ENERGY BALANCES ON THE HUMAN BODY

A Hands-On Exploration of Heat, Work, and Power

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Rowan's two-semester Freshman Clinic sequence is a multidisciplinary course that introduces all freshmen engineering students to engineering principles in a hands-on, active learning environment. Engineering measurements and reverse engineering methods are common threads that tie together the different engineering disciplines in the fall and spring semesters, respectively. One of the reverse engineering projects is a semester-long investigation of the interacting systems of the human body. Students discover the function, interaction, and response to changing demands of various systems in the human body: the respiratory, metabolic, cardiovascular, electrical, and musculoskeletal systems. The project introduces a wide range of multidisciplinary engineering principles and reinforces scientific principles learned in chemistry, physics, and biology.

The module described in this paper uses the respiration system to introduce concepts related to energy balances, heat transfer, and chemical reactions. In a hands-on experiment, students measure physiologic variables such as breathing rate and respiratory gas compositions at rest and during exercise on a bicycle ergometer. We have previously described how a similar experiment is used to teach mass balances and related concepts through the determination of the rates of oxygen consumption, carbon dioxide production, and water loss.[1,2] The module is appropriate for an introductory freshman engineering course or for a sophomore-level course on material and energy balances. These concepts can be explored in greater detail in upper level core and elective courses.

The learning objectives of this hands-on experiment are to

- *Perform energy balances on the body*
- *Determine the total rate of energy expenditure and human mechanical efficiency*
- *Determine the composition of food (% fat and % carbohydrate) oxidized for energy*
- *Use a process simulator to perform mass and energy balances on the breathing process*
- *Analyze the role of breathing in thermal regulation*

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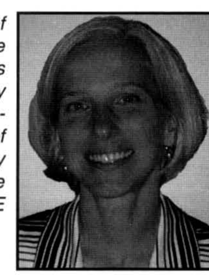

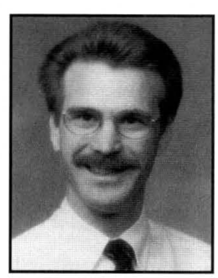

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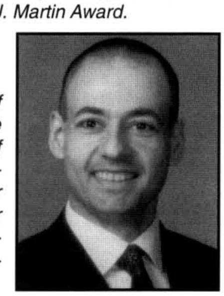

- *Use HYSYS[3] process simulator to explore respiratory heat transfer under different conditions.*

The engineering concepts introduced through this module are summarized in Table 1.

One of the reverse engineering projects is a semester-long investigation of the interacting systems of the human body. Students discover the function, interaction, and response to changing demands of various systems in the human body: the respiratory, metabolic, cardiovascular, electrical, and musculoskeletal systems.

BACKGROUND

The air we inspire (inhale) is approximately 21% O_2 and 79% N_2 on a dry basis. After rapid gas exchange in the lungs, the expired (exhaled) gas contains approximately 75% N_2, 16% O_2, 4% CO_2 and 5% H_2O.[4,5] The inspired air is at ambient pressure, temperature, and humidity, while the expired air is saturated with water vapor at body temperature and ambient pressure, and respiration accordingly plays a role in temperature regulation. Oxygen consumed during respiration is transported by blood to cells for energy production through the oxidation of carbohydrates and fats from food. The reaction stoichiometry and thermodynamics are well known, and the rate of energy production can be calculated from the rates of O_2 and CO_2 exchange.[4] This energy is used to maintain the function of the body (basal metabolism, typically about 60-70% of total energy expenditure) and to do external work (exercise, typically about 30-40% of total).

Energy expended internally (*e.g.*, for pumping blood, maintaining organs, etc.) must ultimately be released as heat, and it has been observed that the energy metabolism at rest is related to the surface area (SA) of the body. This ratio of basal metabolic rate (BMR) to the surface area (SA), [(BMR)/(SA), kcal/h], is a function of age (Y, in years) and gender:[6]

<u>For males:</u>

$$\frac{(BMR)}{(SA)}=\left(54.79\frac{kcal}{m^2h}\right)-\left(1.303\frac{kcal}{m^2h\,yr}\right)*Y+\left(0.0294\frac{kcal}{m^2h\,yr^2}\right)*Y^2-\left(0.0001228\frac{kcal}{m^2h\,yr^3}\right)*Y^3-\left(3.3558*10^{-6}\frac{kcal}{m^2h\;yr^4}\right)*Y^4+\left(2.903*10^{-8}\frac{kcal}{m^2h\;yr^5}\right)*Y^5 \qquad (1)$$

