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Turbulent plume –Week 3
PLUME CHARACTERISTICS and STRUCTURE

General description

The experiment consists of a plume produced by warm water injected at the bottom of a tank of quiescent room-temperature water (Fig. 1). The flow physics of the plume is controlled by the excess buoyancy (temperature excess against the background) and the momentum flux (controlled by a pump) at the plume nozzle exit. Morton length scale (L_M, Eq. 5) defines the relative strength of momentum and buoyancy fluxes at the nozzle exit, and it dictates the characteristics and structures of the plume. For smaller L_M the plume is dominated by momentum, known as jet, and its centerline reduced gravity (Eq. 6) decreases linearly with the distance from the nozzle. For higher L_M the plume is dominated by buoyancy, known as buoyant plume, and its centerline reduced gravity decreases as $z^{-5/3}$, where z is the distance from the nozzle.

In week 3, we will study the characteristics of the buoyancy dominated plume and the effect of stratification. During the experiment, as warm water is being pumped into the cold water filled tank, a stable stratification will develop at the top of the tank, and this stable stratification will destroy the plume. As discussed in week 1, temperatures through the plume are measured with an array of thermocouples. There are four additional thermocouples located behind the thermocouple array far from the nozzle to measure the bulk water temperature, and another thermocouple located immediately beneath the nozzle in the nozzle assembly to measure the plume entry temperature. Positioning of the thermocouple array and data acquisition are controlled with a LabVIEW program.

Objectives: There are three main tasks to be accomplished this week:

1. To measure temperature profiles throughout the plume.
2. To assess the thermal structure of the plume.
3. To test self-similarity and scaling laws.

Procedures

Task 1: Measure temperature profiles throughout the plume.

Take careful measurements, but also move expeditiously through this procedure to minimize the temperature rise of the bulk tank water.

a) Fill the heating pan with hot tap water almost upto its rim and heat it to about 85 ^{0}C with the circulating immersible heater (thermostat set at 8.5). This will act as the source of warm water in the experiment. Add some vegetable dye to the hot water for visualization of the plume.
b) Place the plume nozzle assembly (nozzle inside diameter 1.32 mm) at the bottom of the tank near the center. Make sure the plume nozzle assembly is just below the thermocouples array. To do

that, ***carefully*** bring down the thermocouple array close to the plume nozzle assembly using the VI, and adjust the plume nozzle assembly position by viewing it from top. Using the acrylic positioning fixture, set the position of the thermocouple array directly above the nozzle with the lowest thermocouple 3" above the nozzle exit. To do this, run the VI and use it to move the thermocouple array. Once you have the correct starting position, stop the VI, then restart it. This will re-zero the 'X position' and 'Z position' fields.

c) Fill the tank to the indicator mark with tap water slowly. After filling the tank, stir the water with the stirring paddle to eliminate any temperature gradients, and measure the tank water temperature with the glass thermometer. Match all the thermocouples to the thermometer temperature using the VI. Then let the water stand for about 5 – 10 minutes to allow any residual turbulence and mixing to dissipate.

d) Prime the peristaltic pump into a beaker by immersing the inlet in the hot water pan and disconnecting the pump outlet from the plume nozzle assembly. Reconnect the pump outlet to the nozzle tube and start the pump at volume flow rate of 10 ml/min. Wait for about 5 – 10 minutes for the plume to develop to a vertical steady state, as seen by observing the dye.

e) **Refer to figure 1.** Start taking measurements with the lowest thermocouple at 3" from the nozzle exit at X position 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.7, 0.9, 1.2 inches. Wait for at least 15 seconds when you move the thermocouple array to a new position before taking measurements. When you click the Read button on the VI the thermocouple array will be scanned at 10 Hz for 2000 samples. The scan will take a little over 3 minutes to complete. When completed you will be prompted to save your data. Enter a filename and save. Use the same file for all measurements; subsequent scans will be appended to the existing file. Following the 1.2" scan, move the thermocouple array up by 5", so that lowest thermocouple is at 8". Take measurements at 1.2, 0.9, 0.7, 0.5, 0.4, 0.3, 0.2, 0.1, 0.0 inches.

f) Move the thermocouple down by 5", so that the lowest thermocouple is back at the 3" from the nozzle. Then repeat step (e) for another set of data. For second set of data take measurements upto X position 0.4 inches.

g) After finishing the experiment stop the immersion heater. Flush out residual warm dyed water in the plume nozzle assembly with tap water from a beaker, empty the tank using a siphon and the wet/dry vacuum, remove the plume nozzle assembly and dry it with paper towels. ***Carefully*** empty the hot water pan. Note the thermocouple temperatures during the emptying process of the tank. Stop the VI and clean up the workplace.

