

MAE126A/171A Winter Quarter 2013

(4/1/2013 swr)

Environmental and Mechanical Engineering Laboratory

**Turbulent plume –Week 1
CALIBRATIONS and FLUXES**

Overall description of the experiment:

This experiment consists of determining some characteristics of a thermal plume produced by a source of hot water injected vertically upward from a nozzle at the bottom of a tank of quiescent room-temperature water. The experiment may be considered an analog for a pollution source released into the lower atmosphere. The flow rate of heated water is controlled by a variable-rate peristaltic pump, which pumps hot water from a pan to the plume nozzle. Properties of the plume will depend on both buoyancy effects resulting from temperature (hence density) differences between the water exiting the nozzle and the bulk water in the tank, and also on momentum effects resulting from the flow of water driven by the pump and issuing from the nozzle.

The temperature distribution in the plume is determined using a vertical array of six type K thermocouples spaced one inch apart. Temperature profiles are measured at the plume *centerline* directly above the nozzle, and (in week 2) at successively greater radii away from the centerline. Temperature of the water issuing from the nozzle and temperature of the bulk water in the tank are also measured with thermocouples. Positioning of the thermocouple array and acquisition of the thermocouple data are accomplished using a LabVIEW program.

There are three main tasks to be accomplished this week:

1. Calibrate the flow rate from the peristaltic pump.
2. Calibrate the temperature signals from the thermocouples.
3. a. Determine buoyancy and momentum fluxes for the plume.
b. Measure the centerline vertical temperature profile through the plume.

Procedures:

Note: At this time, prepare the hot water source by filling the water pan with **hot tap water** and clamp the heating stirrer on the holding fixture over the pan. Set the heater thermostat to midway between positions 8 and 9, which will heat the water to approximately 85 °C. Place the yellow hot water temperature probe in the pan through the holder on the side of the heater. Switch on the heater. It will take >10 minutes to heat up. The hot water will be needed later in this experiment to create the plume.

Task 1: Pump flow rate calibration.

Getting good experimental results depends on accurately-measured experimental data. In this experiment a good estimate of the momentum flux depends on an accurate measurement of the volume flow rate produced by the pump. The volume flow rate (ml/min) is directly proportional to the pump rotational rate (RPM). In this task you will determine the relationship between RPM and flow rate.

The flow calibration is simple. Using a stopwatch and a graduated cylinder you will determine how long it takes to accumulate a known volume of water from the pump. This is a so-called *first principles* approach in which we directly measure volume and time.

- a. Fill a beaker with cold tap water. Place the pump pickup tube in the beaker.
- b. Direct the pump outlet tube into an empty graduated cylinder.
- c. Power up the pump. Set the pump rotation to 50 RPM.
- d. Press and hold the Prime button on the pump until you have 10-20 ml in the cylinder. Then release the prime button.
- e. Reset the pump RPM to 15. Press the Start button.
- f. When the accumulated volume in the cylinder reaches an easily measured volume, begin timing. When the accumulated volume reaches 30 *additional* milliliters stop the timing. Record the elapsed time and the volume increment.
- g. Repeat steps e. and f. with RPM settings of 25, 35, and 45 RPM.
- h. Using Excel, plot the measured $\text{ml}\cdot\text{min}^{-1}$ flow rates (y-axis) against the RPM (x-axis). Do a linear fit ($y = m\cdot x + B$) to your data. This will be the calibration equation you will use for volume flow rate in this experiment.

Task 2: Thermocouple calibration.

Successful completion of this experiment depends on good temperature data, particularly in regard to close agreement (matching) amongst the thermocouples (TC). The LabVIEW program and data acquisition system will input and process the small TC voltage signals ($\sim 40 \text{ uV}/^\circ\text{C}$), but there will commonly be small offsets (disagreements) amongst the TC channels. These offsets must be accounted for because the vertical and radial temperature differences through the plume are themselves quite small. Thus, prior to each experiment the TCs must be referenced to a temperature standard, and any offsets present must be adjusted to make them all the TCs agree. In this section you will carry out the TC calibration.

- a. Position the nozzle platform at the floor of the aquarium approximately in the center and directly below the bottom TC. Run the ThermalPlume vi to lower the TC array until the bottom TC is *nearly touching* the nozzle tip. Reposition the nozzle platform as needed. Once you have the correct starting position, *stop then restart the vi* and raise the array 2". This is your starting position. Leave the vi running.
- b. Fill the tank with plain tap water to the fill level marked on the front of the tank.

