A RESPIRATION EXPERIMENT

To Introduce ChE Principles

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Rowan's two-semester freshman clinic sequence introduces all freshman engineering students to engineering in a hands-on, active learning environment. Engineering measurements and reverse engineering methods are common threads that tie together the different engineering disciplines. Previous reverse engineering projects have involved common household products such as automatic coffee makers,[1-3] hair dryers, and electric toothbrushes.[4]

Recently, the human body was added to the repertoire of familiar machines to be reverse engineered. In a semester-long project, freshman engineering students explore the interacting systems of the human body. They discover the function, interaction, and response to changing demands of various systems in the human body—the respiratory, metabolic, cardiovascular, electrical, and musculoskeletal systems.

This paper describes a laboratory experiment in which students are introduced to engineering measurements and calculations, mass balances, and process simulation through their application to the respiratory system. The experiment and module are appropriate for a freshman engineering course or a sophomore material balances course. A subsequent, related experiment introduces students to the chemical reactions involved in the oxidation of foods and concepts associated with energy balances, but these concepts are not addressed here.

According to Webster,[5] inspiration is the "*action or power of moving the intellect or emotions*"—something all professors strive to do in the classroom. A second definition is also given: "*the act of drawing air into the lungs*"—something we all do and a physiologic process with which we are all familiar. It is the familiarity of the physiologic process of breathing that represents its primary appeal as a framework for teaching engineering principles.

In a hands-on experiment, students measure physiologic variables such as breathing flow rate and respiratory gas compositions both at rest and during moderate exercise on an exercise bicycle ergometer. Using their data, students perform mass balances to determine the rates of oxygen consumption, carbon dioxide production, and water loss. They use a psychrometric chart to obtain water content for inhaled and exhaled air and compare those results to calculated values. Finally, the students create a process flow diagram using a HYSYS[6] process simulator and perform mass balance calculations on the lungs.

This experiment and the associated course content are used in the Freshman Engineering Clinic. Our goal in this course is to give students a first exposure to real engineering measurements, principles, and calculations, and to provide motivation for future in-depth study of mass balances during the sophomore year. The experiment and module could also be used very effectively in a sophomore-level material balances course where mastery of the same engineering principles is

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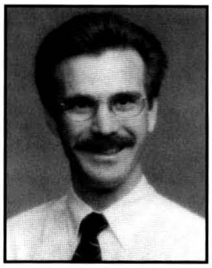

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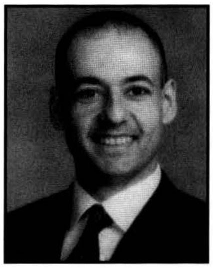

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required. The objectives of the module are

- *To perform measurements of gas concentration and flow rate during breathing*
- *To perform mass balances on the lungs*
- *To represent the process in terms of the relevant unit operations, and to prepare a simple process flow diagram using a process simulator*
- *To use a process simulator to perform mass balances on the lungs*
- *To use a psychrometric chart to estimate the rate of water loss during respiration.*

. . . the human body was added to the repertoire of familiar machines to be reverse engineered. In a semester-long project, freshman engineering students explore the interacting systems of the human body.

The module comprises two 3-hour laboratory periods and three 50-minute classes of combined lecture and cooperative learning exercises. One of the laboratory periods is used to perform the respiration experiment, and the second laboratory period is used for the HYSYS simulation exercise. Each 3-hour laboratory period is sufficient to afford a brief (45-minute) introduction or wrap-up class. The three 50-minute classes are used to introduce the relevant engineering concepts and to perform example calculations using student data in a cooperative learning environment. It should be emphasized that the module is taught inductively—students begin by making experimental observations and afterwards (with structured guidance) "discover" the underlying engineering principles that explain their observations.

BACKGROUND

The air we inspire (inhale) is approximately 21% O_2 and 79% N_2 on a dry basis, while the expired (exhaled) gas from the lungs contains approximately 75% N_2, 16% O_2, 4% CO_2, and 5% H_2O.[7,8] The inspired air is at ambient pressure, temperature, and humidity, while the expired air is saturated at body temperature and ambient pressure. The lungs serve as a mass transfer device that allows rapid and efficient exchange of O_2, CO_2, and H_2O.