NOTE: The columns for the data file from VI are:

Z position (in), X position (in), Bulk mean temperature (^{0}C), Jet mean temperature (^{0}C), Thermocouple mean temperatures (^{0}C, starting from the lowest one), Bulk rms temperature (^{0}C), Jet rms temperature (^{0}C), Thermocouple rms temperatures (^{0}C, starting from the lowest one)

Task 2: Assess thermal structure of the plume.

a) Calculate Morton lengthscale L_M using Eq. 5.
b) Plot the change in bulk temperature during the course of the experiment.

c) Plot normalized reduced buoyancy ($g'B^{-2/3}z^{5/3}$) across normalized plume radius (r/z) over different heights (z), where g', and B are reduced buoyancy (Eq. 6) and buoyancy flux at nozzle exit (Eq. 4) using data collected during Task 1 step e and f..

d) Plot normalized plume centerline reduced buoyancy ($g'zM^{1/2}B^{-1}$) against normalized height (z/L_M), where M is the momentum flux at nozzle exit (Eq. 3) using data collected during Task 1 step e and f..

Task 3: Test self-similarity and scaling laws.

a) From the generated plots of normalized plume centerline reduced buoyancy vs normalized height, find out the critical z/L_M value, below which your data shows buoyancy dominated plume behavior and above which it shows the effect of stratification.

b) Fit a power law curve

$$g'zM^{1/2}B^{-1} = C(z/L_M)^D \tag{1}$$

through the decay of normalized centerline reduced buoyancy for below the critical z/L_M region and above the critical z/L_M region. Determine the coefficient C and power law exponent D for these two regions.

c) Fit a Gaussian curve

$$g'B^{-2/3}z^{5/3} = A_0\exp(-B_0(r/z)^2) \tag{2}$$

through the radial profiles of normalized reduced buoyancy for below the critical z/L_M region and above the critical z/L_M region. Determine the constants A_0 and B_0 for these two regions.

Error analysis

1. Calculate any systematic errors in the measurements you take.
2. Determine random errors from repeated samples.
3. Plot all data with appropriate error bars.

Definitions

The momentum flux (M) at the nozzle exit is determined by

$$M = \int_0^R 2\pi w^2 r\,\mathrm{d}r \sim W^2 A \quad , \tag{3}$$

where R, w, W and A are nozzle radius, vertical velocity at nozzle exit, area averaged vertical velocity at nozzle exit ($=\frac{Q}{A}$, where Q is the volume flow rate) and cross sectional area of the nozzle.

The buoyancy flux (B) at the nozzle exit is determined by

$$B = \int_0^R 2\pi g'_o w r\,\mathrm{d}r \sim g'_o W A \quad , \tag{4}$$

where $g'_0 = g'(r, z = 0)$ is the reduced buoyancy at nozzle exit.

The Morton length (L_M) is determined by

$$L_M = \frac{M^{3/4}}{B^{1/2}}. \tag{5}$$

The reduced density (g') is defined by

$$g'(r,z) = g\,\frac{\rho_w - \rho_h(r,z)}{\rho_w}, \quad (6)$$

where g, ρ_w and ρ_h are gravitational constant (= 9.81 m s^{-2}), density of bulk water in the tank and density of heated water inside the plume at a radial distance r from the plume centerline.

Convert the measured water temperatures into the water density by using Eq 4 of Week 1 procedure.

Note that: B and M are calculated at the nozzle exit and should be constant. Small variations are unavoidable, due to filling effect.

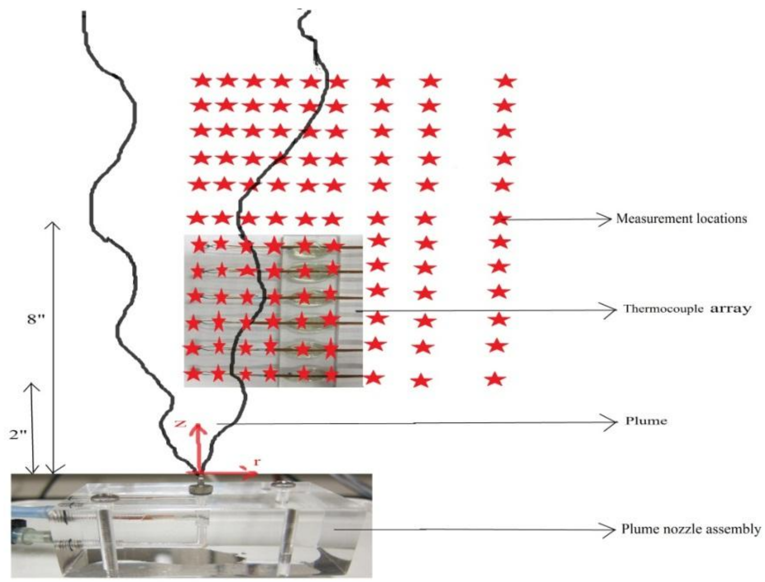

Figure 1. Diagram showing plume experimental setup. Stars indicate points of measurement using the thermocouple array as explained in the text.