<u>For females:</u>

$$\frac{(BMR)}{(SA)}=\left(55.73\frac{kcal}{m^2h}\right)-\left(1.757\frac{kcal}{m^2h\,yr}\right)*Y+\left(0.0414\frac{kcal}{m^2h\,yr^2}\right)*Y^2+\left(5.216*10^{-6}\frac{kcal}{m^2h\,yr^3}\right)*Y^3-\left(1*10^{-5}\frac{kcal}{m^2h\,yr^4}\right)*Y^4+\left(7.979*10^{-8}\frac{kcal}{m^2h\,yr^5}\right)*Y^5 \qquad (2)$$

Surface area can be found from the following correlation that relates surface area to body mass and height:[7]

$$SA=\left(0.202\frac{m^{1.275}}{kg^{0.425}}\right)*m^{0.425}*h^{0.725} \qquad (3)$$

TABLE 1
Summary of the Science and Engineering Concepts Introduced in this Module

Engineering Concept	*Application*
Reaction stoichiometry	Food oxidation reactions
Heat of reaction	Energy production from food oxidation reactions
Energy balance (First Law of Thermodynamics) on an open system	Calculation of energy stored in one day
Heat transfer—relation to surface area; correlations	Determination of energy expenditure
Mechanical efficiency: work, frictional losses, heat	Students performing mechanical work (cycling)
Simultaneous material and energy balance—heat capacity, enthalpy, sensible heat, latent heat, reference state; psychrometric chart	Heat transfer during respiration; HYSYS simulation
Unit operations (heating, humidification)	HYSYS simulation

where SA is in units of (m^2), m is mass in kg and h is height in meters.

The energy needed to maintain the body during rest and during physical activity is derived from the breakdown, synthesis, and utilization of fats, carbohydrates, and protein. Protein is thought to be used primarily in building tissue (anabolic processes), and most of our body's energy needs are met through the intake of carbohydrates and fats. Glucose (a sugar) is a typical carbohydrate, and is oxidized according to the reaction

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \qquad -673\,\text{kcal/mol} \qquad (4)$$

Note that the heat of reaction at STP (-673 kcal/mol) is provided in addition to the reaction stoichiometry. Fats are another class of macronutrient that the body uses to obtain energy. Triolein, a fat, is burned according to the reaction

$$C_{57}H_{32}O_2 + 80O_2 \rightarrow 57CO_2 + 52H_2O \qquad -7900\,\text{kcal/mol} \qquad (5)$$

The reactions shown in Eqs. (4) and (5) are for a specific carbohydrate (glucose) and a specific fat (triolein), and the heats of reaction were evaluated at STP.[8] Dietary carbohydrates are a mixture of molecules with the approximate formula $[C(H_2O)]_n$; similarly, dietary fats are a mixture of esters of various fatty acids. These two macronutrients are therefore commonly represented as typical mixtures (representing typical dietary intake). In the oxidation of a mixture of carbohydrates, the ratio of CO_2 production to O_2 consumption is 1:1, and approximately 113 kcal/mol O_2 (STP) is released. The oxidation of a mixture of fats results in a 0.707:1 ratio of CO_2 production to O_2 consumption, and releases about 104.9 kcal/mol O_2 (STP).[4] Measurement of the rates of O_2 consumption and CO_2 production ($\dot{V}_{O2}$ and $\dot{V}_{CO2}$) allows determination of the rates of energy derived from fats and carbohydrates using these heats of reaction and stoichiometric relationships.

The Respiratory Exchange Ratio (RER) is the ratio of O_2 consumption and CO_2 production and is a convenient expression for use in metabolic calculations

$$\text{RER} = \frac{\#\,\text{moles}\,CO_2\,\text{produced}}{\#\,\text{moles}\,O_2\,\text{consumed}} = \frac{\dot{V}_{CO_2}}{\dot{V}_{O_2}} \qquad (6)$$

Table 2 shows RER values for fats and for carbohydrates, the energy released per LO_2, and the mass of each macronutrient oxidized per LO_2 consumed.[4] When a mixture of carbohydrates and fats is oxidized, the RER will lie between 0.707 and 1.0. The RER is a convenient indicator for the proportion of each macronutrient being oxidized and is related to the total energy expenditure. This is illustrated graphically in Figure 1. The equations of the lines provide relationships between EE and RER, and between the composition of the energy source and RER.

