no danger of overemphasizing the importance of performing simple illustrative experiments that the students can fully comprehend. A wealth of demonstrative experiments are available commercially in kits, but they tend to be expensive and leave the user in some form of dependence on special spare parts in case of breakage.

The experiments described in this paper are cheap to build and rely on materials and instruments readily available in most engineering departments. The equipment needed is

- An electrical oven
- A digital millivoltmeter
- Two thermocouples
- A fan
- A viscometer
- Two ball valves
- Plastic beakers
- An anemometer

and some pieces of metal and nylon rods and acrylic tubing that can be machined in half a day in a rudimentary workshop.

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EXPERIMENT 1
Laminar Film Flow Around Long Cylindrical Bubbles

Most students will be familiar with, or will easily understand, a wetted-wall column, but from our experience, few will have come across the concept of cylindrical bubbles. Yet, these are easily formed during continuous bubbling in narrow bubble columns if the gas flowrate is increased sufficiently, and also in vertical boiler tubes if the heating rate is high.

An easy introduction to cylindrical bubbles is afforded by means of a simple experiment in which a long and narrow acrylic tube is initially filled with water to within a few centimeters of the top. A stopper is then used to close the tube, before turning it upside down. A cylindrical bubble will be seen rising up the tube (see Figure 1a), and its velocity, U, is easily determined by timing the rise along a given height. If the experiment was repeated with tubes of different diameters, D, it would be seen that

$$U = 0.345(gD)^{1/2} \tag{1}$$

where g is the acceleration due to gravity. (The same type of experiment can be performed to show that U is independent of bubble length.)

Equation 1 is valid for cylindrical bubbles in liquids of low-to-moderate viscosity, which according to Wallis[1] corresponds to the criterion

$$N_f = \left(gD^3\right)^{1/2} / \nu > 300$$

where N_f is the dimensionless inverse viscosity and is the kinematic viscosity of the liquid.

The experiment we propose may be seen as a variation of the one described above. If a cylindrical tube is completely filled with liquid and a stopper is used to close it at the top, and if the stopper at the bottom of the tube is removed, a growing gas slug will be seen rising up the tube core while liquid will continuously discharge at the bottom along the wall (see Figure 1b).

The volumetric balance of gas and liquid flowing through any cross section of the tube requires that

$$Q = \frac{\pi}{4}(D - 2\delta)^2 U \tag{2}$$

where Q is the volumetric flowrate of liquid running down along the tube wall, and δ is the thickness of the liquid film. If $\delta / D << 1$, the curvature of the liquid film can be neglected and Nusselt's analysis for film flow is known to give[1]

$$q = \frac{g\delta^3}{3\nu} \tag{3}$$

where $q = Q/\pi D$ is the liquid flowrate per unit wetted perimeter. This equation is deduced for laminar flow, which is normally observed when

$$Re_f = \frac{4q}{\nu} = \frac{U(D - 2\delta)^2}{\nu D} < 1500 \tag{4}$$

where Re_f is the film Reynolds number.

Substitution of Eq. (3) into Eq. (2) leads to

$$U = \frac{4gD}{3\nu} \frac{\delta^3}{(D - 2\delta)^2} \tag{5}$$

and with U from Eq. (1), we get

$$\frac{\delta^3}{(D - 2\delta)^2} = \frac{\nu}{3.86(gD)^{1/2}} \tag{6}$$

It should be remembered that this equation is valid only if $N_f > 300$ and $Re_f < 1500$. For given values of D and g, Eq. (6) is shown to relate δ with ν.

In film flow, a more general relationship between the dimensionless film thickness, ξ, and the film Reynolds number is obtained if the definition of Re_f is substituted in Eq. 3,

$$\xi = \frac{\delta}{D} N_f^{2/3} = 0.909\, Re_f^{1/3} \tag{7}$$

(valid only for laminar flow) as pointed out by Wallis.[1]

Experimental Work

A 1.5-m length of 19-mm i.d. acrylic tube is adapted to one side of a 3/4" ball valve, the other side of which is fitted to one end of a 1-m length of the same tube, and fitted with another ball valve at the other end. The resulting column is aligned vertically above a plastic bucket, as shown in Figure 2, and a stopper is placed at the bottom before filling the column completely with liquid (a detailed drawing of a nylon adapter used to connect the tube with the valves is shown in Figure 2).

