PART 1B EXPERIMENTAL ENGINEERING

SUBJECT:	FLUID MECHANICS & HEAT TRANSFER	EXPERIMENT T4
LOCATION:	HOPKINSON LABORATORY	(SHORT)

HEAT TRANSFER FROM A HEATED CIRCULAR WIRE

OBJECTIVES

(a) To study heat transfer rates from a small circular wire for forced and free convection.

(b) To introduce the use of appropriate dimensionless groups for convective heat transfer.

(c) To determine an empirical relationship for heat transfer in forced convection.

(d) To introduce the concept of a hot wire anemometer.

INTRODUCTION

Heat transfer between a solid surface and a fluid has many engineering applications, including, heat exchangers, boilers and condensers. If movement of the fluid is produced by mechanical means (e.g., by a fan) then *forced convection* is said to occur. If, however, the motion results purely from density changes due to differences in temperature (e.g., the outside of a domestic radiator), then the process is termed *natural* or *free convection*. In both cases, heat transfer rates are usually calculated using a heat transfer coefficient, h, which is defined such that,

$$\dot{Q} = hA\Delta T \tag{1}$$

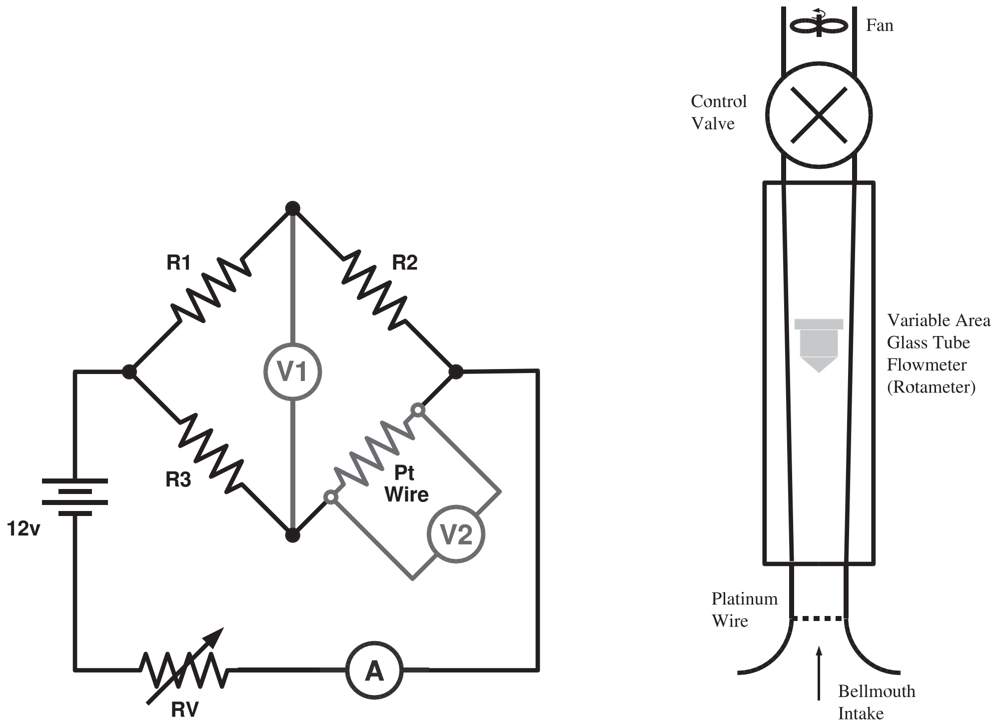
where $\dot{Q}$ is the heat transfer rate, A is the surface area, and ΔT is the temperature difference between the surface and surrounding fluid. The units of h are $\mathrm{Wm^{-2}K^{-1}}$.

Although the heat transfer coefficient is often treated as a constant for a given problem, it is in fact a function of both the flow conditions and the fluid properties. Patterns of heat and fluid flow are usually very complex and not readily amenable to mathematical analysis, so empirical correlations are frequently required. Dimensional analysis is extremely helpful in reducing the number of relationships between the many variables involved.

This experiment examines forced convection, in which air flow is induced by a fan, and natural convection, in which air flow is induced by temperature differences, for a small (25μm diameter) electrically heated wire. Radiation is neglected throughout, but you should bear in mind that radiative heat transfer increases with the fourth power of absolute temperature.

APPARATUS

Figure 1 shows the experimental arrangement. A platinum wire is situated near the entry of a 20mm diameter perspex tube which has a smooth (bell-mouth) intake section. Air is drawn through the tube by means of a fan, and controlled by means of a gate valve. Flow rates are measured with a "rotameter", which comprises an aluminium "float" within a tapered glass tube.



