

T-5. Engines and Efficiency

Teaching Notes

1. Understand the basics of energy flow in a heat engine or refrigerator.
2. Understand the concept of efficiency in general terms.
3. Learn the similarities and differences between the Carnot cycle and other cycles.
4. Compute the efficiency of an engine whose p-V cycle is given.

SAMPLE LESSON PLAN

Discussion Question 1 10 minutes in groups, 5 minutes GSI-led discussion & boardwork.
 Discussion Question 2 10 minutes in groups, 5 minutes GSI-led discussion & boardwork.
 Discussion Question 3 10 minutes in groups, 5 minutes GSI-led discussion & boardwork.
 Discussion Question 4 10 minutes in groups, 5 minutes GSI-led discussion & boardwork.
 Problem 1 or 2 30 minutes in groups, 15 minutes GSI-led discussion & boardwork.

GENERAL TEACHING SUGGESTIONS

In the past, students have viewed the subject of engines and refrigerators as a morass of uninteresting and disconnected formulas ($e = Q_{in}/W_{net}$, $e_C = 1 - T_L/T_H$, $K_{refrigerator} = W_{in}/Q_{out}$, etc.). One important goal of this worksheet is to convey the idea that efficiency is really an intuitive, common-sense notion. (See Discussion Question 1.)

As thermodynamics is traditionally presented in Physics 7B, there are two classes of efficiency formulas: those applicable to *any* reversible engine, and those applicable to a reversible engine operating on the *Carnot cycle*. This profusion of *formulas* is troublesome in itself; but the students' real challenge is to differentiate between *ideas*: those that are generally applicable, and those that apply only to the Carnot cycle. (See Discussion Questions 2, 3, and 4.)

Along these lines, here are two of the more common misconceptions you will encounter:

- “The efficiency of any engine is given by $e = 1 - T_{coldest\ over\ cycle} / T_{hottest\ over\ cycle}$.”

Of course, the efficiency is given by this expression if and only if the cycle is as follows:

isothermal expansion at T_H
 adiabatic expansion to T_L
 isothermal compression at T_L
 adiabatic compression back to T_H

Note that the system in question does not have to be an ideal gas. (Of course, if the equation of state is different from that of an ideal gas, then the p-V diagram for the cycle will not have the familiar shape.)

- “All reversible engines have the efficiency of the Carnot engine.”

Any engine whose cycle can be drawn on the p-V diagram is a reversible engine (neglecting friction in the moving parts). Thus, for example, the cycle in Problem 1 of this worksheet is a reversible cycle. But since this cycle does not consist of isotherm / adiabat / isotherm / adiabat, it cannot possibly have the Carnot efficiency.

Unfortunately, in the text you will find the statement

$$e = e_{\text{Carnot}} \text{ for a reversible engine.}$$

Even granting that the authors’ definition of “reversible” is more careful than the one adhered to in these worksheets, this statement still appears to be incorrect. If a student reading the text becomes confused on this point, perhaps the best thing to do is to replace the equals sign in Equation 26-15 with a less than-or-equal sign: “ $e \leq e_{\text{Carnot}}$ for a reversible engine.” (Even assuming that you can ferret out the textbook’s intended meaning, it would not be terribly helpful to split hairs with your students over the meaning of terms like “reversible” and so on.)

SAMPLE MINI-LECTURE AND BOARD SUMMARY

Even if your students have not yet had a lecture or a lab dealing with heat engines or the Carnot cycle, you should probably not spend much time lecturing at the start of section. One thing you should do, however, is “flesh out” the schematic heat engine and refrigerator diagrams for Discussion Question 1, so as to make contact with everyday notions.

For example, on the heat engine diagram, next to the “hot reservoir,” you can put “burning fuel” or something. Next to the “working substance” you can put “steam” or something. Next to the W_{net} arrow you can put “piston turns drive shaft” or something. Next to the “cold reservoir” you can put “outside air” or something.

