

**ChE Power!****A Hands-on Introduction to Energy Balances on the Human Body**

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**Abstract**

Our lungs are membrane system that allows the exchange of  $O_2$ ,  $CO_2$ , and  $H_2O$  between the body and the air. When air is inhaled, oxygen is transported to the blood by diffusion through the alveolar membrane. Carbon dioxide is simultaneously removed from the blood to the air in the lungs, and is then exhaled. Oxygen in the blood is transported to cells where it oxidizes fats and carbohydrates to release energy, and carbon dioxide is a waste product of this reaction that must be removed. Breathing also plays a role in heat transfer and thermal regulation, since heat transferred to the air in the lungs is removed as sensible and latent heat during exhalation. We have developed a module based on a hands-on experiment that introduces chemical engineering principles through the exploration of the breathing and metabolic processes. Students use this information to (1) perform simple mass and energy balances on the lungs, (2) determine the total rate of energy expenditure (3) determine the composition of food oxidized for energy using reaction stoichiometry (4) use a process simulator to perform mass and energy balances on the breathing process and (5) to analyze the role of breathing in thermal regulation.

**Introduction**

Rowan's two-semester Freshman Clinic sequence introduces all freshmen 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 [1,2,3], 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, freshmen engineering students explore the interacting systems of the human body in a hands-on, active learning environment. 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, estimations and unit conversions through their application to the respiratory system.

Students measure physiologic variables such as breathing rate, and respiratory gas compositions at rest and during moderate exercise on an exercise bicycle ergometer. We have previously

described how these data are used by students to perform mass balances to determine the rates of oxygen consumption and carbon dioxide production [5]. This paper describes how the same experimental data are used to explore energy balances, chemical reactions and heat transfer in the human body.

The learning objectives of this hands-on experiment are (1) to analyze chemical reactions that produce energy from food (2) to perform material and energy balances on the body, (3) to prepare a simple process flow diagram, and (4) to use a process simulator to investigate rates of heat transfer during respiration. Students use their own gas exchange respiration data to calculate their rate of energy expenditure and mechanical efficiency during cycling. They use reaction stoichiometry to determine the quantities of fats and carbohydrates that are used as energy sources. They apply energy balances to determine the rate of heat transfer through respiration, and compare this to the total energy expenditure. Finally, students create a process flow diagram for the respiration process using HYSYS [6] process simulator to determine the sensible and latent heat contributions to total heat transfer.

### Background

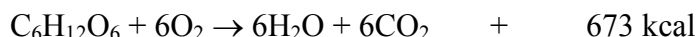
The air we inspire (inhale) is approximately 21% O<sub>2</sub> and 79% N<sub>2</sub> on a dry basis, while the expired (exhaled) gas from the lungs contains approximately 75% N<sub>2</sub>, 16% O<sub>2</sub> and 4% CO<sub>2</sub> and 5% H<sub>2</sub>O [7,8]. The inspired air is at ambient pressure, temperature 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<sub>2</sub>, CO<sub>2</sub>, and H<sub>2</sub>O.

A material balance on the lungs relates the oxygen consumption rate ( $\dot{V}_{O_2}$ , L O<sub>2</sub>/min) to the total air flow rate ( $\dot{V}$ , L/min), and molar oxygen compositions of the inspired and expired air ( $y_{O_2}^{in}$  and  $y_{O_2}^{out}$ ):

$$\dot{V}_{O_2} = \dot{V}^{in} y_{O_2}^{in} - \dot{V}^{out} y_{O_2}^{out} \quad (1)$$

Analogous component balances can be written for carbon dioxide and water.