Nearly everyone is familiar with the concept of reducing caloric intake and increasing exercise to lose weight. This is simply an application of the First Law of Thermodynamics, which reveals that if the energy equivalent of consumed food exceeds the energy expended, the result is a net storage of energy. This excess energy would be stored primarily as fat.

$$\dot{Q} - \dot{W}_s - \dot{n}_{air}\Delta\hat{H}_{air} - \dot{n}_{food}\Delta\hat{H}_r = \dot{E}_{st} \qquad (7)$$

$\dot{Q}$ is the rate of heat transferred to the body from the surroundings, $\dot{W}_s$ is the rate of work done by the body on the surroundings, $\dot{n}_{air}\Delta\hat{H}_{air}$ is the rate of enthalpy change between the inspired and expired air streams due to a change in temperature, $\dot{n}_{food}\Delta\hat{H}_r$ is the rate of enthalpy change due to reaction, and $\dot{E}_{st}$ is the rate of energy storage in the body. Several simplifying assumptions were made to make the analysis appropriate for freshmen: 1) the effect of composition on the molar enthalpy of the inspired and expired air is neglected, 2) the difference in number of moles of inspired air vs. expired air is neglected, and 3) the enthalpy change of the food due to change in temperature is neglected.

The human body doing exercise can be analyzed as a machine

TABLE 2
RER and Energy Expenditure for Carbohydrates and Fats
(At Standard Temperature and Pressure, 0°C and 760 mm Hg)
Values taken from Reference 4.

	Carbohydrate	Fat
RER	1.0	0.707
Energy released per mole of oxygen used (kcal/mol)	113.0	104.9
Energy released per liter of oxygen used (kcal/L)	5.047	4.686
Grams of macronutrient oxidized per liter oxygen used (g/L)	1.231	0.496

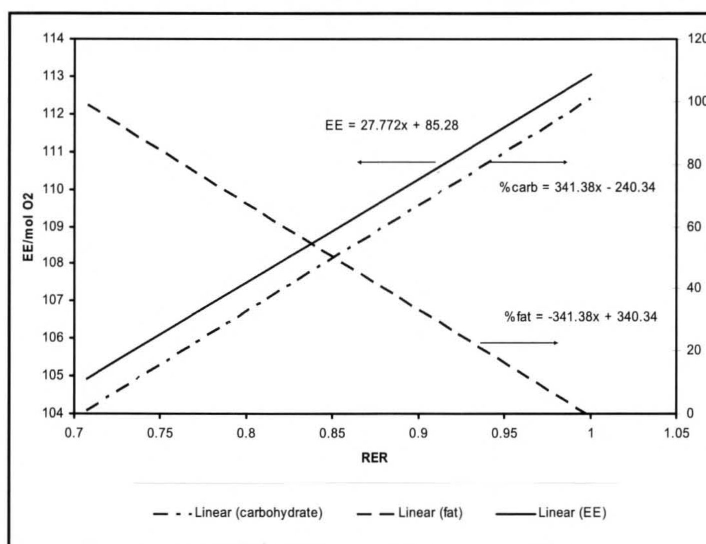

Figure 1. *Fuel composition and energy expenditure as a function of RER (0.707 < RER < 1.0).*

In a hands-on experiment, students measure physiologic variables such as breathing rate and respiratory gas compositions at rest and during exercise on a bicycle ergometer.

doing mechanical work. To do mechanical work such as bicycling or running, the body expends energy. The efficiency, η, of this human machine or a human is expressed by

$$\eta = \frac{\text{mechanical work done}}{\text{energy consumed}} \cdot 100 \tag{8}$$

Energy not used to perform external work is ultimately released as heat. Since this module focuses on respiration, of interest is the total rate of heat transfer associated with respiration. Under normal conditions, about 14%-20% of the body's total cooling is accomplished through respiration, and this percentage can change with exercise and ambient conditions.[7]

During respiration, inspired air is warmed from ambient temperature to body temperature prior to being exhaled. In addition, water evaporates from the moist lung tissue to saturate the air in the lungs prior to expiration. The humid exhaled air removes heat from the body in the form of latent heat of vaporization. The rate of heat transfer ($\dot{q}$, kcal/min) achieved through the process of respiration is

$$\dot{q} = \dot{n}_{air} C_{p\,air}\left(T^{in} - T^{out}\right) + \Delta\hat{H}_{vap}\left(\dot{n}_w^{in} - \dot{n}_w^{out}\right) \tag{9}$$

where $\dot{n}$ is the molar flowrate (mol/min), C_p is the molar heat capacity (kcal/mol K) of the inhaled humid air, T is temperature (K) and $\Delta\hat{H}_{vap}$ is the latent heat of vaporization of water (kcal/mol). Subscripts represent components air or water, and superscripts represent inlet or outlet air.

