ChE class and home problems for teachers

WHEN IS A MAN HALF A HORSE?*

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A bicyclist is pedalling along a level street in Denver at a speed of 40 km/hr on a calm day when the air temperature is 20°C and the barometer normal for that elevation. It is desired to calculate the volume of air he breathes every hour and compare it with the volume he would breathe if he were doing the same thing on the same kind of a day in New York City. The following data and assumptions are to be used:

- The cyclist's body is burning up essentially sugar which may be taken as glucose.
- The efficiency of his body as a thermodynamic machine is 30% compared to a reversible machine.
- His lungs remove 20% of the oxygen from the air passing through them. Air is taken to be 21 mole % oxygen with a M.W. of 29.
- The air resistance of his body and the bicycle is equivalent to a cylinder, 1/2 m in diameter and 3/4 m long, moving with the same velocity as the bicycle with the major axis of the cylinder perpendicular to the motion.
- The road resistance to the tires and the friction in the bearings of the wheels, gears, and chain vary directly as the velocity, and are given by 0.05 N/(km/hr).
- The elevation in Denver is 1650 m while that in New York is 7 m.
- Standard acceleration of gravity holds for the latitudes and elevations involved.

SOLUTION

The first step is to find the work done by the cyclist in one hour. The force against which he is pushing is the sum of the air resistance and the road resistance and bearing friction. The latter is simply

$$F_{r+b} = \left|\frac{0.05\text{N}\bullet\text{hr}}{\text{km}}\right|\frac{40\text{ km}}{\text{hr}}\right| = 2.0\text{ N}$$

To get the air resistance, we employ the drag equation,

$$F_{air} = \frac{CA\rho u^2}{2}$$

where C is the drag coefficient, A is the frontal area of the cylinder, ρ is the density of the air, and u is the velocity of the air relative to the cylinder. For infinite cylinders C = 1.2, but there is air leakage around the ends of a short cylinder which reduces the drag coefficient a little, so 1.1 is assumed. The density of air will be less in Denver than at sea level and this may be calculated by the barometric equation taken at a constant temperature of 20°C.

$$\int_{101.325}^{P} VdP = -g\Delta Z$$

Assuming air as an ideal gas, V = RT/P, so

$$\int_{101.325}^{P} \frac{RT}{P}\,dP = RT\,\ln\frac{P}{101.325} = -g\Delta Z$$

or

$$\ln\frac{P}{101.325} = -\frac{g\Delta Z}{RT}$$

where g = 9.80665 m/s², R = 8.3144 Pa•m³/gmole•K, and T = 293.15K. This formula estimates the normal barometric pressure in Denver at 1650 m elevation as 83.58 kPa and in New York at 7 m elevation as 101.24 kPa. Using these pressures in the ideal gas law, we find the density of air is 994.44 g/m³ in Denver and 1204.6 g/m³ in New York. The air resistance in Denver is calculated from the drag equation as

$$F_{air} = \left[\frac{1.1}{2}\right]\left[\frac{1\text{ m}}{2}\right]\left[\frac{3\text{ m}}{4}\right]\left[\frac{994.44}{1000}\ \frac{\text{kg}}{\text{m}^3}\right]\left[\frac{40\text{ km}}{\text{hr}}\right]^2\left[\frac{1\text{ N}\cdot\text{s}^2}{\text{kg}\cdot\text{m}}\right]\left[\frac{1\text{ hr}}{3600\text{s}}\right]^2\left[\frac{1000\text{ m}}{\text{km}}\right]^2 = 25.32\text{ N}$$

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Similarly, the air resistance in New York is calculated to be 30.67 N.