A flow diagram for the breathing process is shown in Figure 1. Streams information shows the measured variables, with the values given being those for a 19-year-old, 125-pound, 66-inches-tall female student. The ambient temperature, pressure, and relative humidity are recorded; inlet gas compositions are assumed to be 21% oxygen and 79% nitrogen on a dry basis. The experimentally obtained data for flowrate of exhaled breath ($\dot{V}^{out,BTPS}$) is reported at BTPS (body temperature and pressure, saturated) conditions, while the gas compositions ($y^{out}_{O_2}$ and $y^{out}_{CO_2}$) are reported on a dry basis. The ideal gas law and concepts of relative humidity, Raoult's law, and dry/wet bases are therefore employed in the mass balance calculations on this multicomponent system.

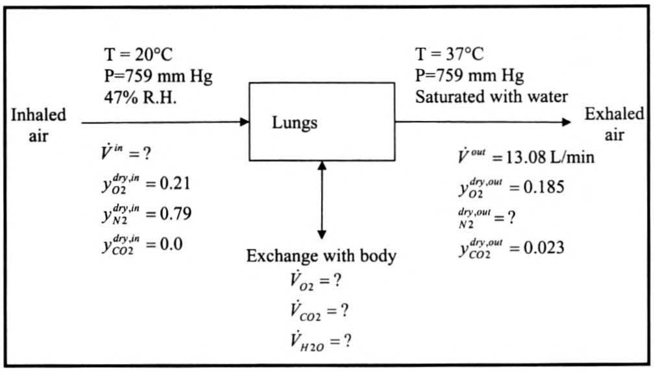

Figure 1. *Flow chart showing the measured variables in the respiration experiment. The values given represent the resting data for a 19-year-old female subject (125 lb, 66 in).*

To illustrate the concepts that are applied through the calculations associated with this experiment, the basic solution procedure for the calculation of oxygen consumption and carbon dioxide production rates, and the rate of water loss is outlined below.

For ease of calculation, the volumetric flow rate of exhaled air obtained experimentally is first converted to a molar flow rate ($\dot{n}^{out}$) using the ideal gas law,

$$P\dot{V}^{out,BTPS} = \dot{n}^{out}RT_b \tag{1}$$

The body temperature, T_b, is 37°C (310K).

The total flow rate of saturated air at body temperature and barometric pressure are next converted to the flow rate of dry air (at the same temperature and pressure). The partial pressure of water in saturated air at 37°C is 47 mm Hg. The mole fraction of water in the exhaled air is therefore 47 mm Hg/P, and the molar flowrate of exhaled air on a dry basis is

$$\dot{n}^{out,dry} = \dot{n}^{out}\left(1 - \frac{47 \text{ mm Hg}}{P}\right) \tag{2}$$

Next, the fraction of nitrogen in the exhaled air is determined on a dry basis

$$y^{out,dry}_{N_2} = 1 - \left(y^{out,dry}_{O_2} + y^{out,dry}_{CO_2}\right) \tag{3}$$

The flow rate of each species in the exhaled breath is next determined

$$\begin{aligned} \dot{n}^{out}_{O_2} &= y^{out,dry}_{O_2}\,\dot{n}^{out,dry} \\ \dot{n}^{out}_{CO_2} &= y^{out,dry}_{CO_2}\,\dot{n}^{out,dry} \\ \dot{n}^{out}_{N_2} &= y^{out,dry}_{N_2}\,\dot{n}^{out,dry} \end{aligned} \tag{4}$$

Since nitrogen is inert, the calculations for the inlet air are begun by equating the inlet and outlet molar flowrates of nitrogen

$$\dot{n}_{N_2}^{in} = \dot{n}_{N_2}^{out} \tag{5}$$

The total flowrate of inhaled air can now be calculated on a dry basis, assuming a composition of 79% nitrogen and 21% oxygen

$$\dot{n}_{N_2}^{in} = y_{N_2}^{in,dry}\ \dot{n}^{in,dry} \tag{6}$$

The molar flowrates of oxygen and carbon dioxide in the inhaled air can be calculated next

$$\dot{n}_{O_2}^{in} = y_{O_2}^{in,dry}\ \dot{n}^{in,dry} \tag{7}$$

$$\dot{n}_{CO_2}^{in} = y_{CO_2}^{in,dry}\ \dot{n}^{in.dry}$$

Finally, the rates of oxygen and carbon dioxide transfer to the body can be calculated using a component balance

$$\dot{n}_{O_2}^{in} - \dot{n}_{O_2}^{out} + \dot{n}_{O_2}^{body} = 0 \tag{8}$$

$$\dot{n}_{CO_2}^{in} - \dot{n}_{CO_2}^{out} + \dot{n}_{CO_2}^{body} = 0$$

The rate of water loss involves calculation of the rates of water vapor inhaled and exhaled, using relative humidity measurement and known flow rates. The molar rates of water vapor in the exhaled or inhaled breath are (respectively)