EQUIPMENT

The equipment used for all cardiorespiratory measurements was a respiratory gas-exchange system coupled with a cycle ergometer. The MedGraphics (St. Paul, MN) CPX/D cardiorespiratory gas-exchange system includes capability for direct oxygen and carbon dioxide measurement and ventilation (flow rate). The system interfaces with a cycle ergometer (Lode Corvial) for exercise testing. Many universities have such equipment available in a physiology or exercise science laboratory, and several companies offer human physiology teaching kits in the $3,000 range (*e.g.*, Biopac Systems, Santa Barbara, CA; ADInstruments, Colorado Springs, CO; Iworx, Dover, NH).

EXPERIMENT

A detailed experimental procedure was described previously by Farrell, *et al.*,[2] and a summary is provided here.

Students work in teams of three, and the team can complete the experiment in approximately 20-30 minutes. One student per team 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 for four minutes resting and for four minutes during exercise. During exercise the subject pedals at a rate of 70-80 rpm with a constant braking power set to 30W. (Braking power is product of the tension on the flywheel and the distance covered by the perimeter of the flywheel per unit time).

The following quantities are measured directly and displayed using Med-Graphics Breeze Suite software: Volumetric flowrate of exhaled air and component mole fractions

$$(\dot{V}^{out}, y_{O_2}^{in}, y_{O_2}^{out}, y_{CO_2}^{in}, y_{CO_2}^{out})$$

and braking power. The gas exchange data are reported at BTPS (Body Temperature and Pressure, Saturated) conditions. In addition, the software provides calculated values of

$$\dot{V}_{O_2}, \dot{V}_{CO_2}, \text{EE, and RER.}$$

ASSIGNMENTS

The first assignment based on this experiment is a laboratory report that focuses on the food oxidation reactions involved in energy production, determination of energy expenditure at rest and during exercise, and the application of the First Law of Thermodynamics. From their experimental data, students calculate the BMR, RER, EE, and mechanical efficiency. Using RER values, students determine the percentage of energy expenditure derived from carbohydrates and from fats, as well as the number of grams of carbohydrates and grams of fat used as fuel. In addition to the data obtained from the experiment described above, students record everything they eat for an entire day and calculate the energy equivalent of this diet using published nutrition tables. They also keep track of their activities during the day and estimate the total amount of energy expended required for this work. This information is used to determine the total net chemical energy storage using the First Law energy balance.

The second assignment is a calculation-based homework that focuses on a thermal energy balance on the respiration process. This energy balance is simplified (for hand calculations) by using a constant heat capacity independent of composition. Only the energy changes associated with heating and humidifying an air stream are considered. Students calculate the rates of latent heat exchange, sensible heat exchange, and total heat exchange associated with respiration. After performing the hand calculations using tabulated values of C_p and $\Delta\hat{H}_{vap}$, students also use a psychrometric chart to determine the rate of heat exchange during respiration.

A subsequent laboratory period is used for a HYSYS process simulation workshop in which students use HYSYS to simulate the respiration process. Students input their own experimental data, use HYSYS to perform material and energy balances on the respiration process, and compare the results of the simulation to their hand calculations. Several simulations are run to explore the effect of ambient conditions on the relative contributions of sensible and latent heat during respiration. Students explore a range of temperatures and relative humidities that correspond to a range of weather conditions (for instance, a dry winter day, a rainy winter day, a hot desert, and a hot steamy swamp).

As shown in the HYSYS flow diagram in Figure 2, the respiration process can be represented by two unit operations: a heater that heats the inhaled air to body temperature (sensible heat effect), and a humidifier that saturates the inhaled air with water (latent heat effect). Students enter the ambient conditions of temperature, pressure, and relative humidity into the weather station. Because HYSYS requires a water vapor mole fraction rather than relative humidity to be provided, students use a spreadsheet to calculate the mole fraction of water in the inhaled air using the Antoine equation. 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. Temperature and pressure values for the intermediate streams called "warm humid air" and "moisture from lung tissue" are also supplied by students.