- c. Observe the temperature traces on the graph. These are the six TC array temperatures, unadjusted for any offsets which may be present. Using the wooden stirring paddle, mix the tank water to eliminate any temperature gradients. Take care to not hit the TC array or the nozzle base.
- d. Measure the water temperature with the glass thermometer. This will be your calibration reference temperature. Immerse the thermometer almost completely for this measurement; stir it gently for 20-30 seconds to fully equilibrate its temperature. Then, still suspending the thermometer in the water, read the temperature through the front glass of the aquarium.
- e. Enter the measured temperature in the Tcal box on the vi front panel. Then ***stop and re-start the vi*** and click the CAL button. The program will go through a calibration routine which takes about 20 seconds. Once completed all the TC temperatures should be matched to the thermometer calibration temperature, and should track across the graph in a single line at the Tcal temperature. Leave the vi running.

Task 3: Buoyancy and momentum flux determinations.

The plume buoyancy flux B is determined by the product of the volume flow rate Q and the *reduced gravity* g' of the plume source water. The reduced gravity term is calculated with

$$g' = g \cdot \frac{\rho_h - \rho_w}{\rho_w} \quad (1)$$

where g is taken as $9.81 \text{ m}\cdot\text{s}^{-2}$, ρ_h is the density of the heated water as it exits the nozzle, and ρ_w is the density of the bulk water in the tank. The densities can be interpolated from Table 1 in the appendix below or calculated from eq. 4. The flow rate is determined by applying the reading on the peristaltic pump to the flow calibration equation from Task 1 above. The buoyancy flux may then be calculated from

$$B = g' \cdot Q \quad (2)$$

The momentum flux M depends on the volume flow rate Q of the source water and the cross sectional area A (see Appendix) of the nozzle at the point where the source water exits the nozzle, according to the relation

$$M = \frac{Q^2}{A} \quad (3)$$

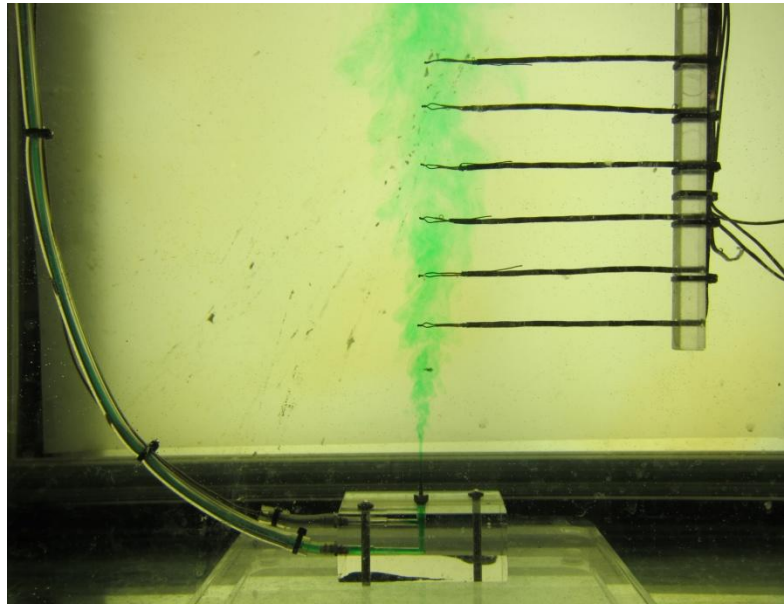
Procedure:

- a. Make sure the tank water is fully quiescent after having stirred the water in task 2 above. Wait 10 minutes. The tank water must be perfectly still; no circulation.
- b. Check the hot water temperature which should be approximately 85° C. Wait until the indicator light on the heater next to the thermostat dial periodically switches on and off, indicating that the hot water has reached the set point temperature.
- c. Carefully, add some vegetable dye to the pan of hot water. Your TA will advise you on how much dye to add. This will allow visualization of the developing plume. Be careful to not stain your clothes.
- d. Place the pickup of the pump inlet tube in the hot water pan. Hook up the delivery tube of the pump to the tube which feeds the nozzle assembly.
- e. Set pump RPM to give a 20 ml·min⁻¹ flow rate, using your RPM/flow rate calibration.
- f. Switch on the pump power and press the Start button. The dyed water will purge through the tubing and you will begin to see the dye exiting from the nozzle and the plume formation. Before proceeding to the next step, observe the T_{jet} temperature to be sure T_{jet} has reached equilibrium. **Important:** It may take 10-15 minutes until T_{jet} reaches equilibrium. T_{jet} may oscillate up and down a few degrees. That's OK.
- g. Observe the developing plume. It should be turbulent and centered above the nozzle. After running the plume for a few minutes so that it is fully developed, click the Read button on the LabVIEW vi. This will start measuring the thermocouple temperatures. The measurement will consist of 2000 data points for each TC over a period of about 3 minutes. Make a notation that the TC array position is X=0.0 in, Z=2.0 in.
- h. Once the measurements have completed a dialog box will open asking if you want to save the data. Click Yes and navigate to where you want to save your data file, often on the desktop, and enter a filename. Save the file on a flash drive for later analysis.
- i. Empty the tank by siphon into the sink. Your TA will show you how to siphon out the water. Observe the array temperatures on the vi graph as each thermocouple in turn emerges from the water and is exposed to the air. Comment on your observation (TC temperature vs air temperature) in the Additional Questions section below.
- j. Calculate the buoyancy and momentum fluxes using your measured data and eqs. 2 and 3 together with the nozzle dimension given in the Appendix.
- k. Using the six TC temperatures you measured in step g. above, plot the temperatures against height above the plume nozzle exit (y-axis = °C; x-axis = height).