(a) Electrical Circuit (b) Flow Path

Figure 1: Experimental arrangement of hot-wire apparatus

The platinum wire forms one limb of the Wheatstone bridge circuit shown in fig. 1(a). The circuit is supplied from a 12v lead-acid battery, and the current may be varied using the variable resistor, R_v. Electrical heating of the wire results in an increase in its temperature and hence its resistance, R_w. Equilibrium is reached when the electrical energy supplied balances heat loss to the air in accordance with equation (1).

The resistances in the upper branch of the Wheatstone bridge (R_1 and R_2) are approximately 10,000 times greater than those in the lower branch (R_3 and R_w), so that nearly all the current registered by the ammeter passes through the platinum wire. By adjusting the current it is possible to "balance" the bridge such that the voltmeter, V_1, reads zero. The ratios of the resistors in the upper and lower branches are then the same – i.e., $R_w/R_3 = R_2/R_1$. In this way an experiment can be conducted at constant ΔT.

WARNING

The platinum wire is delicate, expensive and easily broken. **Do not insert objects into the bell-mouth orifice, and ensure that the wire voltage, V_2, does not exceed 6v for free convection.**

PROCEDURE

Measure the ambient pressure and temperature on the nearby barometer / thermometer. Record the values on the attached results sheet and note also the cold wire resistance, R_o, (measured at ambient temperature) for your rig.

Forced Convection

1. Using the selection switch, set R_2 to its *highest* value. Ensure that the control valve is shut and switch on the fan. Now adjust the valve to obtain a rotameter reading of approximately 10 millimetres. (You may find that the higher fan speed gives more stable flow.) Switch on the battery and adjust the current with R_v until V_1 reads zero (a current of between 300 and 400 mA will be needed for the first point). Record the flowmeter reading, F, the current, I, and wire voltage, V_2.

2. Repeat the readings of step (1), increasing the flow rates by a factor of approximately two each time until maximum flow is achieved. Ensure that you have a set of measurements at close to maximum flow. Calculate the wire resistance as you obtain your results, and verify that this remains approximately constant. **Do not maintain high currents for prolonged periods, and do not switch off the fan at this stage.**

3. Keeping the same (maximum) flow rate, set R_2 to its lowest value and decrease the current to balance the bridge – thus giving a lower ΔT. Record the readings of F, I and V_2 as before. Repeat in decreasing steps of flow rate, using similar values of F as for (2) above.

Free Convection

Switch off the fan and adjust the current so that V_2 reads approximately 6v. **Do not exceed this value.** Observe the wire, and record I and V_2 in the table provided. Repeat the measurements, decreasing V_2 in steps of 1v down to a minimum of 1v. **Switch off the battery when you have finished!**

DATA REDUCTION AND DIMENSIONAL ANALYSIS

NOTE: Dimensional analysis for forced convection is outlined in the appendix. You should read this before proceeding, especially if you have not yet covered this material in lectures. **Each person should do one set of data reduction.**