RESULTS

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 3 shows gas exchange measurements and calculated values for the respiration experiment for a 19-year-old female student (125 lb, 66 in). According to Eqs. (2) and (3), the student has

TABLE 3
Gas Exchange Measurements and Calculations at Rest and During Cycling Exercise

$\dot{V}^{out}$, $y^{in}_{O_2}$, $y^{out}_{O_2}$, $y^{in}_{CO_2}$, and $y^{out}_{CO_2}$ are measured experimentally at BTPS conditions.

$\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ are calculated at STP.

(Ambient Conditions: T=20°C, P=759 mm Hg, RH=47%.)

Power (W)	$\dot{V}^{out}$ (L/min)	$y^{out}_{O_2}$	$y^{out}_{CO_2}$	$\dot{V}_{O_2}$ (L/min)	$\dot{V}_{CO_2}$ (L/min)	EE (kcal/min)	RER
0	13.08	0.185	0.023	0.25	0.23	1.38	0.87
30	20.50	0.175	0.031	0.62	0.52	3.07	0.85

TABLE 4
Energy Value of Consumed Foods and Activity Performed on a Given Day for the Female Subject

Food	*Energy Value (kcal)*	*Activity*	*Energy Value (kcal/h)*
Carnation Instant Breakfast, 10 oz	200	Sleep, 7.5 h	0
Meatballs, 3 x 1 oz	234	Shower, 0.25 h	14
Spaghetti, 1 cup	159	Dressing. 0.25 h	14
Tomato sauce, 1/4 cup	35	Walking, 1 h	170
Kielbasa, 4 oz	320	Driving, 0.5 h	28
Soft pretzel	95	Class, 4 h	178
Cinnamon toast crunch bar	180	Homework, 4 h	178
Brownie	160	Talk on phone, 1 h	46
Milk, 1 cup whole	150	Grocery shopping, 0.5 h	72
Hawaiian Punch, 12 oz	180	Talking with friends standing, 2 hr	89
Pizza, 2 slices plain	480	Eating, 1.5 h	41
		Watching TV 1.5 h	9
Total	***2193***	***Total***	***839***

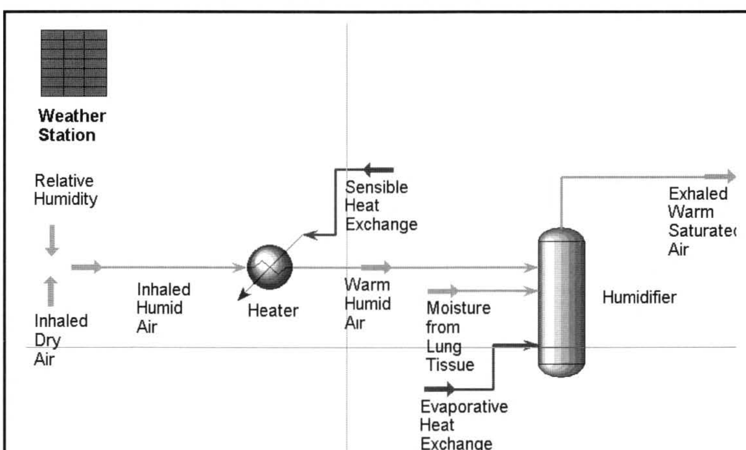

***Figure 2.** The HYSYS respiration process flow diagram.*

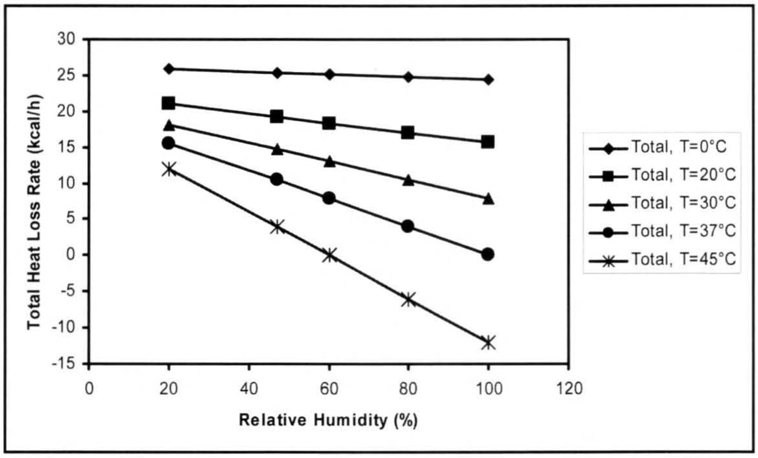

Figure 3. *The effect of ambient temperature and relative humidity on the total heat transfer rate during respiration.*