Additional questions: Include in your lab report responses to the questions below:

1. The array thermocouples are made with 24 AWG wire (type K, chromel-alumel). A brass slug is soldered to the tip of each thermocouple. Comment on the effect of adding mass to the thermocouple junction and why this effect might (or might not) be desirable in this experiment.
2. Referring to your observations in Task 3i, comment on changes in TC-array temperatures as the TCs emerge from the water and are exposed to the air. How do the TC temperatures compare to the air temperature? What physical process(es) might account for what you observe?

Appendix



Example setup showing TC array, nozzle base, and developed plume.

Nozzle outlet inside diameter: 1.32mm

The density ρ_T ($\text{kg}\cdot\text{m}^{-3}$) of fresh water at temperature T ($^{\circ}\text{C}$) can be calculated as

$$\rho_T = 1000 \cdot \left[1 - \frac{(T+288.9414)}{508929.2 \cdot (T+68.12963)} \cdot (T - 3.9863)^2 \right] \quad (4)^1$$

1. McCutcheon, S.C., Martin, J.L, Barnwell, T.O. Jr. 1993. *Water Quality in* Maidment, D.R. (ed.). *Handbook of Hydrology*, McGraw-Hill, New York, NY (p. 11.3)

Table 1. Density of fresh water

The fresh water density table below was calculated from equation 4 which you can use directly, or values can be interpolated from the table:

°C	kg·m ⁻³	°C	kg·m ⁻³
20	998.2336	46	989.8212
21	998.0221	47	989.3920
22	997.8003	48	988.9559
23	997.5684	49	988.5130
24	997.3266	50	988.0633
25	997.0751	51	987.6070
26	996.8141	52	987.1441
27	996.5437	53	986.6746
28	996.2642	54	986.1987
29	995.9757	55	985.7164
30	995.6783	56	985.2277
31	995.3722	57	984.7327
32	995.0575	58	984.2315
33	994.7344	59	983.7242
34	994.4030	60	983.2106
35	994.0635	61	982.6911
36	993.7159	62	982.1654
37	993.3603	63	981.6339
38	992.9970	64	981.0963
39	992.6260	65	980.5529
40	992.2473	66	980.0037
41	991.8612	67	979.4486
42	991.4676	68	978.8878
43	991.0668	69	978.3213
44	990.6587	70	977.7491
45	990.2435	71	977.1713

Example Data Set

Example data file from the thermal plume experiment. Z and X (inches) are the vertical and radial positions of the thermocouple array. T_{bulk} and T_{jet} (deg C) are the temperatures of the bulk water in the tank and at the jet. T1 through T6 are the six individual thermocouple temperatures from the lowest (T1) to the highest (T6), at 1" spacings. In the data shown below the lowest thermocouple T1 was located 2" above the jet, referenced as Z = 0.000", such that thermocouples T1, T2,..., T7 were positioned at 2", 3",... 7" above the jet. Similarly, at the Z = 6.000" position the T1 thermocouple is positioned 8" above the jet. The standard deviation (SD) values are open to some interpretation because of the way in which LabVIEW does the sampling. The resolution of any single temperature measurement is about 0.3 degrees C. The result is that while the sampling means are accurate the standard deviations may be affected by the sampling resolution of the data acquisition system and may not reflect the actual standard deviation of the sample.

