9. Electric Energy and Work, Acoustical Power

PURPOSE AND BACKGROUND

Electricity is one of the most important energy forms. In this laboratory we study electric energy, work, power, voltage, current, and resistance. We measure the power consumption of a conventional incandescent light bulb and compare it with the more efficient compact fluorescent light bulb (CFL) and the yet more efficient light emitting diode (LED). We will determine the energy and dollar savings with a CFL compared to an incandescent light bulb. In a second part of this laboratory we investigate the acoustic power radiated by a loudspeaker by finding the sound intensity level (SIL) in front of the speaker. The speaker efficiency then follows from the acoustic power divided by the electric power. We judge how loud a speaker sounds for a given acoustic power and find out how acute our sense of hearing is.

EQUIPMENT

Loudspeaker, light bulb fixture with incandescent light bulb, compact fluorescent light bulb (CFL), light emitting diode (LED), "Watts UP" power meter for light bulbs, power meter for loudspeaker (General Radio Output Power Meter 1840-A), two multi-meters for current and voltage measurements, PASCO Sine Wave Generator, EXTECH Digital Sound Level Meter.

Some Theory Concerning Power, Energy, Work, and Electricity

Energy is the ability to do work.

Example: 1 gallon of gasoline contains energy to do work. An automobile engine does work and moves a car 30 miles with this energy.

Unit of energy and work: **1 Joule (J)**

Power is the rate at which work is done Power = Work/Time or $\mathbf{P = W/t}$

Work Work = Power·Time $\mathbf{W = P \cdot t}$

The unit of power is Joule/second = Watt **1 J/s = 1 Watt (W)**

Ohm's law of electricity $\mathbf{V = I \cdot R}$, where

V = voltage across a load in **volt (V)**, for instance a light bulb or loudspeaker
I = current through the load in **Ampere (A)**
R = resistance of the load in **Ohm (Ω)**

Electric power $\mathbf{P = V \cdot I}$, or equivalently $\mathbf{P = I^2R}$ and $\mathbf{P = V^2/R}$

Common unit of energy: **kilowatt·hour (kWh)**

Conversion: 1 kWh = 1000 W·3,600 s = 3,600,000 W· s = 3,600,000 J = $\mathbf{3.6 \times 10^6}$ **J**

Example: A sedentary person consumes 2000 kcal (kilocalories) of food energy per day. The conversion is 1 kcal = 4185 Joule. Therefore 2000 kcal = 8,370,000 J. This amount of energy is consumed in a time t = 24 hours = 86,400 s.
Hence the rate of energy consumption is $P = W/t = 8{,}370{,}000\ \text{J}/86{,}400\ \text{s} = 97\ \text{J/s} = 97\ \text{W}$ or about 100 W.
This is typical for the resting metabolic rate of a person. You may know this rate as "2000 Kcal per day" rather than 100 Watt. When we sit around doing little, we burn food energy at the rate of 100 W, i.e. about the same as an old-style 100 W incandescent light bulb consumes in the form of electricity.

EXPERIMENTS

Power and Energy Consumption in Light Bulbs

Use the triple light bulb fixture. Note the brightness from the conventional incandescent light bulb, the compact fluorescent light bulb (CFL), and the light emitting diode (LED) light bulb.

1. After warming up, are the three light bulbs about equally bright? ___________

2. Write down the power rating of the three light bulbs, 40 W, 9 W, 6W, on the next line:

Incandescent light bulb P = ________W CFL P = ________W LED P = ________W

3. Plug the "Watts Up" Power Meter into a household outlet. Plug the triple light bulb fixture into the "Watts Up" meter. Read the power consumed by each light bulb. Compare with their nominal ratings above:

Incandescent light bulb P = ________W CFL P = ________W LED P = ________W

4. Read the current in ampere on the meter of the light bulb fixture. Assume a household voltage of V = 120 Volt. Calculate the power from the formula $P = V \cdot I$.

Incandescent light bulb P = ________W CFL P = ________W LED P = ________W

5. How well do the values for power in questions 2, 3, 4 agree? Express the differences in percent. Explain why the readings from experiment 4 above for the CFL and LED may differ from experiments 2 and 3.
Ask your instructor! (Hint: The AC power for a CFL and LED is not simply $P = V \cdot I$.)

6. Suppose you turn the light bulbs on for 5 hours each day. Calculate the energy used in a 30-day month. Express your answer in Joule and then convert to kWh.

Incandescent light bulb: Energy = _____________J = ______________kWh
CFL light bulb: Energy = _____________J = ______________kWh
LED light bulb: Energy = _____________J = ______________kWh

7. Electricity costs about 13 cents/kWh. What is the electric bill for the light bulbs in a month?

Incandescent light bulb	Electric bill = $____________
Compact fluorescent light bulb (CFL)	Electric bill = $____________
Light emitting diode (LED)	Electric bill = $____________

8. An incandescent light bulb costs $0.75 (if still available), a CFL $1.50, and an LED $5.00. How long does it take to amortize the extra cost of the CFL and LED over the incandescent light bulb?

