

NAME:

Biology 641

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**Lab 3: Methods for measuring mass flux;
or,
How to do marine biology when you don't have an ocean.**

The Physical Basis of Mass Transport

The flux of any material, be it a gas, liquid or solid, between the surface of an organism and the surrounding fluid (air or water) is strongly modulated by the pattern of fluid movement around the creature and the resultant local flows at its surface. This convective regime depends on the organism's size and shape as well as on the characteristics of the moving fluid (viscosity, density, speed, and turbulence levels). With the exception of shape, each of these parameters is known or is easily measured. In contrast, the effects of shape on convective exchange must be extracted experimentally and are traditionally reported as a coefficients of mass transfer [this coefficient is directly analogous to the coefficient of heat transfer, as well as a drag coefficient]. In general, the flux of any dissolved substance (e.g. water vapor in air, CO₂ [in the form of bicarbonate] or O₂ in water) is determined by the local concentration gradient of the solute near the organism's surface, and by the interaction of local flow with the organism's morphology:

$$dm/dt = h_m A (C_s - C_f)$$

where dm/dt is the mass exchange rate, h_m is the coefficient of mass transfer, A is the area over which flux occurs (m²) and $(C_s - C_f)$ is the concentration difference of the solute between the surface of the organism and the surrounding fluid.

To solve for the mass transfer coefficient, we simply rearrange the equation to:

$$h_m = (dm/dt) / (A (C_s - C_f))$$

In air, we often are concerned with rates of water loss because it causes organisms to desiccate, and also because it permits them to evaporatively cool. As water evaporates (changes from liquid to gas), it releases heat energy during the phase change. This release of heat is called the *latent heat of vaporization*, and is usually represented by the symbol lambda, λ , equal to $\sim 2.5 \cdot 10^6$ J/kg. Thus, the rate of heat lost due to evaporation is simply:

$$Q_{\text{evap}} = \lambda \, dm/dt$$

Note that this is a huge amount of heat energy per unit of water lost; a loss of 1g of water per second corresponds to heat loss of 2500 W. We won't discuss this any further for this class, but keep it in mind when you study the ecology of temperate intertidal communities!

For aquatic organisms, the solute that we're interested in most often is oxygen, as the rate of oxygen exchange drives rates of cellular respiration, and in the case of aquatic plants and algae, is a measure of rates of photosynthesis. Usually, this is accomplished by placing the creature in a small experimental chamber so that accurate changes in oxygen concentration can be measured over reasonable time scales (see for example Patterson and Sebens, 1989; Patterson *et al.*, 1991; we'll try to do some of this in Lab 5). Such small chambers, however, make it very difficult to recreate realistic flows, and so it becomes very difficult to measure the interactive effects of shape and water flow on mass exchange. In contrast larger chambers flows, while providing much more realistic flows, (e.g. Atkinson and Bilger, 1992; Thomas and Atkinson, 1997) contain such a high volume that it becomes necessary to measure rates of gas exchange from entire communities of organisms, and this method does not permit the assessment of any localized differences in uptake rates. However, using a few biophysical tricks, it is possible to measure the mass flux of one type of solute to calculate the flux of any other mass item (see Helmuth *et al.* 1997). In fact, we can even measure heat flux to calculate mass flux, since the two mechanisms are analogous.

Today we'll measure the rate of water loss from models in air to calculate the flux of oxygen in water. In order to measure the effects of shape and fluid flow on mass flux, we need to accurately describe the flow environment in our experimental conditions in order to extrapolate to those in the field. We do this using a dimensionless ratio called the Reynolds number (Re). When Re and the scale of turbulence are conserved, one can use fluid flow in air to reliably mimic water flow, and vice versa. Moreover, conservation of Re permits the use of scale models. The Re is a measure of the relative importance of inertial and viscous stresses in a moving fluid and thus its conservation implies geometrically similar flow patterns:

$$Re = (\rho U L) / \mu$$

where U is the velocity of fluid relative to the body (m/s), L is a characteristic dimension (e.g. length) of the body (m), ρ is the density of the fluid (kg/m^3) and μ is the dynamic viscosity of the fluid [$\text{kg}/(\text{m s})$].

Because the parameters ρ and μ often appear together when describing the physical characteristics of a fluid, they are generally combined in a term called kinematic viscosity (ν), where $\nu = \mu / \rho$. Another way of defining Re is thus:

$$Re = U L / \nu$$

As mentioned above, mass flux is also affected by the levels of external turbulence found in the environment, often measured as a turbulence intensity (the

standard deviation of the fluid velocity divided by its mean value). However, to keep matters simple today, we won't worry about measuring this parameter. Just keep this in mind if you ever repeat this experiment "for real."

For our physical analogs we will use life-sized models of coral branches and control air velocity to match Re values found in the field. Because the kinematic viscosity (ν = ratio of μ to ρ) of air at 20°C (= $15 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$) is approximately 17 times greater than that of water at 30°C (= $0.86 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$), values of Re in air can be matched to those in water by increasing air velocity (U) by a factor of 17. Thus, all other factors being equal, an air velocity of 5 m/s corresponds to a water velocity of approximately 30 cm/s (i.e., $0.3 * 17 = 5$).