Z	X	T _{bulk}	T _{jet}	T1	T2	T3	T4	T5	T6	SDT _{bulk}	SDT _{jet}	SD1	SD2	SD3	SD4	SD5	SD6
0.000	0.000	19.092	50.455	21.667	19.678	19.233	19.043	18.608	18.777	2.064	0.645	0.952	0.836	0.711	0.645	0.679	0.636
0.000	0.100	17.727	50.922	21.515	19.900	19.283	19.026	18.567	18.525	2.231	0.679	1.077	0.768	0.672	0.645	0.741	0.657
0.000	0.200	17.712	51.046	20.707	19.827	19.208	18.919	18.481	18.561	2.621	0.649	1.159	0.855	0.674	0.665	0.772	0.623
0.000	0.300	17.512	51.223	19.470	19.287	19.060	18.815	18.418	18.458	2.622	0.601	1.209	0.863	0.680	0.660	0.784	0.645
0.000	0.400	17.744	51.195	18.209	18.780	18.715	18.627	18.380	18.422	2.355	0.676	1.076	0.805	0.658	0.638	0.719	0.622
0.000	0.500	17.798	51.010	17.724	18.159	18.371	18.408	18.191	18.285	2.283	0.640	1.087	0.783	0.649	0.667	0.714	0.618
0.000	0.700	17.595	51.112	17.735	17.622	17.979	18.179	18.019	18.160	1.965	0.635	0.967	0.770	0.667	0.642	0.682	0.617
0.000	0.900	17.627	50.950	17.674	17.511	17.750	17.954	17.809	18.021	1.837	0.634	0.955	0.729	0.643	0.609	0.649	0.630
0.000	1.200	17.845	51.101	17.646	17.578	17.643	17.879	17.801	17.961	1.432	0.663	0.852	0.696	0.792	0.611	0.654	0.643
6.000	1.200	17.877	50.957	18.041	17.923	17.963	18.067	17.864	18.062	1.078	0.660	0.698	0.668	0.627	0.595	0.617	0.610
6.000	0.900	17.862	50.921	18.085	17.914	17.962	18.067	17.867	18.022	1.137	0.653	0.640	0.657	0.621	0.590	0.634	0.633
6.000	0.700	17.726	50.791	18.039	17.927	17.940	18.010	17.788	17.949	1.190	0.689	0.709	0.711	0.635	0.620	0.647	0.615
6.000	0.500	17.733	50.732	18.099	17.913	17.958	17.996	17.800	17.978	1.317	0.732	0.709	0.712	0.663	0.634	0.668	0.660
6.000	0.400	17.735	50.703	18.105	17.894	17.924	17.986	17.793	17.945	1.235	0.711	0.690	0.718	0.647	0.635	0.647	0.638
6.000	0.300	17.704	50.732	18.165	17.967	17.939	17.974	17.807	17.965	1.247	0.729	0.713	0.720	0.659	0.636	0.687	0.662
6.000	0.200	17.749	50.708	18.118	17.948	17.935	17.943	17.795	17.938	1.204	0.690	0.678	0.700	0.657	0.613	0.648	0.661
6.000	0.100	17.790	50.348	18.248	18.055	18.041	18.098	17.885	18.053	1.231	0.722	0.732	0.719	0.644	0.628	0.660	0.652
6.000	0.000	17.893	50.374	18.409	18.171	18.148	18.224	18.008	18.220	1.258	0.748	0.704	0.709	0.628	0.649	0.660	0.630
0.000	0.000	17.767	50.469	21.335	19.653	19.144	18.948	18.597	18.696	2.903	0.690	1.189	0.882	0.700	0.672	0.729	0.677
0.000	0.100	18.068	50.239	21.116	19.772	19.253	19.077	18.775	18.824	3.077	0.916	1.310	1.007	0.809	0.714	0.837	0.707
0.000	0.200	17.386	50.351	20.840	19.994	19.380	19.251	18.874	18.986	3.296	0.915	1.336	1.030	0.796	0.729	0.813	0.750
0.000	0.300	18.707	50.313	19.591	19.561	19.297	19.232	18.913	19.044	2.811	0.867	1.276	0.985	0.808	0.770	0.814	0.726
0.000	0.400	18.815	50.578	18.632	19.211	19.262	19.256	18.945	19.114	2.509	0.927	1.121	0.916	0.760	0.758	0.792	0.697
6.000	0.400	18.660	50.562	19.125	18.939	18.941	19.034	18.854	19.086	1.548	0.962	0.816	0.835	0.724	0.729	0.744	0.720
6.000	0.300	18.785	50.613	19.256	19.030	19.048	19.161	18.953	19.191	1.317	0.739	0.713	0.720	0.655	0.657	0.635	0.655
6.000	0.200	18.944	50.839	19.428	19.227	19.200	19.319	19.121	19.342	1.167	0.723	0.727	0.689	0.636	0.620	0.656	0.655