Oxygen consumed during respiration is transported by blood to the body, where it is used by cells to produce energy through the oxidation of carbohydrates and fats from food. The reaction stoichiometry and thermodynamics are well known, and the rate of energy production may be calculated from the rates of O<sub>2</sub> and CO<sub>2</sub> exchange [7]. For instance, energy is released in the oxidation of glucose (evaluated at STP [9]):



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 must ultimately be released as heat. In the late 1800s, it was observed that the energy metabolism at rest is related to the surface area (SA) of the body. A

series of experiments using different mammals (hen, rabbit, dog, man, pig, and cow) revealed that the ratio of BMR to SA is relatively constant. This ratio  $\left(\frac{(BMR)}{(SA)}, \frac{kcal}{m^2 h}\right)$  is a function of age (Y, in years) and gender (Wasserman Correlation, Medgraphics):

Male:

$$\begin{aligned} \frac{(BMR)}{(SA)} = & \left[ 54.79 \frac{kcal}{m^2 \cdot h} \right] - \left[ 1.303 \frac{kcal}{m^2 \cdot h \cdot yr} \right] * Y + \left[ 0.0294 \frac{kcal}{m^2 \cdot h \cdot yr^2} \right] * Y^2 \\ & - \left[ 0.0001228 \frac{kcal}{m^2 \cdot h \cdot yr^3} \right] * Y^3 - \left[ 3.3558 * 10^{-6} \frac{kcal}{m^2 \cdot h \cdot yr^4} \right] * Y^4 \\ & + \left[ 2.903 * 10^{-8} \frac{kcal}{m^2 \cdot h \cdot yr^5} \right] * Y^5 \end{aligned} \quad (1)$$

Female:

$$\begin{aligned} \frac{BMR}{SA} = & \left[ 55.73 \frac{kcal}{m^2 \cdot h} \right] - \left[ 1.757 \frac{kcal}{m^2 \cdot h \cdot yr} \right] * Y + \left[ 0.0414 \frac{kcal}{m^2 \cdot h \cdot yr^2} \right] * Y^2 \\ & + \left[ 5.216 * 10^{-6} \frac{kcal}{m^2 \cdot h \cdot yr^3} \right] * Y^3 - \left[ 1 * 10^{-5} \frac{kcal}{m^2 \cdot h \cdot yr^4} \right] * Y^4 \\ & + \left[ 7.979 * 10^{-8} \frac{kcal}{m^2 \cdot h \cdot yr^5} \right] * Y^5 \end{aligned} \quad (2)$$

Surface Area can be found from the following correlation which relates SA to mass and height [10]:

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

Where SA is in units of (m<sup>2</sup>), *m* is mass in kg and *h* is height in meters.

Foods used to obtain energy: Carbohydrates and Fats

#### 1. Carbohydrates

Almost all of our energy needs come from carbohydrates and fats. (Proteins, another type of food, are used for other purposes and is not used to meet our energy needs). Glucose (a sugar) is a typical carbohydrate, and burned according to the reaction:



## 2. Fats

Fats are another class of food that the body uses to obtain energy. Palmitic acid, a typical fatty acid, is burned according to the reaction



### Typical mixed diet

The reactions shown in Equations 4 and 5 are for a specific carbohydrate (glucose) and a specific fat (palmitic acid). Since our diet comprises a mixture of various fats and carbohydrates, reactions for typical mixtures are often used:



Measurement of the rates of  $\text{O}_2$  and  $\text{CO}_2$  exchange allows determination of the rates of carbohydrate and fat consumption and the rate of energy expenditure using Equations 6 and 7.

### Respiratory Exchange Ratio

The Respiratory Exchange Ratio (RER) is the ratio of carbon dioxide production to oxygen production, and is a convenient expression for use in metabolic calculations:

$$\text{RER} = \frac{\# \text{ moles CO}_2 \text{ produced}}{\# \text{ moles O}_2 \text{ consumed}} = \frac{\dot{V}_{\text{CO}_2}}{\dot{V}_{\text{O}_2}} \quad (8)$$

Based on Equations 6 and 7, the following RER values and heats of reaction for typical mixtures of carbohydrates and fats are 1.0 and 0.707 respectively, as shown in Table 1:

**Table 1. Energy Expenditure and RER for Carbohydrates and Fats**

	<b>Carbohydrate</b>	<b>Fat</b>
<b>RER</b>	1.0	0.707
<b>Energy released per mole of oxygen used (kcal/mol)</b>	113.0	104.9
<b>Energy released per liter of oxygen used (kcal/L)</b>	5.047	4.686