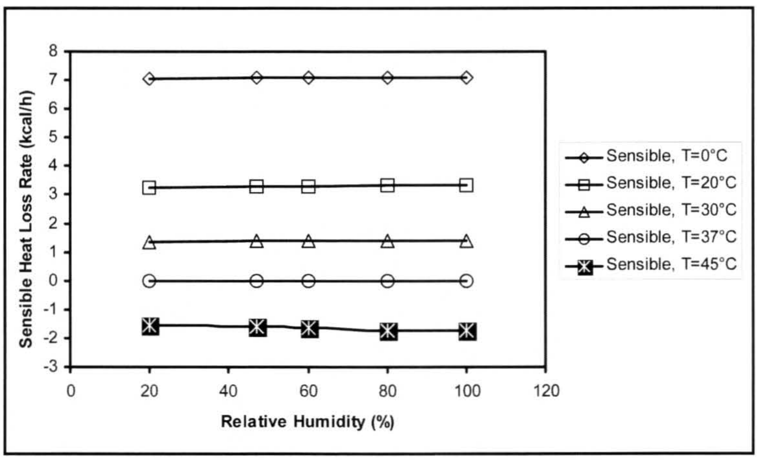

Figure 4. *The effect of ambient temperature and relative humidity on the sensible heat transfer rate during respiration.*

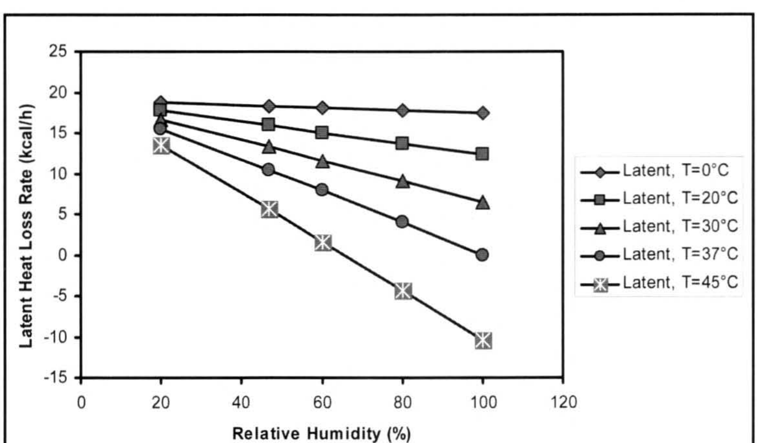

Figure 5. *The effect of ambient temperature and relative humidity on the latent heat transfer rate during respiration.*

a surface area of about 1.59 m^2 and an expected basal metabolic rate of 57.5 kcal/h. The basal metabolic rate is the minimum energy required for maintenance of the body's vital functions and is about 70% of the body's actual measured energy expenditure at rest (resting energy expenditure, REE). The resting energy expenditure is therefore expected to be 82.2 kcal/h.

Comparison of exercise data to resting data reveals that the breathing rate is substantially faster during exercise, and the oxygen concentration of expired air is slightly lower than its resting value. This translates into higher rates of oxygen consumption and carbon dioxide production during exercise. The energy expenditure is calculated using the equation of the line in Figure 1, which provides a relationship between EE and RER. These results are summarized in Table 3. The mechanical efficiency, calculated using Eq. (8), is only 23.4%, because a significant amount of energy is required to overcome internal friction in moving joints and inefficiencies of muscle contraction.[4] (Cycling is, in fact, one of the most efficient exercises!)