The profile of a solute gradient is termed a diffusion boundary layer (DBL), much in the same way that a gradient in momentum is visualized as a momentum boundary layer. Indeed, the two are closely related, and momentum boundary layers with steeper profiles lead to sharper concentration gradients in mass and thinner DBLs, thus enhancing convective mass transfer. Both are affected by the geometry of the organism, as well as by Re and turbulence intensity. The coefficient of mass transfer, h_m , is an empirically-derived metric for the degree to which the geometry of the organism interacts with ambient flow to drive mass transfer. Since two physical phenomena, diffusion and convection, affect mass transfer and its coefficient, we use another nondimensional parameter, the Sherwood number (Sh), to capture their effects:

$$Sh = h_m L / D_i$$

where D_i is the molecular diffusivity of species i in the fluid of interest. This nondimensional number measures the relative contributions of diffusive and convective phenomena and thus depends upon Re with the same characteristic length. This dependence upon Re arises from the relative dimensions of the diffusional and momentum boundary layers surrounding an object. Their relative dimensions, in turn, scale as the 1/3 power of the diffusivity of momentum (kinematic viscosity, ν) and that for mass flux (diffusivity of the chemical species of interest, D_i). Sadly, this introduces yet another nondimensional term, the Schmidt number (Sc):

$$Sc = \nu D_i^{-1}$$

Once we know values of Sh for any mass/fluid combination, we can calculate any other combination by multiplying it by Sc raised to the 1/3 power. Thus, for example, if we measure Sh - Re relationships for water loss in air, the same relationship can be used to estimate CO_2 (bicarbonate) or O_2 flux in water as long as (1) Re is conserved, (2) Turbulence intensity is conserved, and (3) the Sc is adjusted for the kinematic viscosity of water and the diffusivity of CO_2 or O_2 in water. As a result, once the effects of geometry on the flux of any one mass species i have been extracted as a relationship between Sh and Re , it is then possible to calculate values of Sh for any other mass species in any other fluid by adjusting values of D_i and ν to the mass item and fluid in question. In this instance, Sc for both O_2 and CO_2 flux in 30°C water is approximately 430, while

that for water vapor in air is approximately 1. Sh for water flux in air may be adjusted to gas flux in water by multiplying by the ratio of the cube roots of each of these values, a factor of 7.5.

Procedure:

Methods for measuring water loss rates in air are fairly simple. Pieces of filter paper have already been fitted with foil backings using a small amount of glue. Using calipers, measure the surface area (m^2) of each numbered filter paper. Affix a small piece of double-stick tape to four of these, and saturate them with distilled water, shaking off any extra water beaded on the surface until only water held by the filter remains. Weigh each filter paper, and quickly affix it to one of the models. Repeat this until you have filter papers in each of four regions (e.g. upstream, downstream, top, middle, bottom, etc). Place the model with attached filter papers in front of a fan (normally this would be done in wind tunnel), and allow the papers to lose water via convection for 10-15 minutes. During this 10 minute period, use an anemometer to measure the wind speed (m/s) at a “mainstream” location (upstream of the model before the moving fluid interacts with it). Use the sling psychrometer to measure wet and dry bulb temperatures (a measure of relative humidity) at or near this same location. Assuming that the temperature of the wet filter is similar to that of the wet bulb, calculate the vapor densities of the filter and air using the equations (units in kg/m^3 ; temperature in $^{\circ}C$):

$$C_s = 0.0052 \exp(0.598T_{wet})$$

$$C_f = C_s - 0.0005 (T_{air} - T_{wet})$$

At the end of the run, use the thermocouple thermometer to measure the temperature of one of the filter papers. While losing water, the filter has cooled via evaporative water loss and is likely to be much cooler than the temperature of the surrounding air. Interestingly, the filter rapidly cools to a fixed temperature, and then remains at that temperature, even though water continues to be lost. This temperature is called the *dew point*, and occurs when liquid water spontaneously forms at the object’s surface.

Immediately weigh the filter papers to the nearest 0.01g to calculate the rate of mass flux (dm/dt , in units of kg/s). You now should have all of the pieces necessary to calculate h_m , Re and Sh :

$$Re = UL / \nu$$

$$h_m = (dm/dt) / (A (C_s - C_f))$$

$$Sh = (h_m L / D_i) Sc^{1/3} = 7.5 h_m L / D_i$$

Where:

$$\nu = 15 \cdot 10^{-6} \text{ m}^2 \text{ s}^{-1}; D_i = 24.2 \cdot 10^{-6} \text{ m}^2 \text{ s}^{-1}$$

Repeat this procedure for 3-4 flow speeds, and graph Sh as a function of Re for each region of your “coral.”

Questions to address in your report:

1. What differences, if any, did you observe in different regions of your colony? What implications might this have for coral physiology?
2. What assumptions does this technique make, and what factors might limit its usefulness for studying gas or nutrient exchange in corals?
3. What questions might you be able to address using this technique?
4. What does this lab tell you about trade-offs in morphological design that result from multiple selective pressures?