Exercise in Chemical Engineering for Freshmen

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Abstract

The human body is an exquisite combination of interacting systems that can be analyzed through the application of chemical engineering principles. Familiar examples include fluid flow of blood through arteries and veins, mass transfer in the lungs, pumping of the heart, and chemical reactions in cells. Biomedical topics in Chemical Engineering are explored in many curricula through advanced level elective courses, and are sometimes worked into homework problems in core courses.

This paper describes a freshman level engineering experiment that is used to introduce students to a wide range of chemical engineering principles through their application to physiological processes. Students take measurements of physiologic variables both at rest and during exercise, and then perform engineering calculations that involve basic principles of mass and energy balances, fluid flow, chemical reactions, energy expenditure, mechanical work and efficiency.

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]. 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 human body.

The student recreational facility serves as the laboratory setting for this experiment. Students measure physiological variables such as blood pressure, breathing rate, and pulse rate at rest and during moderate exercise on a LifeCycle exercise bicycle. Using their data, students perform engineering calculations to determine oxygen consumption, energy expenditure, mechanical work, and blood flow rate.

Experiment

Respiration

The air we inspire is approximately 21% O_2 and 79% N_2, while the expired gas from the lungs contains approximately 75% N_2, 16% O_2 and 4% CO_2 and 5% H_2O [5,6]. The lungs serve as a mass transfer device that separates O_2 and N_2, and allows the exchange of O_2, CO_2, and H_2O. The objectives of this module are (1) to introduce the lungs as a mass transfer device, (2) to calculate the rate of O_2 consumption and CO_2 production under various breathing conditions, and (3) to perform simple mass balances on the lungs.

The volume of air in one breath is measured by exhaling through a tube into an inverted graduated cylinder filled with water and observing the volume of water displaed. Students count the number of breaths taken in one minute while breathing at a normal rate, both at rest and during exercise. The oxygen consumption rate **(**$\dot{V}_{O_2}$, L O_2/min**)** is calculated using a material balance on the lungs:

$$\dot{V}_{O_2} = \left[\frac{\text{breaths}}{\text{min}}\right]\left[\frac{\text{volume air}}{\text{breath}}\right]\left[\text{fraction } O_2 \text{ inhaled} - \text{fraction } O_2 \text{ exhaled}\right]$$

For a typical breathing rate of 12 breaths per minute, lung volume of 500 ml, and using the oxygen concentrations for inspired and expired air provided above,

$$\dot{V}_{O_2} = \left[12\frac{\text{breaths}}{\text{min}}\right]\left[0.5\frac{\text{ml air}}{\text{breath}}\right]\left[\frac{0.21\text{ L } O_2}{\text{L air}} - \frac{0.16\text{ L } O_2}{\text{L air}}\right] = \frac{0.30\text{ L } O_2}{\text{min}}$$

During moderate exercise, a student might observe a breathing rate of 35 breaths per minute with a volume of 1 L/breath. This would result in an oxygen consumption rate of 1.75 L/minute. Figure 1 shows a student performing moderate exercise on a bicycle ergometer.

Figure 1. A student performing moderate exercise on a bicycle ergometer.

Metabolism

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 rate of O_2 consumption [5]. For instance, energy is released in the oxidation of glucose:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6H_2O + 6CO_2 \quad + \quad 686 \text{ kcal/mole}$$

The heat of reaction is equivalent to approximately 4.86 kcal per liter of oxygen consumed. This energy is used to maintain the function of the body (basal metabolism) and to do external work (exercise). Since the energy expended during metabolism becomes heat, which is dissipated from the skin, the basal metabolic rate is proportional to body surface area. The objectives of this section of the experiment are (1) to determine the rate of energy expenditure (at rest and during exercise) and (2) to determine the mechanical work accomplished during cycling exercise.

The rate of energy expenditure (EE) is related to the rate of O_2 consumption ($\dot{V}O_2$) and heat of reaction:

$$\mathrm{EE} = \dot{V}O2 \times 4.862 \frac{\mathrm{kcal}}{\mathrm{L\ O_2}}$$

From their calculations of the rate of O_2 consumption, students calculate the rate of energy expenditure at rest and during exercise. The student who consumed 0.3 L O_2 per minute would expend 1.46 kcal per minute, or 87.5 kcal per hour. The calculated value of energy expenditure during moderate exercise using the values of breathing rate and volume above, would be 408 kcal/hr. This value is compared with the value displayed on the LifeCycle exercise equipment.

The ergometer used for the exercise test indicates energy expenditure as calculated through its relationship to braking power (equal to the rate of work done by the subject) and efficiency:

$$\eta = \frac{\text{work done}}{\text{energy consumed}}$$

Using a typical value of efficiency for cycling of 20% [7], students can calculate the actual mechanical work accomplished through their exercise.

Cardiovascular System

The cardiovascular system is explored to introduce students to the function of the heart as a pump, and to blood as the fluid that transports O_2 to the body. They explore how the heart increases pumping capacity (heart rate and the heart stroke volume) to transport more O_2 to the body during exercise. The objectives of this module are (1) to determine the hydrostatic effects on blood pressure through blood pressure measurement and (2) to determine the blood flow rate at rest and during exercise.

Students perform heart rate and non-invasive blood pressure measurements at rest and during exercise. A polar heart rate monitor is used to measure the heart rate (beats per minute), and a sphygmomanometer is used to measure blood pressure.