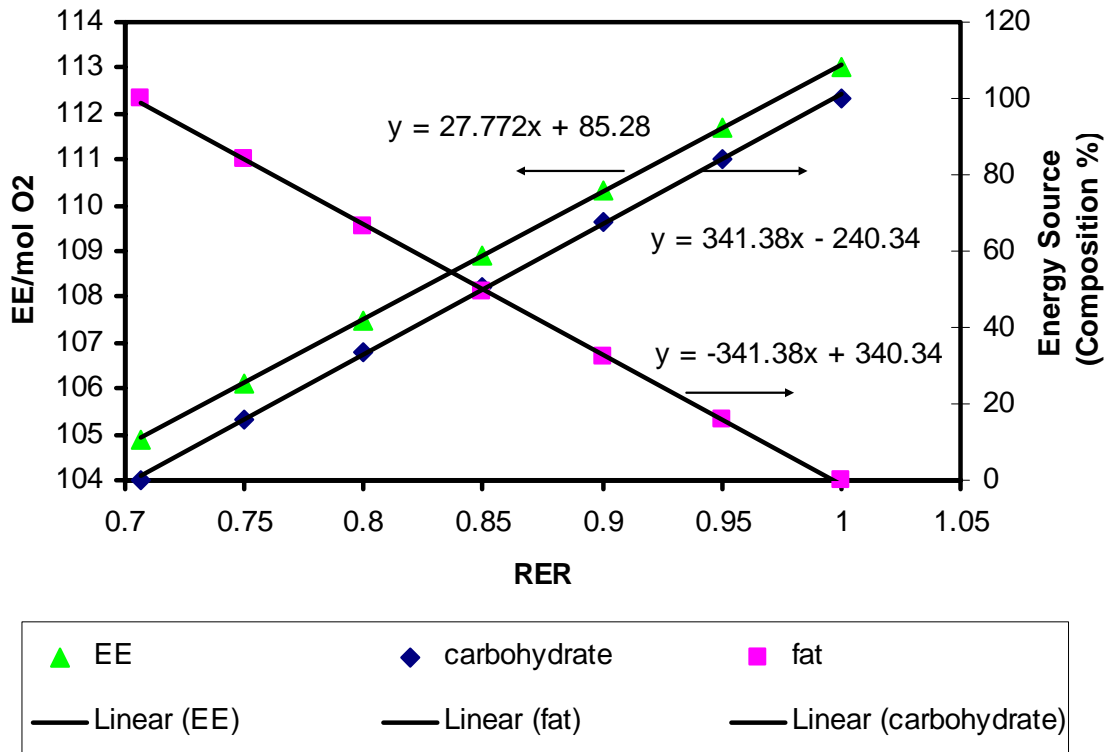
(At Standard Temperature and Pressure, 0°C and 760 mm Hg)

The RER is therefore a convenient indicator for the proportion of carbohydrates and fats being burned, and is related to the total energy expenditure. This is illustrated graphically in Figure 1. The trendline equations provide relationships of between EE and RER, and between the composition of the energy source and RER.

The First Law of Thermodynamics reveals that if the energy equivalent of consumed food exceeds the energy expended, the result is a net storage of energy in the form of fat. The human body doing exercise can be analyzed as a machine doing mechanical work. To do mechanical work such as bicycling or running, the body consumes energy supplied by oxidation of food. Because the body is not perfectly efficient, the energy consumed is greater than the actual

mechanical energy expended. The efficiency,  $\eta$ , of this human machine or a human is expressed by the following equation:

$$\eta = \frac{\text{mechanical work done}}{\text{energy consumed}} \cdot 100 \quad (9)$$



**Figure 1. Energy source composition and energy expenditure as a function of RER**

#### Heat transfer through respiration

Energy that is not used to perform external work is ultimately released as heat through radiation, convection evaporation of sweat, and respiration. In this module, we are concerned with the rate of heat transfer by respiration.