Now, in one hour the cyclist's work output is the product of total force and distance. In Denver the total force is 2.0 + 25.32 = 27.32 N and the work output in one hour is

$$W = (27.32\ \mathrm{N})\ (40\ \mathrm{km}) \left[\frac{1\ \mathrm{kJ}}{\mathrm{N{\cdot}km}}\right]$$
$$= 1092.8\ \mathrm{kJ} \sim 0.41\ \mathrm{HP\ in\ Denver.}$$

In New York the total force is 2.0 + 30.67 = 32.67 N and the work output in one hour is

$$W = (32.67\ \mathrm{N})\ (40\ \mathrm{km}) \left[\frac{1\ \mathrm{kJ}}{\mathrm{N{\cdot}km}}\right]$$
$$= 1306.8\ \mathrm{kJ} \sim 0.49\ \mathrm{HP\ in\ New\ York.}$$

The cyclist's air volume breathed every hour is related to the glucose burning rate. For a reversible machine

$$-W_r = \Delta G_T$$

Thus we need ΔG for the combustion of glucose. This is not given in any of the ordinary tables of thermochemical properties, so the usual approach would be to estimate it by a group contribution method applied to the glucose molecule.

Fortunately, it is not necessary to do this, as the biomedical literature* reports that the oxidation of glucose is one of the few reactions whose ΔG has been measured in living systems. The following is given:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O,$$
$$\Delta G = -708\ \mathrm{kcal/gmole}$$

Thus, the amount of glucose consumed by the cyclist operating at 30% efficiency in Denver is

$$n_{gl} = \left[\frac{1092.8\ \mathrm{kJ}}{0.30}\right] \left[\frac{\mathrm{gmole}}{708\ \mathrm{kcal}}\right] \left[\frac{\mathrm{kcal}}{4.184\ \mathrm{kJ}}\right]$$
$$= 1.2297\ \mathrm{gmole}$$

The amount of oxygen required from combustion stoichiometry is

$$n_o = 6\,(1.2297) = 7.3782\ \mathrm{gmole}$$

and the amount of air required (21% oxygen and 20% of the oxygen absorbed by the body) is

$$n_{air} = \frac{7.3782}{(0.21)\ (0.20)} = 175.67\ \mathrm{gmole}$$

From the ideal gas law the hourly volume of air breathed in Denver at a pressure of 83.58 kPa is

$$V = \frac{nRT}{P} = 5.123\ \mathrm{m^3\ in\ Denver}$$

Since the bicyclist does more work pedalling in New York, the glucose consumed there is

$$n_{gl} = \left[\frac{1306.8\ \mathrm{kJ}}{0.30}\right] \left[\frac{1\ \mathrm{gmole}}{708\ \mathrm{kcal}}\right] \left[\frac{1\ \mathrm{kcal}}{4.184\ \mathrm{kJ}}\right]$$
$$= 1.4705\ \mathrm{gmole}$$

and the moles of air required are

$$n_{air} = \frac{6\,(1.4705)}{(0.21)\ (0.20)} = 210.07\ \mathrm{gmole}$$

Thus, the ideal gas hourly volume of air in New York at a pressure of 101.24 kPa is

$$V = \frac{nRT}{P} = 5.057\ \mathrm{m^3}$$

This is slightly less air volume than is required in Denver. Note the work is more in New York, but air supplies more oxygen because of its higher density. If sitting-up exercises were being done, air resistance would not be a factor, so the work in Denver would be practically identical to the work in New York. Because of less dense air the air volume required in Denver would then be much greater than in New York.

COMMENT

This problem was designed to be realistic, based on extensive discussions with doctors, physiologists and athletes. If a similar problem is designed by others, some of the restrictions should be noted:

- Regardless of respiration rate while exercising, the lungs absorb roughly 20% of the oxygen passing through them.
- It is only for rather rapid exercise that a

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*Vishniac, W., Horecker, B. L. and Ochou, S., Advan. Enzymol. *19*, 1, 1957.
Ingraham, L. L. and Pardee, A. B. "Free Energy and Entropy in Metabolism," Metabolic Pathways, Vol. I, third edition, Greenburg, D. M. Editor, Academic Press, New York (1967).
Ostrand and Rodahl, Textbook of Physiology, McGraw-Hill, New York (1970).

human being can get to 1/2 HP. For slow lifting the power is less.