The valve at the top is then closed and the stopper at the bottom is removed to let a growing gas slug form and rise up the tube. The slug will be allowed to rise freely until its nose is some 0.3 to 0.4 m above the ball valve, at which time the valve will be suddenly closed and a plastic beaker placed (simultaneously) right under the column. The liquid collected in the beaker will then be that making up the film running down the tube wall over the length H, measured

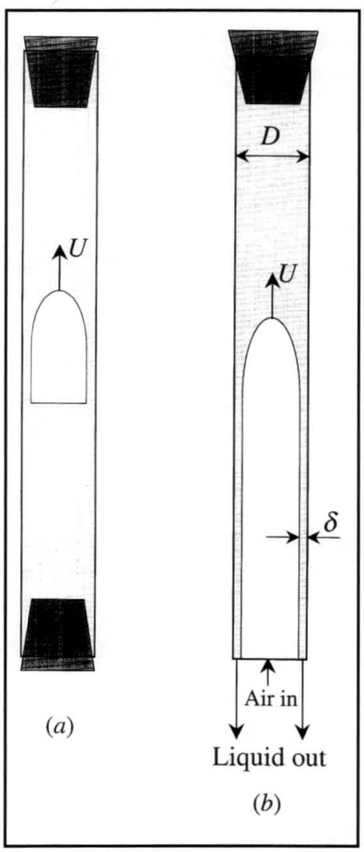

Figure 1. *(a) Slug rising in a closed vertical tube; (b) film flow around a growing slug.*

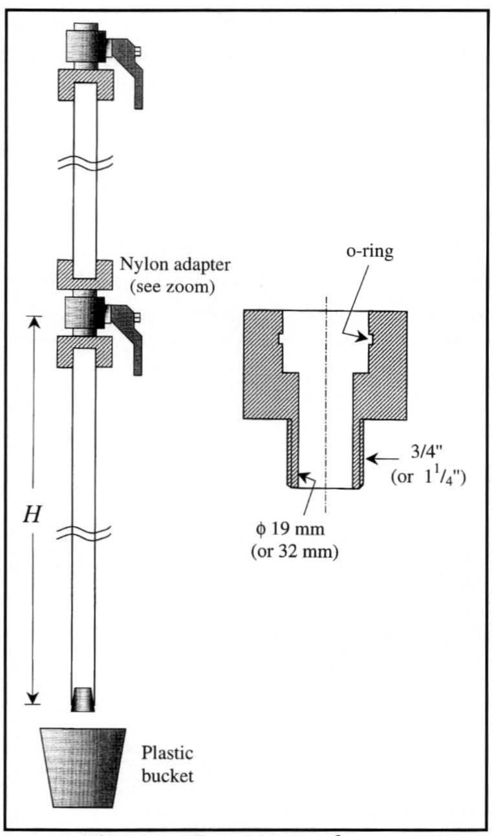

Figure 2. *Experimental setup.*

between the bottom of the column and the ball valve. The thickness, δ, f the liquid film is determined from the volume of liquid collected, V, through

$$V = \frac{\pi}{4} H\left[D^2 - (D - 2\delta)^2\right] \tag{8}$$

It is a simple matter to repeat the experiment with liquids covering a range of viscosities (we used glycerol solutions with viscosities up to 15×10^{-3} kg/ms). A 32-mm i.d. column can also be used, with 1 1/4" ball valves (note that the internal diameter of the ball valve must be exactly the same as that of the column). Measurement of slug velocity is also simple through timing of the passage of its "nose" between two marks about 1m apart.

Results and Discussion

Results obtained by our students are plotted in Figures 3 and 4, and the agreement between theory and experiment can be seen to be excellent (average deviation in δ less than 50 μm, or about 5%).

Although the experimental technique is rather crude, our experimental points fall closer to the theory than those reported in Figure 11.8 of Wallis.[1]

Pedagogical Comments

The study of laminar flows is an important part of a fluid mechanics course. The two most common experimental illustrations are laminar flow in a tube (Poiseuille's formula) and free settling of a sphere in a viscous liquid (Stoke's law). Film flows are an important class of laminar flows (*e.g.*, in lubrication, wetted-wall columns, and filmwise condensation), but they are not normally illustrated experimentally. This experiment provides a vivid illustration of the theory of laminar film flow and, as an additional bonus, it combines it with a very simple analysis of two-phase flow

The actual demonstration is deceptively simple for the students. They only have to remove a cork and a few seconds later close a valve while simultaneously placing a beaker under the column. But from our experience, the interpretation of the results—namely, the interplay between upwards gas flow and downwards liquid flow, (with volume conservation (!))—is very instructive. Invariably the students are amazed when they find the close agreement between experimental and theoretical values of δ.