$$\dot{n}_{H_2O}^{out} = y_{H_2O}^{out}\ \dot{n}^{out} \tag{9}$$

$$\dot{n}_{H_2O}^{in} = y_{H_2O}^{in}\ \dot{n}^{in} \tag{10}$$

When $y_{H_2O}^{out}$ must be determined from the relative humidity and the vapor pressure at the appropriate temperature (body temperature for outlet conditions, ambient temperature for inlet conditions)

$$y_{H_2O}^{in} = RH\frac{P^{vap}}{P} \tag{11}$$

$\dot{n}^{in}$ can be determined from the molar flow rate of dry air (Eq. 5) and the mole fraction of water in the inhaled air

$$\dot{n}^{in} = \frac{\dot{n}^{dry,in}}{1 - y_{H_2O}^{in}} = RH\frac{P^{vap}}{P} \tag{12}$$

Although most of the calculations are done using molar flow rates, the conversion to volumetric flow rates are more meaningful to students and are well worth one extra calculation step.

EQUIPMENT

The equipment used for all cardiorespiratory measurements was a gas-exchange system coupled with a cycle ergometer. The MedGraphics CPX/D cardiorespiratory gas-exchange system includes capability for direct oxygen and carbon dioxide measurement and ventilation (flow) determination. The system interfaces with a cycle ergometer (Lode Corvial) for exercise testing. To prevent cross contamination between patients (students), disposable PreVent™ pneumotachs were used once and then discarded. The system was purchased from MedGraphics (St. Paul, MN) for approximately $35,000. While this may be prohibitively expensive for an engineering program if it is not used for research purposes, many universities have such equipment available in a physiology or exercise science laboratory. In addition, several companies offer human physiology teaching kits in the $3,000 range that allow respiratory flow and volume measurements (*e.g.*, Biopac Systems, Santa Barbara, CA; ADInstruments, Colorado Springs, CO; Iworx, Dover, NH).

EXPERIMENT

Prior to commencing the experiment, the MedGraphics CPX/D system pneumotach is calibrated for air flow rate using a calibration syringe. Gas calibrations for oxygen and carbon dioxide are performed using a reference gas (21% oxygen, balance nitrogen) and a calibration gas (12% oxygen, 5% carbon dioxide). In addition, the barometric pressure and ambient relative humidity are entered manually to the MedGraphics Breeze Suite software.

One student per team of four students is selected as the test subject for the experiment. Using the MedGraphics CPX/D cardiorespiratory test system coupled with the Corvial Cycle ergometer, measurements are taken at rest (for four minutes) and during exercise (for four minutes, pedaling at 70-80 rpm at 30 W braking power). A student is shown performing the experiment in Figure 2.

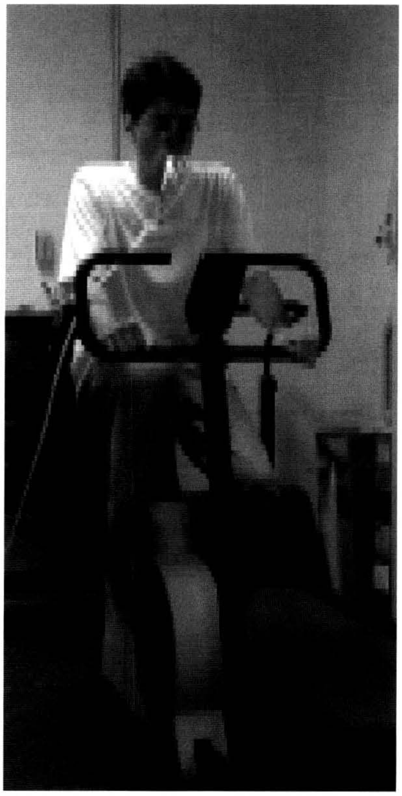

***Figure 2.** A student performing the respiration experiment.*

The following quantities are measured directly and displayed using MedGraphics Breeze Suite software:

$$\dot{V}^{\mathrm{out}}, y_{O_2}^{\mathrm{out,dry}}, y_{CO_2}^{\mathrm{out,dry}}, y_{O_2}^{\mathrm{in,dry}}, y_{CO_2}^{\mathrm{in,dry}}$$

and braking power. As mentioned previously, the experimentally obtained data for flowrate of exhaled breath ($\dot{V}^{\mathrm{out,BTPS}}$) is reported at BTPS (body temperature and pressure, saturated) conditions, while the gas compositions are reported on a dry basis. The software offers many options for the convenient display of automatically calculated values for quantities such as oxygen consumption rate, carbon dioxide production rate, and energy expenditure, but for educational purposes it is preferable to perform calculations by hand. If desired, the calculation/display options can be exercised in order to provide numbers against which students can check their calculations.