Amortization time: CFL ________months LED ________months

9. How much money is saved over the lifetime of 10,000 hours of a CFL and 20,000 hours of an LED, compared to the 2000 hours for an incandescent light bulb?
Include in your calculation the number of incandescent light bulbs you would need during the lifetime of a CFL and LED.

Money saved: CFL $ _____________ LED $ _____________

10. What are the energy savings in percent when using a CFL and LED instead of an incandescent light bulb? (Hint: Compare the wattages of the three bulbs.)

Energy savings in percent when using a CFL = ______% or LED = ________%

Electric Power to a Loudspeaker

Connect a signal generator (e.g. PASCO WA 9867 sine wave generator) to a loudspeaker (not the dedicated computer speakers). Do not plug the signal generator into the household outlet yet. Connect a multi-meter, set to the Ammeter mode, in-line between the loudspeaker and the signal generator. Connect a multi-meter, set to the Voltmeter mode, in parallel to the speaker inputs.

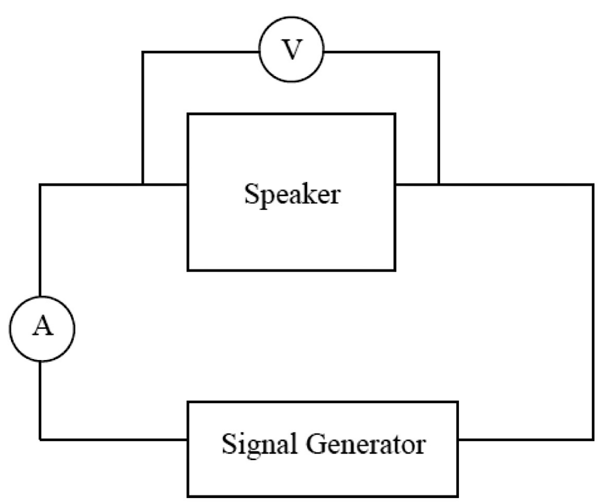

Figure 1. Schematic of the speaker connections to a signal generator, voltmeter, and ammeter.

Select *AC alternating current settings* (not DC settings!) on the ammeter and voltmeter. Choose an initially high range for Amperes and Volts on the meters. Turn down the amplitude on the signal generator. Now plug the signal generator into the household outlet and choose a frequency in the mid-range, i.e. 500 Hz. Observe the voltage and current on the meters. Play with the amplitude and frequency settings and listen to the loudness and pitch of the sound.

11. At a comfortable loudness from the speaker, note the current through the speaker and the voltage across its terminals.

Current $I =$ _______Ampere Voltage $V =$ ________Volt

12. Calculate the power to the loudspeaker from the formula $P = I \cdot V$.

Power $P =$ ________W

13. Loudspeakers of hi-fi systems often are rated at 100 W or higher.
How does your answer for our loudspeaker compare with such ratings?

14. Do you think a power of several hundred Watt is necessary? Why or why not?

Resistance or Impedance of a Loudspeaker, Power Continued

The reaction of a loudspeaker to an applied AC voltage is called *impedance*, labeled with the letter Z. Impedance is not the same as resistance because it also includes capacitance and inductance. We ignore this here and use resistance for impedance. Use Ohm's law $V = IR$ and calculate the resistance from $R = V/I$. Use the value of R to get an estimate for the impedance.

15. Obtain the impedance of the loudspeaker from your measured voltage and current. Compare this with the specification on the loudspeaker enclosure.

Impedance $Z = V/I =$ ______/______ = ______Ω
Written on enclosure $Z =$ ______Ω

16. Obtain the power to the loudspeaker from the expression $P = I^2R$.

Power $P = (\_\_\_\_\_\_)^2 \cdot (\_\_\_\_\_\_) =$ _______W

Compare your answer with the result from question 12: $P =$ _________W

Loudspeaker Power Measured Directly with a Power Meter

Do not change the amplitude and frequency settings on the signal generator. Feed the output from the signal generator directly into the *"General Radio Output Power Meter"* without the loudspeaker, voltmeter, and ammeter in the circuit. Set the impedance dial on the power meter to the same value as for the impedance found in question 15.

17. What is the reading on the power meter? Compare with your calculated results from questions 12 and 16.

Power read from power meter:	a) P = ______W
Power from question 12:	b) P = ______W
Power from question 16:	c) P = ______W

Acoustical Power and Loudspeaker Efficiency

Keep a note of the power read from the “General Radio Output Power Meter”. Keep the amplitude and frequency settings on the signal generator. Remove the power meter from the signal generator and replace it with the loudspeaker.

Use a sound level meter, e.g. the EXTECH Digital Sound Level Meter. Choose setting “A” on it corresponding to the human ear response. Measure the sound intensity level (SIL) at various locations in front of and close to the speaker. For instance, measure the SIL at a distance between 0.5 m and 1 m from the speaker. Move the sound level meter around the speaker in a circular arc, left to right, and up and down, always at the same distance from the center of the speaker. Note the reading on the sound level meter.

