An Inquiry Activity in Diffusion

Laura P. Ford
University of Tulsa

Abstract

In Spring 2022, a quick experiment was done during class to measure the diffusivity of a body splash in air. The measured diffusivity was three orders of magnitude higher than typical literature values. The students then discussed the weaknesses of the experiment. Performance on this discussion was compared to a related question on the final and overall student performance in the course, but no correlations were found.

Keywords

Chemical Engineering, diffusion, inquiry activity

Introduction

An inquiry activity was done during lecture in ChE 3084, a junior-level chemical engineering course. The course content is roughly 2 credit hours of separations, 1 credit hour of simulations, and 1 credit hour of mass transfer. The experiment was to measure a diffusivity, to compare it to literature values, and to develop of list of weaknesses of the experiment.

The diffusivity is a measure of how quickly a compound moves through another due to a concentration gradient. Fickian diffusivities of alcohols in air are on the order of 1 x 10^{-5} m^2/s at room temperature [1]. Experimental data were analyzed with the concept of diffusion time, in which the time for a molecule to diffuse an average distance in one dimension is given by Equation 1 [2].

$$t = \frac{x^2}{2\,D} \tag{1}$$

in which t = time,
x = distance, and
D = diffusivity.

During lecture, Equation 1 was related to the solution for unsteady binary Fickian diffusion with no convection. In this case, the concentrations in an infinitely thick solid slab are given as a function of a dimensionless distance ζ in Equation 2.

$$\zeta = \frac{x}{2\sqrt{Dt}} \tag{2}$$

When Equations 1 and 2 are compared, the diffusion time must be when the dimensionless distance ζ is equal to one. This lecture material was intended to seed the students with assumptions for the analysis which may or may not apply to the experiment, primarily the assumption of no forced convection.

Methods & Results

In the experiment, the professor opened a bottle of body splash and set it on a table at the front of the classroom. The students were asked to record the elapsed time to when they smelled the body splash. After some time spent on other activities while the body splash diffused across the room, the professor collected the times from the students, estimated the distances from the body splash to each student, and then calculated the diffusivity. Results are shown in Table 1.

Table 1. Diffusivity of body splash in air at room temperature

Student	Distance, ft	Time, minutes	Diffusivity, ft^2/min
A	12	5.60	13
B	10	4.80	10
C	17	2.55	57
D	18	2.67	61
E	19	6.10	30
F	25	9.10	34
G	19	7.10	25

The average diffusivity was 30 ft^2/min or 5×10^{-2} m^2/s.

Why were the results so much larger than the literature value of about 1×10^{-5} m^2/s? No distances were actually measured, so the values were not expected to be correct, but a difference of three orders of magnitude cannot reasonably be explained by poor distance estimates. The students described the weaknesses of the experiment in a written activity that was submitted for participation credit. Students were allowed to talk to each other, so the work was not independent, even though the participation credit awarded was. A summary of paraphrases of the student's listed experimental weaknesses is given in Table 2. Assignment sheets are available for only 17 of the 29 students in the course.

The many comments that were categorized as "other" were given by only one student, were irrelevant, or were incorrect. These "other" responses were

- the concentration in the room is different from that in the bottle,
- temperature, pressure, and concentration were constant so there was nothing impacting diffusivity,
- we assumed constant concentration in the bottle or that we assumed a particular value,
- we assumed the perfume will diffuse throughout the room,
- we assumed a closed environment,
- uniform diffusion assumed,
- only 1 trial,
- small pool of people to detect,
- website used for the equation gave no references, and
- vapor cannot spread easily from the small bottle opening.

Table 2. Percentage of 17 students citing different weaknesses of the experiment

Reason	Percentage citing
Detection equipment was faulty (unknown scent, masks worn, different sensitivities to smell)	100
Convection was present	53
The distance measurements were not exact	53
Ventilation was present	47
Temperature and/or pressure was changing	29
Equations are not accounting for temperature and pressure	24
Initial concentration was not zero as assumed	18
Assuming one directional diffusion	18
Other	47

The faulty detection equipment (our noses, some covered by masks), was cited by everyone in the course. Slow detection equipment would make the measured diffusivity *smaller* than the literature diffusivity, as it would take longer for us to detect the body spray than it should. Our measured diffusivity was *larger* than it should have been, so faulty detection equipment could not have been why.