Figure 2: Measurement of blood pressure with arm in an elevated position.

Students investigate hydrostatic pressure effects by measuring blood pressure in the arm at different elevations relative to the heart, as shown in Figure 2. The average blood pressure (P_1) in the elevated arm can be calculated using the relationship:

$$P_2 = P_1 - \rho g h$$

where P_1 is the blood pressure in the arm in a “normal” relaxed position, h is the distance the arm is raised above the normal position, g is the acceleration of gravity, and ρ is the density of blood (1.056 g/cm^3). The average blood pressure during the heart's pumping-filling cycle is calculated by

$$BP_{avg} = \frac{\text{systolic} + 2 * \text{diastolic}}{3}.$$

For example, if the average blood pressure in the arm in a "normal" relaxed position is 83 mm Hg, the pressure with the arm extended upward 30 cm would be:

$$P_2 = 83\,\text{mm Hg} - \left(1.056\frac{g}{cm^3}\right)\left(980\,\frac{\text{cm}}{\text{s}^2}\right)(30\,\text{cm})\left(\frac{760\,\text{mm Hg}}{1010000\,\text{g/cm s}^2}\right)$$
$$P_1 = 59.6\,\text{mm Hg}$$

The calculated value of pressure is compared with the measured value.

There is a linear relationship between heart rate and O_2 consumption, as both increase to meet the body's rising demand for oxygen during exercise [5, 8].

$$\dot{V}_B = 3\frac{L}{\min} + 8\dot{V}_{O_2}$$

Using their calculated value of oxygen consumption rate, students calculate the flowrate of blood through the body at rest and during exercise. For example, the student who consumed 0.3 L/min oxygen would calculate a blood flow rate of:

$$\dot{V}_B = 3\frac{L}{\min} + 8 * \left[0.30\frac{L\,O_2}{\min}\right] = 5.4\frac{L}{\min}$$

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 human body. Students study fluid flow of blood through arteries and veins, mass transfer in the lungs, pumping of the heart, and chemical reactions in cells. Students take measurements of physiologic variables both at rest and during exercise, and then perform engineering calculations that involve basic principles of mass balances, stoichiometry, energy expenditure, mechanical work and efficiency, fluid flow, and hydrostatics. Students rated this experiment highest in the "interesting and informative" category: 4.7/5.0 in comparison to the average rating of 4.0/5.0 for all twelve Freshman Engineering experiments.

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Biographical Information

Stephanie Farrell is Associate Professor of Chemical Engineering at Rowan University. She received her B.S. in 1986 from the University of Pennsylvania, her MS in 1992 from Stevens Institute of Technology, and her Ph.D. in 1996 from New Jersey Institute of Technology. Prior to joining Rowan in September, 1998, she was a faculty member in Chemical Engineering at Louisiana Tech University. Stephanie has research expertise in the field of drug delivery and controlled release, and she is currently focusing efforts on developing laboratory experiments related to membrane separations, biochemical engineering,and biomedical systems, for all level students at Rowan. Stephanie won the ASEE Outstanding Campus Representative Award in 1998, the Dow Outstanding Young Faculty Award in 2000, and the Joseph J. Martin Award in 2001.

Robert Hesketh is Associate Professor of Chemical Engineering at Rowan University. He received his B.S. in 1982 from the University of Illinois and his Ph.D. from the University of Delaware in 1987. After his Ph.D. he conducted research at the University of Cambridge, England. Prior to joining the faculty at Rowan in 1996 he was a faculty member of the University of Tulsa. Robert's research is in the chemistry of gaseous pollutant formation and destruction related to combustion processes. Nitrogen compounds are of particular environmental concern because they are the principal source of NOX in exhaust gases from many combustion devices. This research is focused on first deriving reaction pathways for combustion of nitrogen contained in fuel and second to use these pathways to reduce NOX production. Robert employs cooperative learning techniques in his classes. His teaching experience ranges from graduate level courses to 9th grade students in an Engineering Summer Camp funded by the NSF. Robert's dedication to teaching has been rewarded by receiving several educational awards including the 1999 Ray W. Fahien Award, 1998 Dow Outstanding New Faculty Award, the 1999 and 1998 Joseph J. Martin Award, and four teaching awards.

Edward C. Chaloupka is Associate Professor in the Department of Health and Exercise Science at Rowan University in New Jersey. He is the Co-Director of the Exercise Science Research Laboratory and teaches courses in human anatomy and physiology, exercise physiology, therapeutic exercise, therapeutic modalities, and introduction to allied health professions. He is also a physical therapist in outpatient general orthopedics and sports physical therapy for the Cooper Hospital/University Medical Center in New Jersey. Dr. Chaloupka holds a B.A. in health and physical education and a M.S. in education from Queens College of the City University of New York, a Graduate Certificate of Proficiency in physical therapy from Hahnemann Medical University and a Ph.D. in exercise physiology from The Ohio State University. Dr. Chaloupka is a member of the American College of Sports Medicine and the Mid-Atlantic Regional Chapter. In the past he has presented his research at both the national and Mid-Atlantic meetings. He was a member of the Graduate Research Awards Committee for the Mid-Atlantic Chapter in 1998 and a member of the Fund Raising Committee for the 1999 Mid-Atlantic Chapter meeting. Dr. Chaloupka is also a member of the Research Awards Committee for national ACSM for 1999-2002.