- The air resistance of the bicycle and man is very complex with pumping legs, but the equivalence to a short cylinder is not a bad assumption, though the drag coefficient may be high.
- At rest a man breathes about 0.007 m^3/min. A few people can get to 0.12 m^3/min, but this appears to be a maximum. The bicyclist in Denver is averaging 0.085 m^3/min, which is 12 times that at rest.
- Some doctors feel that 3/4 pound glucose is the most a body can handle in an hour. This leads to efficiencies of the body as a thermodynamic machine up in the 30% range, or too much glucose will be required, not to mention air. In New York the bicyclist is burning up a little more than one-half pound of glucose in an hour. □

ASEE SUMMER SCHOOL FOR CHE FACULTY

REQUEST FOR INFORMATION

There have been eight ASEE Summer Schools for Chemical Engineering Faculty to date, but complete records only seem to exist for the 1977 and 1972 schools. T.W.F. Russell and S. I. Sandler, ChE Department, University of Delaware, Newark, DE 19711, the directors of the 1982 Summer School are writing a history of the summer schools and badly need any information our readers may possess. They are particularly interested in the following:

- Date of the summer school, location, and directors.
- Program and those presenting it.
- Number of participants and number of schools represented.
- Budget details.
- Any documentation, final reports, correspondence, etc., particularly with regard to the early efforts in 1931 (Univ. of Michigan) and 1939 (Penn State).

REQUEST FOR FALL ISSUE PAPERS

Each year CHEMICAL ENGINEERING EDUCATION publishes a special Fall issue devoted to graduate education. This issue consists mainly of articles on graduate courses written by professors at various universities, and of advertisements placed by ChE departments describing their graduate programs. Anyone interested in contributing to the editorial content of the Fall 1979 special issue should write to the Editor indicating the subject of the paper and the tentative date the paper can be submitted. This information should be sent to Ray Fahien, Editor, CHEMICAL ENGINEERING EDUCATION, c/o Chemical Engineering Dept., University of Florida, Gainesville, Florida 32611.

ChE book reviews

OPERATIONAL AMPLIFIERS IN CHEMICAL INSTRUMENTATION

By Robert Kalvoda, Ellis Horwood Limited, 1975.
Reviewed by Kenneth R. Jolls
Iowa State University.

Dr. Kalvoda's book provides a relatively brief but sufficiently thorough discussion of the operational amplifier, particularly as its use pertains to electroanalytical instrumentation. For the chemical engineer to whom modern electronics has become important in his experimental work, control studies, or computer automation, the operational amplifier is an invaluable tool. It has become so much the "black box," however, that many of us lose sight of its limitations, its nontypical applications, and the ways in which its functions may be modified through external circuitry. This book attempts to cover these areas as well as the more familiar ones.

The book is organized into eight chapters as noted below:

I. The General Scheme of the Measuring Apparatus
II. The Operational Amplifier—an Introduction
III. Basic Operational Amplifier Circuits
IV. Further Circuits Using Operational Amplifiers
V. Important Parameters in Application of Operational Amplifiers
VI. Types of Operational Amplifiers
VII. Applications of Operational Amplifiers in Chemical Instrumentation
VIII. Operational Amplifier Module Kits

Chapter I describes the usual signal processing scheme encountered in instrumentation. Chapter II provides a brief history of the OA and some of its important macroscopic characteristics. A detailed analysis of the external feedback circuitry used to implement operational amplifier functions is presented in chapter III. The current follower is explained with emphasis being given to the concepts of virtual ground and input impedance. The inverting voltage amplifier naturally follows and is discussed in terms of its transfer function dependence upon resistance ratios and signal frequency. Non-inverting circuits including the simple follower and follower with gain are described in adequate detail, and their higher input resistances are noted. Several configurations of differential amplifiers are discussed as are a number of OA circuits for precise voltage and current sources.

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