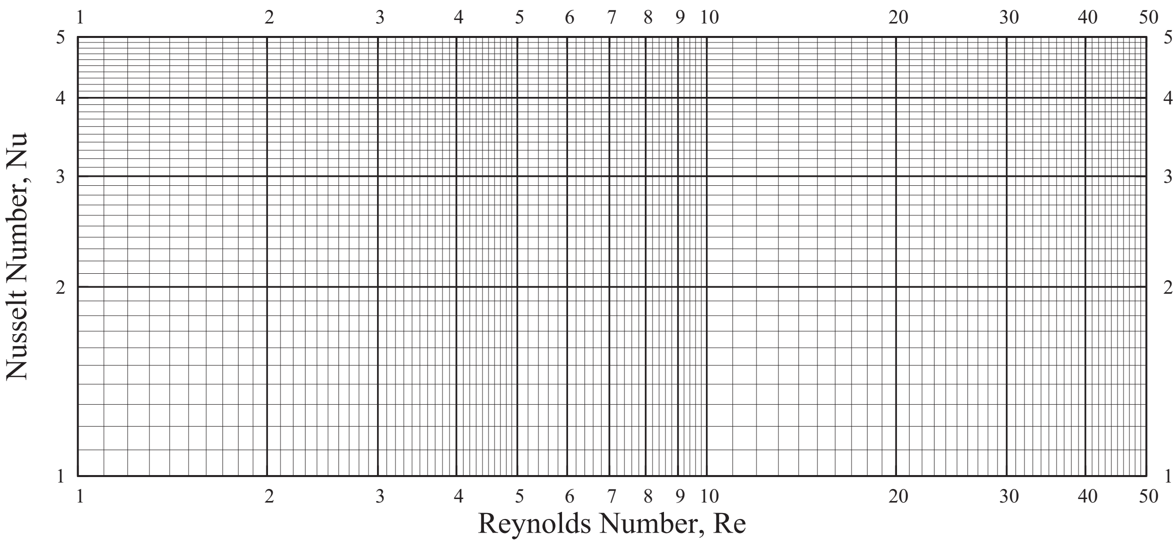
Forced Convection

1. The fractional increase in the resistance of platinum with temperature is almost constant at $\alpha = 3.5 \times 10^{-3}\text{K}^{-1}$ (i.e., $R_w/R_o = 1 + \alpha\Delta T$). Use this to determine the difference in temperature, ΔT, between the wire and atmosphere for the highest setting of R_2.

2. Calculate the "film" temperature ($T_f = T_a + \frac{1}{2}\Delta T$) and use this and the graphs provided to determine the dynamic viscosity, μ, and thermal conductivity, λ. **Treating air as a perfect gas**, calculate also the film density (i.e., the density of air at T_f).

3. Determine the mean flow velocities, U, from the rotameter readings and the calibration curve provided.

4. Compute the Nusselt number, Nu, and Reynolds number, Re, at each flow velocity, and plot the results on the log-log graph below. **Note that your results should fall within the ranges given on the axes.** Repeat for the lower R_2 setting (i.e., lower ΔT) and comment on the two curves.



5. An empirical relationship often used in forced convection problems is

$$\mathrm{Nu} = A\mathrm{Pr}^a\mathrm{Re}^b, \tag{2}$$

but since the Prandtl number remains almost constant over the temperature range considered here, this equation may be written as

$$\mathrm{Nu} = C\mathrm{Re}^b. \tag{3}$$

Use your graph to determine the constants b and C.

$b =$ .... $C =$ ....

Free Convection

6. Determine an expression for the heat transfer coefficient, h, in terms of I, V_2, ΔT and the wire dimensions.

Check your expression with the demonstrator and then compute h and ΔT for the different wire voltages. Comment on the results and explain why h varies with ΔT. Are there likely to be any systematic sources of error?

DISCUSSION AND FURTHER QUESTIONS

7. Compute the forced convection heat transfer coefficient at the highest ΔT and lowest flow speed. Compare with the free convection value at the same ΔT (you may need to interpolate in your table). Comment on the comparison.

Free Convection, $h =$ .... Forced Convection, $h =$ ....

8. The Reynolds numbers in the forced convection experiment are limited to below 50. At much higher Reynolds numbers, the flow over a cylinder may be turbulent, either due to natural transition in the boundary layer or by the presence of upstream obstacles. Would you expect turbulence to increase or decrease the heat transfer coefficient? Explain your reasoning.

9. In natural convection, the fluid velocity is not under our direct control so cannot be considered as an independent variable. Instead, the heat transfer coefficient is a function of the following variables,

$$h = \mathrm{fn}(d, \rho, \mu, c_p, \lambda, g, \beta, \Delta T), \tag{4}$$

where $\beta = (1/v)(\partial v/\partial T)_p$ is the thermal expansivity (which for a perfect gas is $1/T$). Explain why h depends on g and β.

Eq.4 may be reduced to the form,

$$\mathrm{Nu} = \mathrm{fn}(\mathrm{Pr}, \Pi), \tag{5}$$

where Π is a dimensionless parameter which may be expressed as the ratio between two forces. Which two types of force are relevant?

$$\Pi = \frac{\qquad\qquad\text{forces}}{\qquad\qquad\text{forces}}$$

Hence determine a possible form for this parameter.

(Note that the Buckingham-Pi formula appears not to work here as it would give 5 dimensionless groups. This is because some of the the variables in eq. 4 only appear in certain combinations in the governing equations, and so are not truly independent.)

10. The *hot wire anemometer* comprises a small platinum wire connected into a bridge circuit in a similar manner to the current experiment. It is used to measure fluid velocities, and may be made sufficiently small that it effectively measures the instantaneous velocity at a point. In a particular experiment, a wire of 5μm diameter and 1mm length is maintained at 200°C by a current of 59mA in a flow of air at 1 bar and 20°C. Using your results from section (4), estimate the air velocity.