During respiration, inspired air is warmed from ambient temperature to body temperature prior to being exhaled. In addition, water evaporates from the wet alveolar membranes 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 cooling ( $q$ , kcal/min) achieved through the process of respiration is:

$$q = \dot{m}_{air} C_{p,air} (T^{out} - T^{in}) + \Delta H_{vap,w} (\dot{m}_w^{out} - \dot{m}_w^{in}) \quad (10)$$

Where  $m$  is the molar flowrate (mol/min),  $C_p$  is the molar heat capacity (kcal/mol K),  $T$  is temperature (K) and  $\Delta H_{vap}$  is the latent heat of vaporization of water (kcal/mol). Subscripts represent components air or water, and superscripts represent inlet or outlet air. Under normal conditions, about 14% of the body's total cooling is accomplished through respiration, and this percentage can change with exercise [10] and ambient conditions.

### 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). The system interfaces with a cycle ergometer (Lode Corvial) for exercise testing. To prevent cross contamination between patients (students), disposable PreVent<sup>TM</sup> pneumotachs were used once and then discarded. This system was purchased from MedGraphics, St. Paul, MN for approximately \$35,000. While this price may be prohibitively expensive for an engineering program to purchase if not used for research purposes, many universities have such equipment available in a physiology or exercise science laboratory.

### 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, and these values are stored by the software.



**Figure 2.** A student performing the gas exchange test while cycling.

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.

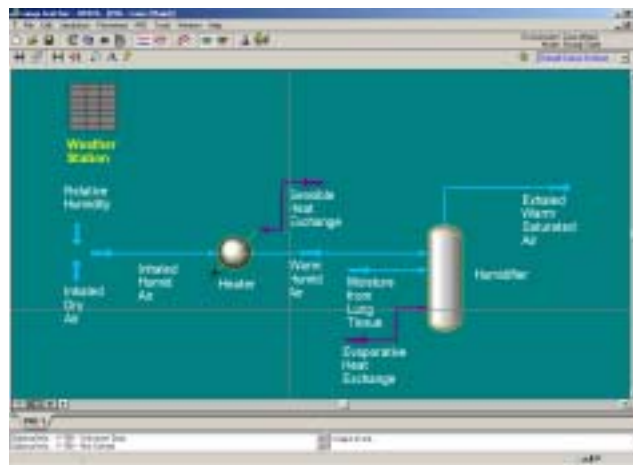
The following quantities are measured directly and displayed using MedGraphics Breeze Suite software:  $\dot{V}^{out}$ ,  $y_{O_2}^{in}$ ,  $y_{O_2}^{out}$ ,  $y_{CO_2}^{in}$ ,  $y_{CO_2}^{out}$ , and braking power. The gas exchange data are reported at BTPS (Body Temperature and Pressure, Saturated) conditions. The software offers many options for the convenient display of automatically-calculated values; however, these direct measurements at BTPS conditions are the only values necessary to perform the calculations involved in this experiment. The calculation/display options may be exercised in order to provide numbers against which students may check their calculations.

For their laboratory report, students perform all calculations by hand. The energy balance on the respiration process is simplified by neglecting the composition change due to oxygen and carbon

dioxide exchange, since this has an insignificant impact on heat capacity of the exhaled mixture. In other words, only the energy changes associated with heating and humidifying an air stream are considered. In a subsequent laboratory period, students are introduced to the process simulator, HYSYS. In an in-class activity, students 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 they 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.

Using HYSYS process simulator, the experimental gas exchange resting measurement data are used to simulate the process of respiration. The feed stream represents inspired air at ambient temperature, pressure and relative humidity. In the first unit, the air is heated to body temperature, and in the second unit it is humidified to saturation. The HYSYS respiration process flow diagram is shown in Figure 3. Dry air at the specified ambient temperature is first mixed with water to produce humid air equivalent to the specified ambient humidity. This ambient air is heated to body temperature in a heater, and the sensible heat change is calculated. The warm air is then saturated with water, and the latent heat change is calculated.