For their laboratory report, students perform all calculations by hand. In a subsequent laboratory period, they are introduced to the process simulator, HYSYS, and in an in-class activity, they use HYSYS to draw a simple process flow diagram of the respiration cycle. They provide their data and allow HYSYS to perform material and energy balances on the respiration process, and then they compare the results of the simulation to their hand calculations.

Finally, the psychrometric chart is introduced and students use it to determine the water content of inhaled and exhaled air. The point on the chart for inhaled air is identified using the ambient temperature and relative humidity, and the exhaled air point is at body temperature (37 °C) and is saturated with water vapor. The water content of each stream is read off the chart, and the water loss during respiration is calculated and compared with previously calculated values. In this exercise, the relatively small changes in oxygen and carbon dioxide compositions are ignored, as is any slight deviation from atmospheric pressure.

TABLE 1

Gas Exchange Measurements and Calculations at Rest and During Cycling Exercise.

- $\dot{V}^{\mathrm{out}}$ *is reported at BTPS conditions.*
- *All mole fractions ae reported on a dry basis.*
- $\dot{V}^{\mathrm{in}}$, $\dot{V}_{O_2}$, *and* $\dot{V}_{CO_2}$ *are calculated at ambient conditions.*
- *Ambient conditions:* $T = 20$ °C, $P = 759$ mm Hg, $RH = 47\%$.

Measured Variables				*Calculated Values*			
Power (W)	$\dot{V}^{\mathrm{out,BTPS}}$ (L/min)	$y_{O_2}^{\mathrm{out}}$	$y_{CO_2}^{\mathrm{out}}$	$\dot{V}_{O_2}$ (L/min)	$\dot{V}_{CO_2}$ (L/min)	$\dot{V}^{\mathrm{in}}$ (L/min)	$\dot{V}_{H_2O}$ (mL/min) Liquid Equivalent
0	13.08	0.185	0.023	-0.303	0.267	11.81	0.476
30	20.50	0.171	0.031	-0.665	0.563	18.51	0.767

RESULTS

Experiment

Gas-exchange measurements were taken at rest and during exercise as described above. Nearly everyone is aware of the body's physiologic responses to exercise: the body's increased demand for energy is met with an increased breathing rate and heart rate. By comparing the resting and exercise gas exchange measurements, students quantify this physiologic response. Table 1 shows gas exchange measurements and calculated values for the respiration experiment for a 19-year-old female student (125 lb, 66 in). The calculations reveal that oxygen is consumed and carbon dioxide is produced during breathing, and that both of these rates increase during the very mild (30 W) exercise performed in this experiment. In addition, it is interesting to note that the total volume of air inhaled is smaller than the volume exhaled; while there is a slight change in the molar flow rate, the difference is primarily due to the temperature change. The volumetric liquid equivalent of the rate of water loss is 0.48 mL/min at rest—this increases to 0.75 mL/min during the mild exercise.

There are three sources of variance in the measurements that are examined by students in the experiment:

1. *Reproducibility of the equipment used for experimental measurement*
2. *Breath-by-breath variation on a single subject*
3. *Person-to-person physiologic variations*

The first is illustrated by taking five consecutive measurements of the ambient air composition and determining the average and standard deviation of the oxygen concentration. The second is explored by observing ten consecutive breath-by-breath analyses of flow rate and gas compositions for a single subject. The third is explored by examining software-predicted results and experimental results between different students. Factors such as gender, height, and weight are considered.

The oxygen measurements are very reproducible (±0.03%), as is required of equipment used for medical testing. The breath-by-breath analysis demonstrates a much higher level of variation, and students observe that the variation decreases a few minutes into the test. This is a common phenomenon witnessed with respiratory testing—the subject has difficulty breathing naturally and regularly at the beginning of the protocol when he or she is thinking about the test, but after a few minutes when the subject's thoughts are not as focused on breathing, it exhibits a much more normal and regular pattern. Still, the breath-to-breath variation is about ±5%. The person-to-person variations are by far the greatest source of variance, and it is not uncommon to observe ±30% variations in oxygen-consumption rates between male and female students.