A majority of the students mentioned the assumption of no convection, which is a very confusing topic in mass transfer. Convection here refers to the one-way movement of material, without corresponding movement of another component in the opposite direction. An example with convection is water vapor diffusing from a liquid water/air interface, but the air does not diffuse to the interface. The air is unlikely to dissolve in the water in appreciable amounts, which would lead to a buildup of air at the interface if there were air diffusion to the interface. Convection is unlikely to occur inside the bottle of body splash, so the assumption of no convection would be used to model the diffusion within the bottle and the drop of the liquid interface with time. The experiment, however, was modeling the diffusion of the body splash from the bottle to the students in the room. The air in the room can counter-diffuse towards the bottle to replace the body splash diffusing outwards, maintaining room pressure and density above the bottle. The assumption of no convection was therefore a good assumption, and half of the students were wrong.

As mentioned before, the inexact distance measurements cited by half of the class would not account for the three orders of magnitude difference between our measured diffusivity and literature. The distances in Table 2 would need to be about 6 inches rather than about 15 ft for the diffusivity to match literature values.

Almost half of the students mentioned the ventilation in the room – that it would either help the spread of the body splash or hinder its spread, depending on air flow direction. A similar comparison would be heat transfer coefficients for free and forced convection. Analogies are commonly made between mass transfer coefficients and heat transfer coefficients, and mass transfer coefficients are proportional to diffusivity. Forced convection heat transfer coefficients are five to twenty times higher than those for free convection [3], so forced convection could account for some of why the experimental diffusivity was higher than the literature value.

An improvement on this exercise would be to modify the question the students were given. They were asked to list the weaknesses of this experiment. Given that some of the responses would not explain the discrepancy between the experimental diffusivity and the literature value or would even give the opposite trend of what was seen, a better assignment would be for them to list weaknesses and to explain how each listed weakness would cause the experimental diffusivity to be higher than the literature value.

This activity could be done on the first day of mass transfer as a motivating exercise, as proposed by a reviewer. One could also attempt to run the activity with a fan to provide forced convection so that different diffusivities could be compared. A pool or puddle of body splash might also provide a more concentrated source for diffusion than the open bottle.

Student responses in this activity were compared to scores on the related final exam question and overall course grades for the sixteen responses with names. No response sheets for the four students who earned a D or an F in course were available. There were no statistically significant differences in scores at the 5% confidence level on the related final exam question or the course overall based on whether or not the students included convection or ventilation in their responses.

Summary

An inquiry-based activity was done in a mass transfer course to measure a gas diffusivity, compare to literature, and describe weaknesses in the experiment. All of the students blamed faulty detection equipment, which would have given smaller diffusivity rather than the larger one that was found. Half of the students incorrectly said the assumption of no convection did not hold. About half of the students mentioned the likely main weakness of ventilation in the room. No correlations between student responses for the activity and a related final exam question or overall course grade were found.

References

[1] P. C. Wankat, Separation Process Engineering, 4th ed., Boston, MA: Prentice Hall, 2017.

[2] "Diffusion Time Calculator," [Online]. Available: https://www.physiologyweb.com/calculators/diffusion_time_calculator.html. [Accessed 4 8 2022].

[3] "Convective Heat Transfer Coefficients Table Chart," Engineers Edge, 4 8 2022. [Online]. Available: https://www.engineersedge.com/heat_transfer/convective_heat_transfer_coefficients__13378.htm.

Laura P. Ford

Laura P. Ford is an Associate Professor in the Russell School of Chemical Engineering at the University of Tulsa. She has earned degrees in chemical engineering from Oklahoma State University (BS) and the University of Illinois at Urbana-Champaign (MS and PhD). She teaches engineering science thermodynamics and fluid mechanics, separations and mass transfer, senior lab, and advanced controls lab. She advises the Engineers Without Borders – USA chapter and is working with the Refining Technologies Joint Industry Project.