EXPERIMENT 2
Heat Transfer in Free and Forced Convection Around Cylinders

A metal rod (typically 0.15m to 0.25m long and 15mm to 30mm in diameter) is initially heated in an oven to around 90°C, and then suspended from two thin wires with its axis horizontal, as shown in Figure 5. A thin sheathed thermocouple is then introduced into a hole with a diameter only slightly larger than the thermocouple and drilled near the axis of the rod. This thermocouple is connected to a reference thermocouple immersed in an ice-water mixture and to a mV meter, from which values of e.m.f. are read at regular time intervals (of between 30s and 90s, depending on the cooling rate of the rod). More "advanced" options are the use of thermocouple compensation and direct data logging on a computer.

In the natural convection experiment, the rod is allowed to cool in still air, whereas in the forced convection experiment an electrical fan is used to blow the air in a direction perpendicular to the axis of the rod. An anemometer is then needed to measure the velocity of the air near the rod.

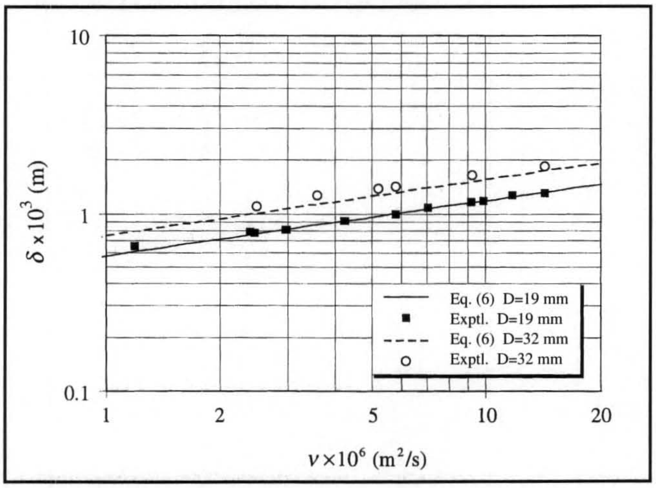

Figure 3. *Film thickness as a function of the kinematic viscosity for D=19mm and D=32mm. Comparison between Eq. (6) and experimental results obtained by students.*

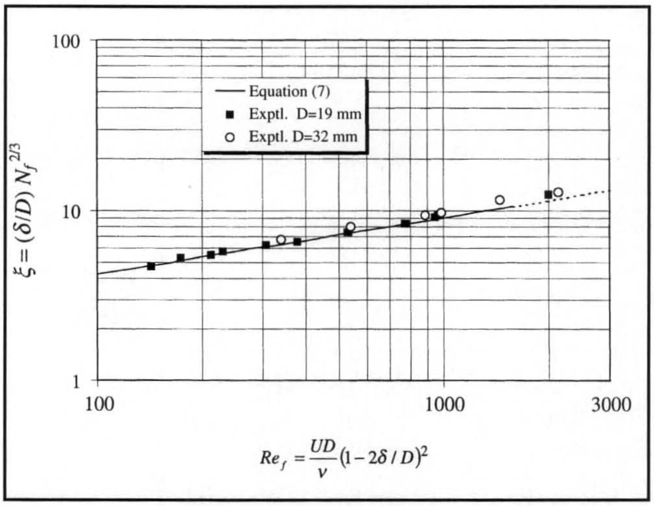

Figure 4. *Effect of Reynolds number on dimensionless film thickness. Comparison betwen experimental points obtained by students and Eq. (7).*

Data Treatment

If a heat transfer coefficient, h, is defined, the cooling law for the rod is

$$-mC_p \frac{dT}{dt} = hA(T - T_0) \qquad (9)$$

where m is the mass of the rod, with external area A and specific heat capacity C_p. The temperature of the rod at time t is T, and T_0 is the temperature of the air far from the rod, taken to be invariable in time. If the variable $\theta = T - T_0$ is defined, integration of Eq. (9) from t=0, for which time $\theta = \theta_i (= T_i - T_0)$, leads to

$$\ell n\,\theta = \ell n\,\theta_i - \left(hA / mC_p\right)t \qquad (10)$$

where hA/mC_p has been taken to be constant over the time interval considered. Equation (10) suggests a representation of the experimental data as $\theta = \theta_i$ vs t in a semilog plot, and in Figure 6 the data obtained in our lab with a Dural rod (L=0.250m, d=0.0250m) cooling in still air are reproduced.