PROCESS SIMULATION

Process simulators have become an essential tool in modern chemical engineering education. In the past, most chemical engineering programs viewed process simulation as a task inherent to the capstone plant design course, but chemical engineering programs have recently been integrating process simulators throughout the entire curriculum.[9] At Rowan we have vertically integrated the use of process simulators in most of the chemical engineering courses, starting with the freshman clinic.

Using a HYSYS process simulator, the experimental gas-exchange resting-measurement data are used to simulate the process of respiration. The process is represented by two unit operations: a heater that heats the inhaled air to body temperature and a humidifier that saturates the inhaled air with water. The HYSYS respiration process flow diagram is shown in Figure 3.

The HYSYS flow sheet has been set up to simulate the respiration process by providing the experimentally measured values of flow rates, composition, temperature, pressure, and relative humidity. Students enter the ambient conditions of temperature, pressure, and relative humidity into a spreadsheet operator called the "weather station." A hidden spreadsheet takes these data and calculates the mole fraction of water in the inhaled air, using the Antoine equation to determine the vapor pressure of water at the ambient temperature. These steps were necessary because HYSYS requires a water vapor mole fraction rather than relative humidity to calculate water content of a given stream.

The "inhaled humid air" stream represents inspired air at ambient temperature, pressure, and relative humidity. The stream called "exhaled warm saturated air" represents the exhaled air at body temperature and pressure, saturated with water vapor. Students supply temperature, pressure, flow rate, and composition of this stream using their experimental data. They also supply temperature and pressure values for the intermediate streams called "warm humid air" and "moisture from lung tissue." HYSYS completes the material balances and students compare their process simulation results with their hand-calculated results.

ASSESSMENT

An assessment plan based on the rubrics developed by Newell, *et al.*,[10] was developed to map student work directly to the individual learning outcomes of these freshmen. The learning outcomes specifically address ABET criteria and AIChE- and program-specific goals. This assessment was based on reasonable expectations for *freshman* students who have had their first introductory exposure to engineering principles.

Four instruments were chosen for the evaluation: a team laboratory report, an individual in-class quiz, a formal oral presentation, and an interactive poster presentation. The laboratory reports and quizzes were evaluated by the course in-