Students also ran several cases of the respiration simulation to examine the effect of ambient conditions on the rate of heat transfer by respiration, and on the relative contributions of sensible heat and latent heat. 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).



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

## Results

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 3 shows gas exchange measurements and calculated values for the respiration experiment, for an 19 year female student (125 lb, 66 in). According to Equations 2 and 3, the student has a surface area of about  $1.59 \text{ m}^2$  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 what the body actual measured energy expenditure at rest (resting energy expenditure, REE). The resting energy expenditure is therefore expected to be 82.2 kcal/h.

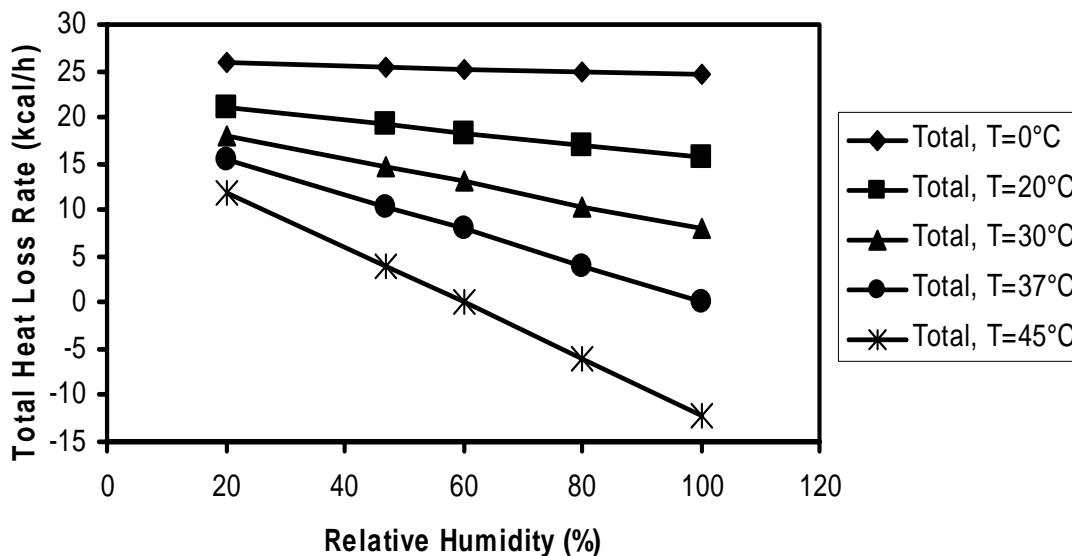
Comparison of exercise data to resting data reveals that the rate breathing rate is substantially faster during exercise, the oxygen concentration of expired air is slightly lower than its resting

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 trendline in Figure 1, which provides a relationship between EE and RER. This information is summarized in Table 2. The mechanical efficiency, calculated using Equation 9, is only 23.4%, because a significant amount of energy is required to overcome internal and external friction [7]. (Cycling is in fact one of the most efficient exercises!)

Table 3. Gas exchange measurements and calculations at rest and during cycling exercise. :  $\dot{V}_{O_2}^{out}$ ,  $y_{O_2}^{in}$ ,  $y_{O_2}^{out}$ ,  $y_{CO_2}^{in}$ , and  $y_{CO_2}^{out}$  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=755 mm Hg, RH=47%)

Measured variables				Calculated Variables			
Power (W)	$\dot{V}_{O_2}^{out}$ (L/min)	$y_{O_2}^{out}$	$y_{CO_2}^{out}$	$\dot{V}_{O_2}$ (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

Using the HYSYS process simulator to simulate the sensible heat and latent heat changes that take place during respiration, the role of respiration in thermal regulation of the body can be investigated. Figures