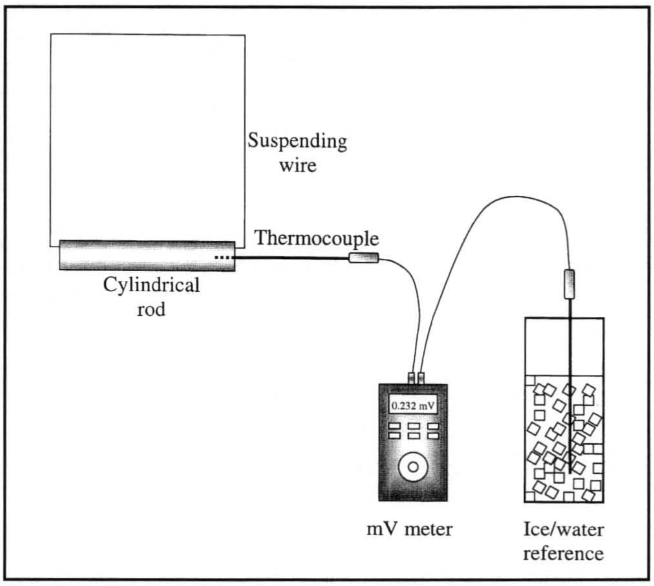

Figure 5. *Diagram of experimental setup.*

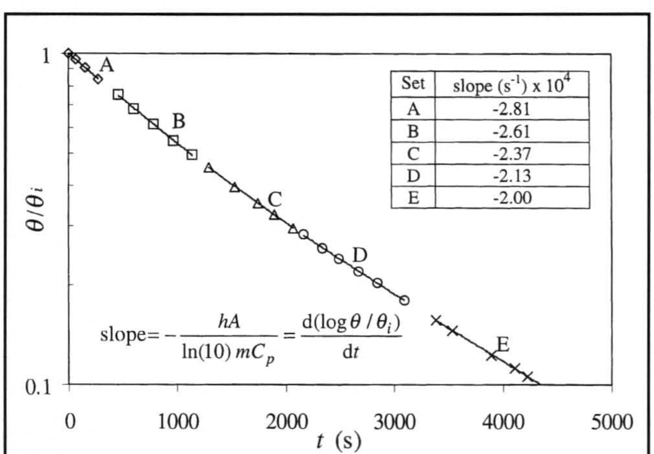

Figure 6. *Cooling curve for natural convection (dural rod, d=0.0250m, L=0.250m).*

Natural Convection

It is important in this part of the experiment to use well-polished rods that are not covered by a thin oxide layer, so that the contribution of radiative transfer becomes negligible. A careful look at Figure 6 shows a slight upward curvature in the alignment of the experimental points; this is because h decreases with the temperature of the rod, for natural convection. If the data in Figure 6 are sliced into a number of successive time intervals, with each containing a number of experimental points, it is possible to determine the best-fit straight line for each time interval, and from the corresponding slope the value of h is found.

The values of h obtained in this way are represented in Figure 7, and they are seen to compare extremely well with the correlation given by Holman,[2] which for atmospheric air at moderate temperatures reduces to

$$h = 1.32\,(\theta / d)^{1/4} \qquad (11)$$

with h in W/m^2K, θ in K, and d (the diameter of the rod) in meters.

Forced Convection

For the conditions in our experiments, the heat transfer coefficient for cooling under forced convection has a negligible dependence on the temperature of the rod and as a result log θ / θ_i vs. t plots as a straight line for each value of air velocity.

In order to compare the values of h obtained from these lines with predictions from Fand's correlation[2]

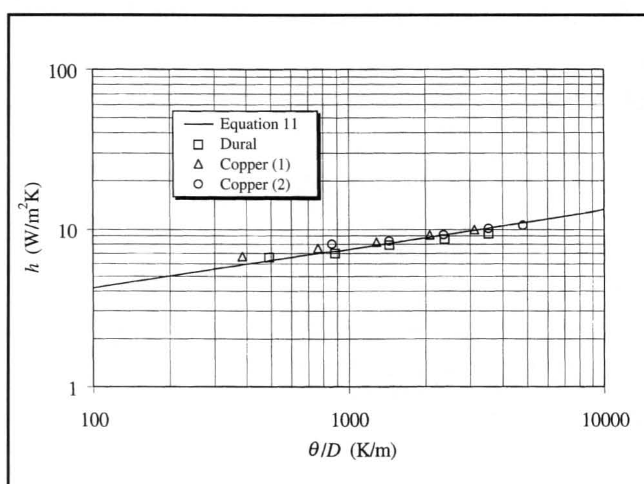

Figure 7. *Heat transfer coefficients in natural convection.*

$$Nu = \left(0.35 + 0.56\ Re^{0.52}\right) Pr^{0.3} \qquad (12)$$

it is necessary to measure the velocity with which the air approaches the cylinder, u_∞. In Eq. (12), $Nu = hd/k$ is the Nusselt number, $Re = \rho u_\infty d/\mu$ the Reynolds number, and $Pr = C_p\mu/k$ Prandtl's number. All the physical properties are for air at mean film temperature $\left(= (T + T_0)/2\right)$. In our experiments, where transient cooling is observed, values of Nu, Re, and Pr could be evaluated at different times (in each experiment we evaluated these dimensionless groups near the beginning and near the end of the cooling period, to obtain two points on the plot in Figure 8).