ANS: $\sim 35m/s$

APPENDIX: Dimensionless Groups for Forced Convection

For forced convection, the heat transfer coefficient may be written as a function of the following variables:

$$h = \mathrm{fn}(d, U, \rho, \mu, c_p, \lambda), \tag{6}$$

where ρ, μ, c_p and λ are the fluid density, dynamic viscosity, isobaric specific heat capacity and thermal conductivity respectively. Using the usual methods of dimensional analysis, eq. 6 may be reduced to the dimensionless form,

$$\mathrm{Nu} = \mathrm{fn}(\mathrm{Re}, \mathrm{Pr}),$$

where Nu is the *Nusselt* number, Re is the *Reynolds* number, and Pr is the *Prandtl* number. Rather than presenting a formal analysis here using, for example, the Buckingham-Pi method, we will attempt to give each of these groups a physical interpretation.

Nusselt Number. All dimensionless groups are obviously ratios between two like quantities. The Nusselt number is a dimensionless heat transfer coefficient and may be interpreted as the ratio between heat transfer due to convection and a notional heat transfer rate, $\dot{Q}_\lambda$, which would occur if conduction through the fluid were the only mechanism available. Even for simple geometries, calculating $\dot{Q}_\lambda$ is difficult and not required anyway, so we approximate it by $\dot{Q}_\lambda = \lambda A(\Delta T/d)$. Thus, using eq. 1,

$$\mathrm{Nu} = \frac{\dot{Q}}{\dot{Q}_\lambda} = \frac{hA\Delta T}{\lambda A(\Delta T/d)} = \frac{hd}{\lambda}. \tag{7}$$

Reynolds Number. This is often interpreted as the ratio between inertial and viscous forces,

$$\mathrm{Re} = \frac{\text{Inertial Forces}}{\text{Viscous Forces}} \sim \frac{\rho U^2 A}{\mu(U/d)A} = \frac{\rho U d}{\mu}. \tag{8}$$

The ratio between these forces (together with the shape of the solid boundary) determines the trajectory of fluid particles, and hence governs the flow field. The Reynolds number is important in heat transfer because it determines the growth of boundary layers, and the state of the flow (i.e., laminar or turbulent).

The Prandtl Number. This depends only on fluid properties and not on the flow. It may be interpreted as the ratio between momentum diffusivity, α_M, and thermal diffusivity, α_T:

$$\mathrm{Pr} = \frac{\alpha_M}{\alpha_T} = \frac{(\mu/\rho)}{(\lambda/\rho c_p)} = \frac{\mu c_p}{\lambda}. \tag{9}$$

The Prandtl number thus controls the relative thickness of the velocity and thermal boundary layers. For liquid metals (which have high thermal conductivities) the Prandtl number is small, and the thermal boundary layer is much thinner than the velocity one. For most gases, however, the Prandtl number is close to unity because momentum and heat diffusion are brought about by essentially the same mechanism (i.e., by molecules bouncing off each other).

Fluid properties such as λ, ρ and μ are, in general, functions of temperature and so care must be taken in evaluating the above groups since temperatures obviously vary through the thermal boundary layer. The usual practice is to evaluate properties at a "film" temperature, which is often taken as the arithmetic mean of the surface and fluid temperatures.

RESULTS FOR RIG ......

Ambient pressure, P_a .... bar   Ambient temperature, T_a .... K

Ambient wire resistance, R_o .... Ω

Forced Convection

Highest setting for R_2							Lowest setting for R_2						
F mm	I mA	V_2 v	R_w Ω	U ms^{-1}	Re	Nu	F mm	I mA	V_2 v	R_w Ω	U ms^{-1}	Re	Nu

Average resistance, R_w	.... Ω	.... Ω
Temperature difference, ΔT	.... ^{o}C	.... ^{o}C
Film temperature, $T_f = T_a + \frac{1}{2}\Delta T$	.... K	.... K
Film density*, ρ	.... kgm^{-3}	.... kgm^{-3}
Thermal conductivity, λ	.... Wm^{-1}K^{-1}	.... Wm^{-1}K^{-1}
Dynamic viscosity, μ	.... kgm^{-1}s^{-1}	.... kgm^{-1}s^{-1}
$\mathrm{Re} = (\rho d/\mu)U =$	.... $\times U$	.... $\times U$
$\mathrm{Nu} = I^2 R_w/(\pi \ell \lambda \Delta T) =$	.... $\times I^2$	.... $\times I^2$

Free Convection

V_2 (v)						
I (mA)						
R_w (Ω)						
ΔT (^{o}C)						
h (Wm^{-2}K^{-1})						

Expression for heat transfer coefficient, $h =$

*The gas constant for air is 287 J/kgK