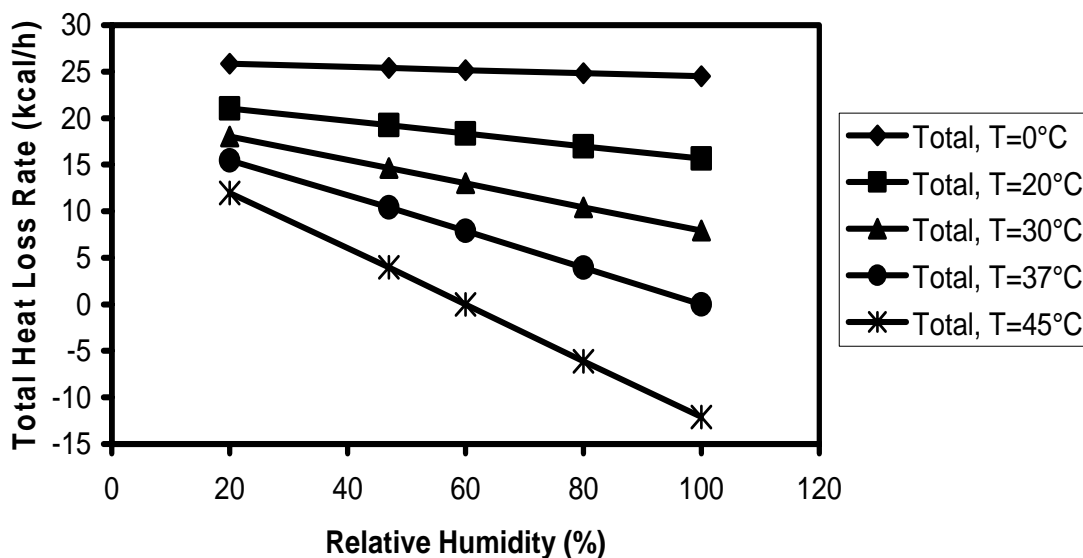


Fig

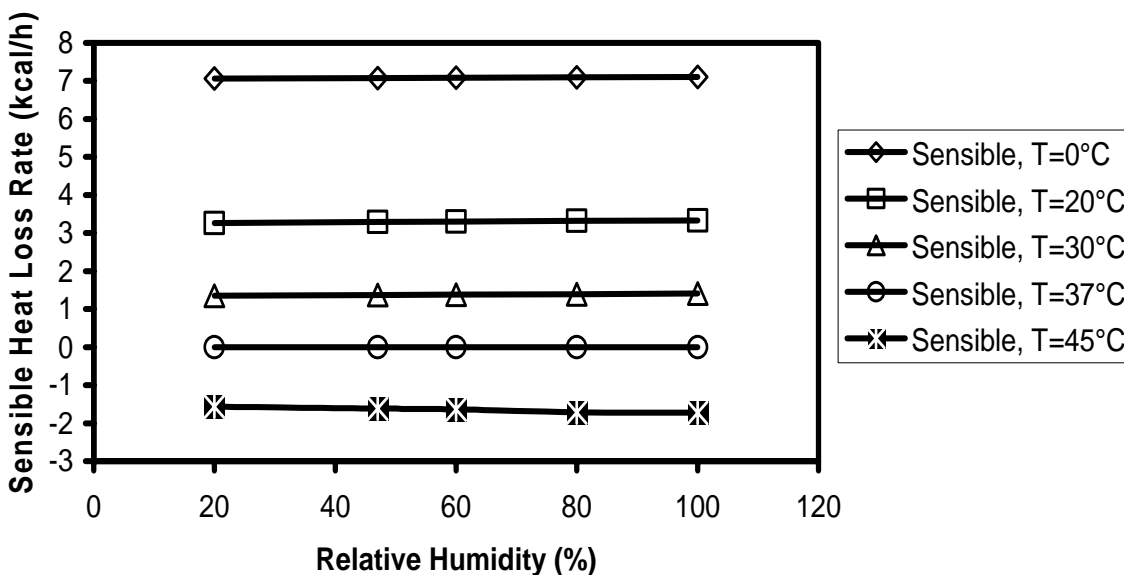
ure 4, Figure 5, and Figure 6 show the total, sensible, and latent heat transfer rates (respectively) under varying ambient temperature and relative humidity. Using the resting data above, the overall rate of heat transfer through respiration at rest (and at ambient conditions of the experiment) is about 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:



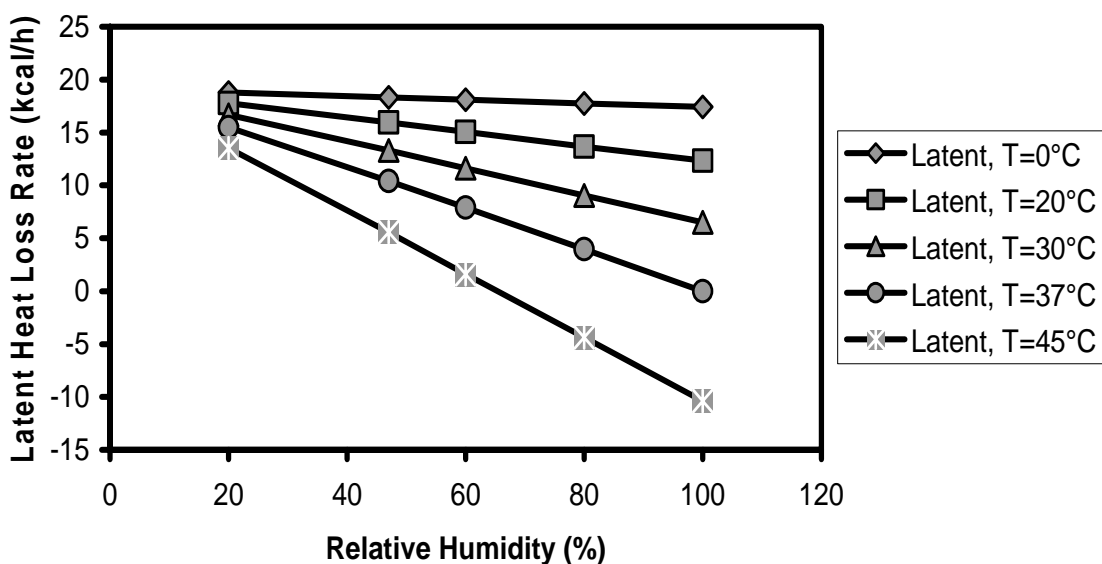
1. The total rate of heat loss via respiration decreases with increasing RH and with increasing temperature. Heat loss is positive except under the most extreme conditions of high T and RH when the heat loss is negative and heat is transferred to the body via respiration. This extreme combination of high temperature and humidity is an uncommon weather condition; however, the transfer of heat to the body under these conditions explains why it is necessary to limit steam saunas to short periods of time. 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). In extreme hot, humid conditions, the latent heat loss becomes negative because water can actually condense in the respiratory system (causing further distress to the person who stays in the steam sauna for an extended time!). (In order to obtain the data for hot humid conditions in which water condenses in the respiratory tract, the order of the heater and humidifier were reversed on the HYSYS flowsheet). From the HYSYS stream information, it is interesting to note that approximately 20 ml/h of water are lost via respiration in hot, dry conditions (45 °C and 20%RH).



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



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



**Figure 6.** The effect of ambient temperature and relative humidity on the latent heat transfer rate during respiration.

## Conclusions

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 and energy balances, chemical reaction stoichiometry and

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heats of reaction, work and efficiency. 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 students 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 the analysis of the data. Using a familiar system, sensory experiences, and hands-on active learning is thought to increase understanding and retention of the new concepts.

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### Biographical Information

Stephanie Farrell is Associate Professor of Chemical Engineering at Rowan University. She received her Ph.D. (1996) from NJIT. Stephanie has developed innovative classroom and laboratory materials in biomedical, food, and pharmaceutical engineering areas. She is the recipient of the 2000 Dow Outstanding Young Faculty Award, the 2001 Joseph J. Martin Award, and the 2002 Ray W. Fahien Award.

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Mariano Savelski is Assistant Professor of Chemical Engineering at Rowan University. He received Ph.D. in 1999 from the University of Oklahoma. His research is in the area of process design and optimization with over seven years of industrial experience. His prior academic experience includes two years as Assistant Professor in the Mathematics Department at the University of Buenos Aires.