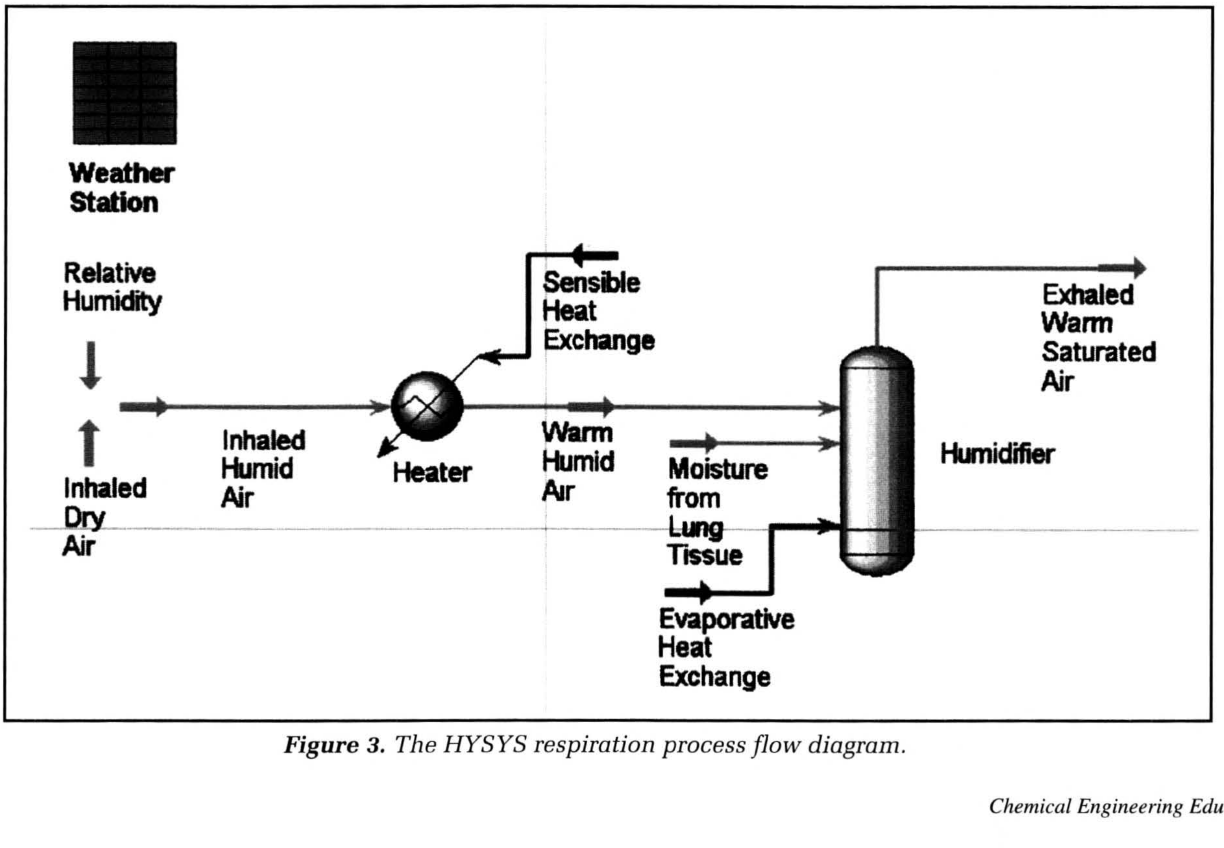

***Figure 3.** The HYSYS respiration process flow diagram.*

structor only, and the formal and poster presentations were graded by two engineering professors. These were evaluated for two consecutive years. The first column in Table 2 shows the stated objectives/outcomes that were evaluated on a four-point *ordinal* scale to describe student performance, as discussed previously in the paper by Newell.[10] The second column provides numerical results that indicate the average score for the four instruments.

We believe that the student and faculty scores indicate that we were successful in achieving our stated learning objectives. In using traditional classroom surveys, the students responded that the module contributed to their enthusiasm for engineering, as evidenced with a score of 3.6 out of 4.

SUMMARY

This paper describes a simple and exciting laboratory experiment in which a wide range of chemical engineering principles are introduced through application to the process of respiration. Students take measurements of physiologic variables both at rest and during exercise, and then perform calculations involving mass balances. Through these calculations, students apply the ideal gas law and concepts of partial pressure and relative humidity. Students are also introduced to chemical process simulation software when they simulate the process of respiration using HYSYS.

Basic physiologic responses are already familiar to students through "common knowledge" and sensory experiences, and most of them have a natural curiosity to learn how their own bodies work. In a series of hands-on experiments that use engineering measurements and reverse engineering methods, these physiologic responses are quantified. This establishes a framework within which new engineering concepts are introduced through analysis of the data. Using a familiar system, sensory experiences, and hands-on active learning are thought to increase understanding and retention of the new concepts.

TABLE 2
Assessment Results
(1 = low to 4 = high)

Objective/Outcome (to demonstrate...) and Mapped to Goal	*Av. Fac. Score*	*Av. Stud. Score*
A working knowledge of ChE principles (mass balances, psychrometric chart, unit operations): AIChE Professional Component	*3.4*	*3.2*
A working knowledge of chemistry (ideal gas law, vapor pressure, partial pressure): AIChE Professional Component	*3.3*	*3.0*
An ability to function on multidisciplinary and/or diverse teams: ABET-D	*3.4*	*3.5*
An ability to approach tasks involving experimental results in a logical and systematic fashion (measurements, recording, analysis, and intepretation): Program	*3.1*	*N/A*
An understanding of contemporary issues relevant to the field (current technical material, finding relevant current information and use in curricular assignments: ABET-J	*2.9*	*3.7*
An ability to use techniques, skills, and modern engineering tools necessary for engineering practice (spreadsheets, word processors, and process simulators) to assist in problem solving: ABET-K	*3.6*	*3.8*
Effective oral and written communication skills: ABET-G	*3.4*	*3.5*

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NOMENCLATURE

$\dot{n}$	molar flow rate (mol/min)
P	pressure (barometric) (mm Hg)
P^{vap}	vapor pressure of water (mm Hg)
R	universal gas constant
RH	relative humidity (fraction)
T	temperature (K)
$\dot{V}$	volumetric flow rate (L/min)
y	mole fraction

Subscripts

a	ambient
b	body

Superscripts

BTPS	body temperature and pressure, saturated
dry	on a dry basis
in	inlet stream or inhaled air
out	outlet stream or exhaled air

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