Results and Discussion

Our students performed experiments with three different metal rods (see Table 1), and the data obtained were used to organize the plots in Figures 7 and 8. It can be seen that the experimental points fall quite close to the correlations suggested in the literature, even though the experimental technique is rather crude.

Pedagogical Comments

Students like this work for a variety of reasons. (1) They have an opportunity to successfully test the theory of transient heat transfer for lumped parameter systems. (2) They obtain individual values of the heat transfer coefficient, which (some are surprised to see) compare well with those given by available correlations. (3) If two rods of the same size are used, one made of duralumin and the other made of copper, the latter cools more slowly under otherwise similar conditions, due to its higher heat capacity. For the weaker students, it is intriguing to see that the same heat transfer coefficients are obtained for both rods. (4) The effect of temperature difference on the heat transfer in natural convection is also brought out vividly. (5) The importance of radiative heat transfer is brought to evidence if two equal rods are used in the natural convection experiment, of which one has been allowed to oxidize so as to lose its shiny appearance.

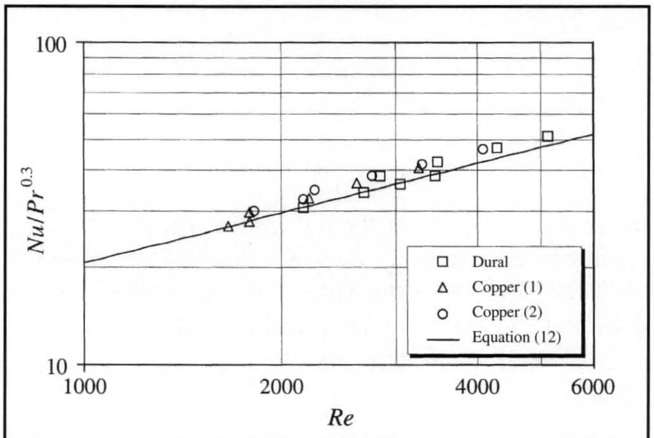

Figure 8. *Dimensionless heat transfer coefficients in forced convection.*

TABLE 1
Characteristics and Properties of the Metal Rods Used in the Experiments

	d(m)	L(m)	m(kg)	$C_p^{(*)}$(J/kg.K)
Copper (1)	0.0158	0.250	0.440	383.1
Copper (2)	0.0199	0.250	0.693	383.1
Duralumin	0.0250	0.250	0.334	883.0

(*) Ref. 2.

NOMENCLATURE

- A area for convection (m^2)
- C_p specific heat capacity (J/kgK)
- D column internal diameter (m)
- d diameter of rod (m)
- g acceleration of gravity (m/s^2)
- H length between bottom of column and ball valve (m)
- h heat transfer coefficient (W/m^2K)
- k thermal conductivity (W/mK)
- L length of rod (m)
- m mass of rod (kg)
- N_f dimensionless inverse viscosity (-)
- Nu Nusselt number evaluated at mean film temperature (-)
- Pr Prandtl number evaluated at mean film temperature (-)
- Q volumetric flowrate of the liquid (m^3/s)
- q liquid flowrate per unit wetted perimeter (m^2/s)
- Re Reynolds number evaluated at mean film temperature (-)
- Re_f film Reynolds number (-)
- t time (s)
- T temperature of rod (K)
- T_0 ambient temperature (K)
- U velocity of cylindrical gas bubble (m/s)
- u_o air velocity (m/s)
- V collected volume (m^3)
- δ film thickness (m)
- μ dynamic viscosity (kg/ms)
- ν kinematic viscosity of the liquid (m^2/s)
- θ temperature difference, $T-T_0$ (K)
- θ_i value of θ at t=0 (K)
- ρ density (kg/m^3)
- ξ dimensionless film thickness (-)

REFERENCES

1. Wallis, G.B., *One-Dimensional Two-Phase Flow,* McGraw-Hill, New York, NY, Chap 10-11 (1969)
2. Holman, J.P., *Heat Transfer,* 8th ed., McGraw-Hill International Edition, Chap 6-7 (1997) ❐