On the refrigerator diagram, next to the “hot reservoir,” you can put “warm kitchen air.” Next to the “working substance” you can put “Freon.” Next to the “cold reservoir” you can put “cold air in icebox.” Next to the W_{net} arrow you can put “electric motor.”

Likewise, for a heat pump you can supply your own schematic. Label it with words like “warm household air”, “cold outside air”, and so on.

REMARKS ON THE DISCUSSION QUESTIONS AND PROBLEMS

Discussion Question 1

See the remarks in the above Mini-Lecture for ways to make this question less abstract.

In discussing this question, emphasize that the definitions given here are applicable to all heat engines, not just those that run on a particular cycle.

Try not to get bogged down discussing sign conventions. I just treat all quantities as positive and put in the signs by hand. Some lecturers use absolute value signs on the all of the quantities—ask what your lecturer’s conventions are.

Discussion Question 2

If your students have not yet had a lecture or a lab dealing with the Carnot cycle, then you may have to say a few words about it yourself. See section 26-4 of the text.

Discussion Question 3

As a follow-up to this question, you might ask, “Can we find the efficiency of a Carnot engine using the formula $e = W_{\text{net}}/Q_{\text{in}}$?”

	General	Carnot
Engine efficiency	$e = W_{\text{net}}/Q_{\text{in}}$	$e = 1 - T_L/T_H$
Refrigerator performance	$K = Q_L/W_{\text{net}}$	$K = T_L/(T_H - T_L)$
Heat pump performance	$K = Q_H/W_{\text{net}}$	$K = T_H/(T_H - T_L)$

This will give you a chance to draw a distinction between the formulas that are general and the formulas that apply only to the Carnot cycle. You might even draw a table on the board,

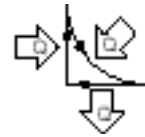
perhaps along these lines.

Discussion Question 4

Part (a) of this question requires the students to “read” the p-V diagram and translate it into more physical terms. Your students need this kind of practice, so avoid the temptation to blow through part (a).

Problem 1

In part (a), after the students have decided on the signs for the heat flows, have them draw large arrows on the p-V diagram, like so. This is a good start towards visualizing the energetics of the cycle, and it will help in detecting sign errors later in the problem.



Notice that part (b) leads the students through the “1-4 drill” for analyzing transformations. Don’t let this escape their notice.

When you discuss part (d), which is the actual computation of $W_{\text{net}}/Q_{\text{in}}$, emphasize that not all of the legs contribute to Q_{in} . As per the discussion of efficiency in the Discussion Questions, the only legs that contribute are those in which heat flows *into* the gas. (Refer them back to the arrows they’ve drawn.) This is why the “ Q_{in} ” box in the table is offset: the entry in this box is not simply the sum of the four Q’s. (Compare with the “ W_{net} ” box.)

If you have time, an excellent set of follow-up questions would be the following (these are essentially the same as parts (b) - (d) of Problem 2). **For definiteness, take $V_A = 7V_B$.**

- Where in this cycle does the gas reach its highest and lowest temperatures? Find these extreme temperatures. (Your answers should be in terms of p_0 , V_B , and N .)
Answer: $T_L = p_0 V_B / Nk$ and $T_H = 7T_L$.
- What would be the efficiency of a *Carnot* engine operating between these two temperatures? **Answer:** 86%
- Are your calculated efficiencies consistent with the fact that the Carnot engine is the most efficient engine possible?

Problem 2

It takes quite a while to compute the efficiency of a cycle. If you are pressed for time, or if you think the time could be better spent doing something else, then you may want to modify Problem 2. For example, you can tell your students to fill in only the first two rows of the table.

If you do this, it would be a good idea to tell your students to look up the final answer for the efficiency, and then proceed with parts (b) - (d), which are instructive and not very time-consuming.

If you don't get to Problem 2 at all, then point out to your students that this problem would serve as excellent exam practice.

Encourage the students to think about the heat flows in the cycle before delving into the calculations. As in Problem 1 above, have them draw arrows on the p-V diagram representing the heat flows.