The energy equivalent of the food consumed by this student in one day was 2193 kcal, as shown Table 4. From the basal metabolic rate of 57.5 kcal/h, this student's minimum resting metabolic requirements are 1380 kcal per day. Since no external mechanical work is done by the body at rest, all of this energy is assumed to be transferred to the surroundings in the form of heat. The energy expended on daily activities (external work) is also shown in Table 4. These values represent the energy required in excess of the basal metabolic rate and are gathered from widely available published and Internet sources (such as <www.caloriesperhour.com>). This student estimated an energy expenditure of 839 kcal per day for her activities. The result of the First Law energy balance indicates that this student expended 26 kcal more than her intake for the day, which would result in a (very small) weight loss! It should be noted that the published values of energy expenditure during activity are estimated values based on averages for many test subjects performing. In addition, BMR is determined using correlations based on age, height, mass and gender. These correlations were developed using data of many test subjects, and thus represent physiologic estimates. This provides an ideal opportunity to explore the uncertainties related to the use of estimated values as well as those associated with experimental measurements.

Using the HYSYS process simulator to simulate the sensible heat and latent heat changes during respiration, the role of respiration in thermal regulation of the body is investigated. Figures 3, 4, and 5 show the total, sensible, and latent heat transfer rates (respectively)

In using traditional classroom surveys, the students responded that the module contributed to their enthusiasm for engineering—as evidenced with a score of 4.75 out of 5.0.

under varying ambient temperature and relative humidity. The data in these figures is obtained using HYSYS, but essentially represents Eq. (9). Graphical representation of the equation is a useful visual tool that helps students grasp the effects of ambient temperature and humidity on the sensible and latent heat exchange rates. Using the resting data above, the overall rate of heat transfer through respiration at rest (and at ambient conditions of the experiment) is about 19 kcal/h, or 23% of the total resting energy expenditure. By performing HYSYS simulations at different combinations of ambient temperature and relative humidity, students can make the following important observations about heat transfer during respiration:

1. *The total rate of heat loss via respiration decreases with increasing relative humidity (RH) and with increasing temperature. Heat loss is positive except under the most extreme conditions of high T and RH when the heat loss is negative and heat is transferred to the body via respiration. Heat loss occurs via evaporative cooling in dry conditions, and this effects a net cooling effect even when the ambient temperature is higher than body temperature.*
2. *The sensible heat transfer contribution becomes more significant when ambient temperatures are farther from body temperature (at cold and hot extremes). Sensible heat losses are greater at cool temperatures and show little dependence on relative humidity. When the ambient temperature exceeds body temperature (37°C), sensible heat losses are negative.*
3. *The latent heat loss rate decreases with increasing RH and with increasing temperature. When the ambient air is at 37°C and 100% RH, the total sensible and latent heat losses are exactly zero. In very hot and dry conditions, an overall cooling effect is achieved by a high rate of evaporative cooling (note that at 45°C and dry conditions the total heat loss and the latent heat loss are both positive, while the sensible heat loss is negative).*

ASSESSMENT

An assessment plan based on the rubrics developed by Newell, *et al.*,[9] was developed to map student work directly to the individual learning outcomes of these freshmen. The learning outcomes specifically address ABET criteria, AIChE, and program-specific goals. This assessment was based on reasonable expectations for *freshmen* 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. These were evaluated for three consecutive years.

Table 5 shows the stated objectives/outcomes that were evaluated on a four-point ordinal scale to describe student performance, using detailed rubrics as discussed previously in the paper by Newell.[9] In these rubrics, levels of student performance are assigned values of 1 to 4 on an ordinal scale. A score of 4 represents an expert who has mastered the given

TABLE 5
Desired Educational Objectives for this Project

Objective/Outcome (to demonstrate . . .)	Mapped to Goal . . .
A working knowledge of chemical engineering principles (energy balances, work, efficiency, psychrometric chart, unit operations	AIChE Professional Component
A working knowledge of chemistry (reaction stoichiometry, heat of reaction)	AIChE Professional Component
An ability to function on multidisciplinary and/or diverse teams	ABET - d
An ability to approach tasks involving experimental results in a logical and systematic fashion (measurements, recording, analysis, and interpretation)	Program
An understanding of contemporary issues relevant to the field (current technical material, find relevant current information, and use in curricular assignments	ABET - j
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
Effective oral and written communication skills	ABET - g

objective; a score of 3 represents a skilled problem solver; a score of 2 represents a student who has some skills but lacks competence; a score of 1 represents a complete novice. The complete rubrics are available on a website at

< http://engineering.rowan.edu/~newell/rubrics>

Students were also surveyed regarding their perceived ability to demonstrate the same skills. The results of the assessment by faculty are shown in Figure 6, and the results of student self-assessment are shown in Figure 7. Both student self-assessment and faculty assessment scores were consistent and highly satisfactory; the percentage of students receiving a rating of 3 or 4 was above 89% for each objective.