18. Write down the SIL readings from the sound level meter.

SIL_{center} = ____dB, SIL_{left} = ____dB, SIL_{right} = ____dB, SIL_{up} = ____dB, SIL_{down} = ____dB

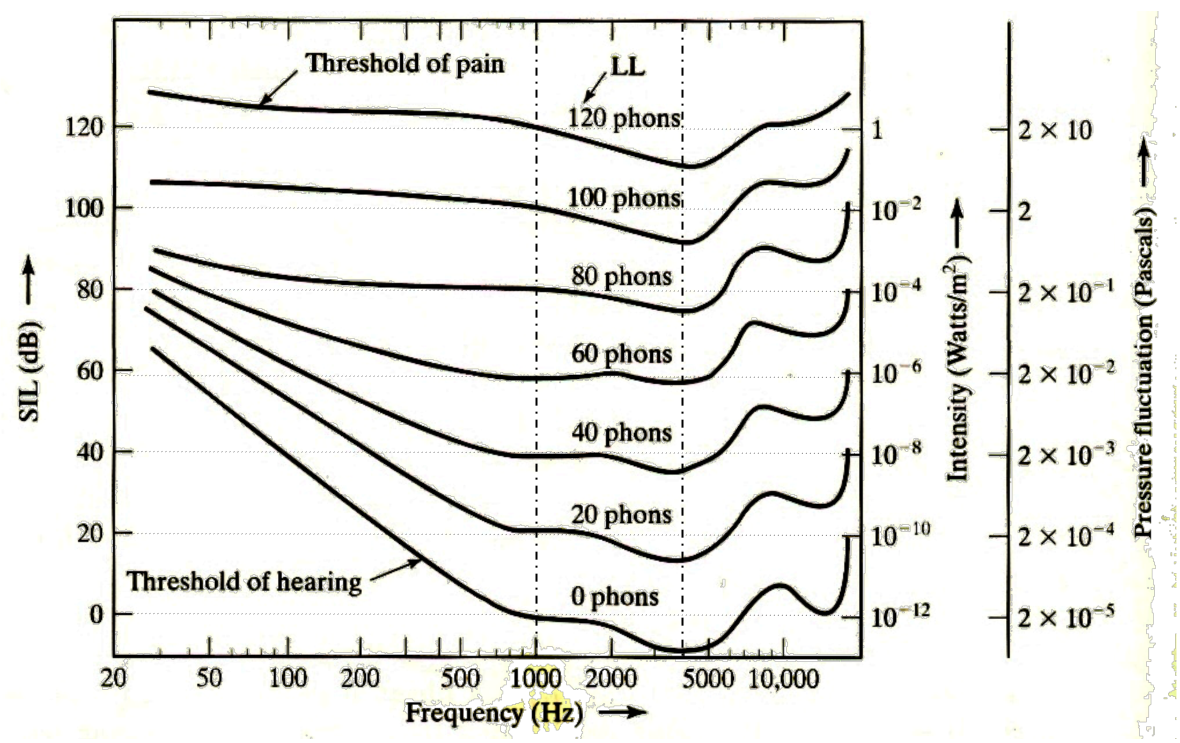

Figure 2: Fletcher-Munson curves of equal loudness. (“Physics of Sound” by R. A. Berg and D.G. Stork.)

19. Take the average of these sound intensity level values.

$SIL_{average}$ =______dB

20. Consult the Fletcher-Munson curves in Figure 2 and write down the sound *intensities* (not the sound intensity levels!) in Watt/m^2 corresponding to your SIL values.
Example: For SIL = 80 dB we have a sound intensity I = 0.0001 Watt/m^2 = $1\cdot10^{-4}$ Watt/m^2.

I_{center} = _________, I_{left} = __________ , I_{right} = __________ , I_{up} = __________ , I_{down} = _________

Average of these intensity values: I_{ave} = _______$\cdot 10^{-4}$ W/m^2

21. Calculate the total acoustical power radiated by the loudspeaker. Assume that the acoustical power is radiated into a cone in front of the speaker. For the area of the base of the cone at a distance *r* in front of the speaker take $A = 0.6\pi r^2$. Write down the distance where you took the measurements with the SIL meter and calculate the area through which the effective acoustical power went.

Distance r = _____m Area A = _____m^2

22. Multiply your value for the average intensity $I_{average}$ from question 20 by the area A. This is a good estimate for the total radiated acoustical power.

Acoustical power $P_{acoustical} = I_{average} \cdot A$ = _______W/m^2 · _______m^2 = ________Watt
You can now compare the radiated acoustical power with the electric power to the speaker (see result from 17a) and obtain the *loudspeaker efficiency.*

Speaker efficiency = $P_{acoustical}/P_{electric}$ x100 = _______%

23. Use your answer for the speaker efficiency to comment on the conversion of electrical to acoustical power.

24. Compare the acoustical power output from a speaker with the light output from a compact fluorescent light bulb. Assume that the same electrical power (e.g. 10 W) goes into the speaker and the CFL. For the CFL assume a conversion efficiency of 20% from electric power to light. Write down the acoustical output from the speaker and the light output from the CFL.

Speaker output $P_{acoustical}$ = ______W CFL output P_{light} = ______W

Your result should indicate that that the emitted acoustical power is much lower than the light output from a CFL.