

STRUCTURE OF CHEMICAL PLUMES

Background & review

Structures of chemical plumes in shear or turbulence vary with both time and distance from the source. They also can depend in subtle ways on the geometry of the source. In anticipation of the sessions on sensory cues, imagine what cues might be exploited in the plume structure to tell how far away and in what direction the source is found. To exercise your understanding of plume structure, first study streaklines and dye “particle” paths released in a smooth-turbulent boundary layer at various heights. Include one release right at the seabed, one a little higher but still within the viscous sublayer, and one in the turbulent log layer.

This morning you began looking at the molecular diffusion coefficient, D [$L^2 T^{-1}$], that characterizes the rate at which random thermal motions of molecules produce a flux, J , across a boundary [$mol T^{-1} L^{-2}$]:

$$J = -D \frac{\partial C}{\partial y}. \quad (1)$$

Don't ask “y” for now, but do think about the cross-stream direction most intensely for today's exercise. It's the dimension to which we have given least attention, but it is by no means unimportant to animal search strategies. We looked at two other coordinate systems this morning, z , for the case of a diffusive boundary layer and r for the case of a single bacterium. We picked a very simple situation, that of constant flux, which means that the concentration gradients must be constant in time, with material being taken away at one end of the gradient and being supplied at the other at exactly the same rate as this flux.

With a one-dimensional, diffusive boundary layer of thickness δ , Eq. 1 simplifies to

$$J = -\frac{D}{\delta}(C_{\infty} - C_0), \quad (2)$$

where C_{∞} = the concentration in the log layer or anywhere far from the bed and C_0 is the concentration at the sediment-water interface. This equation is an important one in oceanography for calculating the fluxes of dissolved oxygen and other oxidants into the seabed or reduced materials, such as ammonium ion, out of the seabed. Notice what happens if $C_{\infty} < C_0$: The flux reverses, *i.e.*, comes out of the sediments. That actually happens when diatoms on the bottom produce oxygen. It also happens for many substances that are produced by organic decay, such as ammonium from protein degradation.

We also observed that for constant flux to a spherical organism the gradient in concentration away from the surface has to decline (get less steep) as r^2 because the surface area through which the flux moves grows as r^2 , where r is distance from the center of the cell. In this case we can calculate the area of cell surface and come up with a flux per cell rather than per unit area of cell. Curiously, it comes out linear in cell radius, r_0 :

$$J = -4\pi D r_0 (C_{\infty} - C_0). \quad (3)$$

One reason that it is worth doing the calculation is that faulty intuition or careless application of Eq. 1 or 2 might lead one instead to believe that the flux to a cell should be proportional to its surface area.

Today's exercise

In the flow downstream of a dye source, consider the factors that contribute to cross-stream transport of dye. The mean flow won't do it, so **what spreads a plume cross stream?** Turbulence will move material in all three directions (unless tightly constrained by some barrier such as a solid wall or a strong density gradient), so it is definitely a candidate. Molecular diffusion will move material down gradient (as per the minus signs in the equations) so it also acts. I could throw more equations, but let me try something else, whose success I will judge by reading your essays. Once we are far from the dye source, and in particular if it is obvious that the dye is spreading in a plume, then the situation must be different from the steady states of Eq. 2 and 3. Flux is moving material down gradient, so absent a resupply mechanism the gradient must be getting weaker. So molecular diffusion is always working to make gradients weaker, *i.e.*, the concentration more uniform. Remember that shear works in all directions in turbulence but is oriented along the vertical axis in the viscous sublayer. Shear can accelerate molecular diffusion in two ways. It can stretch a filament of dye into previously clear water. The stretching not only decreases the scale of the concentration difference (steepens the gradient by making the same concentration difference span a smaller distance) perpendicular to the shear, it also expands the surface area over which molecular diffusion can operate. One way to get an appreciation for what pure shear does is to inject dye in the middle of the diffusive sublayer and watch from the side of the flume.

The requests and questions are meant to stimulate your thinking. **Take the time to organize your answer in a parsimonious, logical order rather than answering the questions in the sequence that they occur. Describe the structure of the plume on both large and small scales. Consider both time and distance from the source, as well as the local boundary-layer structure (turbulent or not).** Water moves slower near the bed, so by the time it gets to the end of the flume it has spent more time (*e.g.*, for diffusion) in the flume than water traveling nearer the surface. **Where and when after leaving the source do you think that molecular diffusion is moving the most material laterally (cross stream) per unit of time?** Explain your reasoning. **Where and when do you find the greatest number of distinct dye filaments in a cross section of the flow, and what does that observation tell you about the instantaneous importance of molecular diffusion at that section and time? Where and when is molecular diffusion moving the least material across stream per unit of time and why? What differences do you expect between instantaneous plume structure and mean plume structure and why? Use any combination of text, illustrations and equations to support your answer. Even if you don't write out the equations, consider both strength of the gradient and the area over which it can operate.**

Thinking (and writing) ahead

Answers to the following questions also should be included in your essay. **How could a chemosensing organism utilize the information in a chemical plume to localize and move toward the source? Could it tell from the structure of the plume whether the source is near or far away?** Think like a lobster (unless you are feeling crabby). Come up with an idea of how it should move if it follows the stimuli that you suggest. Compare your ideas with your colleagues'. There is no harm in trying an experiment to test your ideas. If you run a crab or lobster in the flume, if you crush a mussel, add some food coloring so that you can visualize where the food "odor" goes. Incidentally, crabs in the field find clams by sniffing for dissolved cues in their exhalent plumes (clam "breath"). For the sake of consistency, if you discuss chemosensing, refer to chemosensing at a distance as using odor or smell and chemosensing by physical contact as using the sense of taste.