We believe that the 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 4.75 out of 5.0.

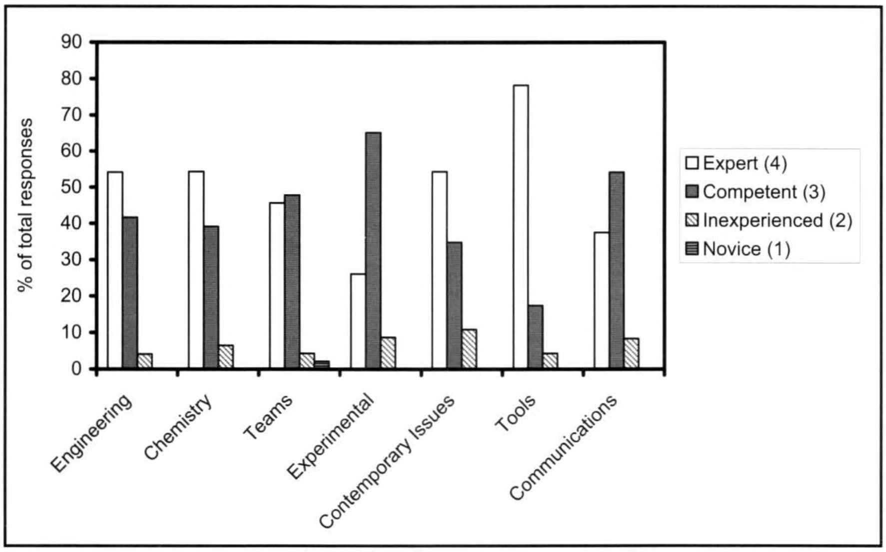

Figure 6. *Results of faculty assessment for this project.*

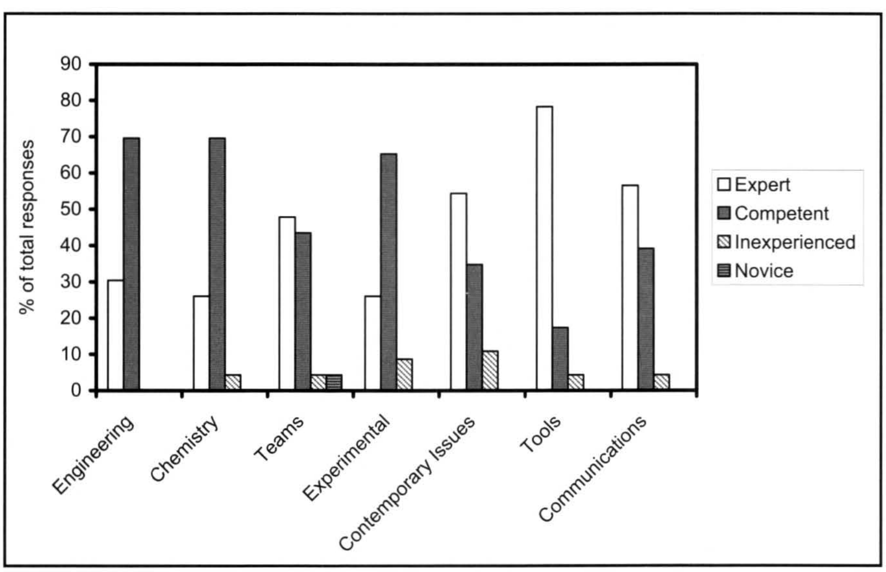

Figure 7. *Results of student assessment of this project.*

CONCLUSIONS

This paper describes a module with a hands-on experiment and associated follow-up activities in which principles of energy balances are introduced through application to the process of respiration. Basic physiologic responses are already familiar to students through "common knowledge" and sensory experiences, and most students have a natural curiosity to learn how their own bodies work. This hands-on experiment and the associated assignments focus on quantifying and analyzing the physiologic system. This establishes a framework within which new engineering concepts are introduced. Students learn concepts related to energy balances, chemical reaction stoichiometry and heats of reaction, work, power, and mechanical efficiency and are exposed to the use of thermodynamic property tables, psychrometric charts, and process simulation software.

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