# T-2. Thermal Expansion, Kinetic Theory, and Calorimetry

## Teaching Notes

### THE MAIN POINT

Linear Expansion
1. Learn how to approach linear expansion problems.

Kinetic Theory
2. Understand how the microscopic picture of atoms relates to the larger picture of thermodynamics through statistics.

Calorimetry
3. Learn to calculate final (equilibrium) temperatures of a system that has parts that start at different temperatures (and perhaps phases).

### SAMPLE LESSON PLAN

Part 1: Linear Expansion (approximately 25 min)
Mini-Lecture....................... 5 min.
Discussion Questions
and Problems.................... 10 min. in groups, 10 min. GSI-led discussion and boardwork.
Part 2: Kinetic Theory (approximately 25 min)
Mini-Lecture....................... 5 minutes
Discussion Questions
and Problems.................... 10 min. in groups, 10 min. GSI-led discussion and boardwork.
Part 3: Calorimetry (approximately 45 min)
Discussion Questions 1-3... 10 minutes.
Mini-Lecture........................ 10 minutes.
Problem 2............................ 15 minutes in groups, 10 minutes GSI-led discussion & boardwork.

## Part 1: Thermal Expansion

### GENERAL TEACHING SUGGESTIONS

I generally like to emphasize linear expansion's connection to the microscopic picture of atoms. A good way to model these linear expansion problems is to consider a solid as being made up of atoms connected by springs. The springs expand with temperature due to our discussion of the equipartition theorem. Then, I use the example of volume expansion to introduce the power of approximations in physics problems.

### SAMPLE MINI-LECTURE AND BOARD SUMMARY

To Be Added

### REMARKS ON THE DISCUSSION QUESTIONS AND PROBLEMS

*Discussion Question 1*

Students often want to say that the atoms want to get further apart, so they "push into" the hole to get away from each other. I usually begin teaching this by drawing a grid of atoms. As the temperature increases, the separation between each atom in the grid gets farther apart. Thus each square of the grid gets large, expanding the entire object. But if there were one atom missing in the grid, in order to keep the same structure, the atoms around is still increase their separation, making the area around the missing atom even larger.

*Discussion Question 2*

Physics applies to real life!! Even though both objects expand, the key to this problem is the *difference* in how much they expand. Students are usually familiar with the concept of running a jar under hot water to help pop the top off, but make sure they understand *why* this works.

*Problem 1*

This is a standard thermal expansion problem.

*Problem 2*

This problem I would show them both ways, one with doing the expansion of the radius and using that to get the new volume of the sphere, and one using the coefficient of volume expansion, $\beta$, which is $3\alpha$. While they won't agree completely, it's close enough to make your point. Behold the awesome power of approximations!

## Answers to Problems

1. $T_f = -75°C$
2. $\Delta T = 1667$ K

# Part 2: Kinetic Theory

### GENERAL TEACHING SUGGESTIONS

Here is there first chance to really see how the microscopic and macroscopic pictures of the gas connect. An important thing to emphasize is the concept of a statistical distribution. Connect this to their more intuitive picture of statistics by approximating the distribution with a crude bar graph. You can use this picture to explain how one takes an average of a distribution, which will come into play in problem 1.

### SAMPLE MINI-LECTURE AND BOARD SUMMARY

To Be Added

### REMARKS ON THE DISCUSSION QUESTIONS AND PROBLEMS

*Discussion Question 1*

Before going into this, I would sketch the Maxwell distribution and tell them that the total number of molecules is the area under the curve, and show on the sketch how you would get the graphically the number of molecules that have a speed within v and v + dv. You can also show them the limiting cases; that it goes to zero at v = zero and infinity. The idea in the problem is to get them to realize that, even at lower temperatures, there will be some molecules moving fast enough to escape the surface tension. The second part allows you to bring up the idea that, if confined, there's a good chance the fast moving particle will eventually break back into the water, keeping the amount of liquid constant. If you have enough time, you can even go into ideas of vapor pressure and that for any liquid, there eventually reaches a point when the number of molecules leaving equals the number entering, so the liquid level remains the same.

*Discussion Question 2*

Remind students that the peak shifts at higher temperatures, but also decreases in height, since the number of particles remains constant (so the area must remain constant). The second part is just to give them an idea that a distribution gives the general shape, but if you added more the shape would remain the same but it would just change the amplitude.

*Problem 1*

This problem is basically meant to remind students that they *will* be using integrals in this class! Also, it lets them practice with finding an average of a distribution and shows that the equipartition theorem is compatible with the Maxwell Distribution.

*Problem 2*

Thermodynamics is *emergent*. We need a whole lot of particles for the averages that thermo is based on to become extremely valid. 10 just won't cut it!

## Answers to Problems

To Be Added

# Part 3: Calorimetry

## GENERAL TEACHING SUGGESTIONS

*Standard strategy for calorimetry problems.* Talented problem-solvers usually have little trouble solving calorimetry problems without internalizing a fixed strategy. But even these students will occasionally miss a sign if they're treating every problem in an ad hoc manner. In particular, students who use "$Q_{lost} = Q_{gained}$" will often flub a sign if there are more than two objects involved. So for everyone's benefit, I like to teach a standard strategy for calorimetry problems.

Calling it a "standard strategy" is actually a bit grandiose, because it's really just a standard *starting point*. I begin all my calorimetry solutions with the statements

$$Q_{\text{added to system}} = 0$$

$$Q_{\text{added to 1}} + Q_{\text{added to 2}} + Q_{\text{added to 3}} + \ldots = 0$$

Each Q term associated with a temperature change will be of the form $mc\Delta T$, and there will be $mL$ terms added if there are phase changes. For each $\Delta T$, always subtract in the order ($T_{final}$ - $T_{initial}$). (For the "hot object" this will be negative, reflecting the fact that heat flows *out* of the hot object.")

The statement $Q_{\text{added to system}} = 0$ might not be the most natural starting point for a two-component mixture problem, especially since the goal is to find a *temperature*, and not a heat flow itself. But this should not be a great stumbling block, since composite-rod heat conduction problems presented a similar situation.

I adopted this starting point while teaching the Intensive Sections because the alternatives, such as "The heat added to 1 equals the heat taken from 2" for example, invite sign errors and do not generalize well to many-component mixing problems. (These do appear on exams regularly.) Another attractive feature of this starting point is that it makes explicit the basic assumption of almost all calorimetry problems: that the mixtures in question are thermally isolated from their surroundings. Note that if the students are ever presented with a "trick question" in which some heat leaks through the container, then this starting point can be easily modified.

You will probably have to remind students about the *latent heats*: the *latent heat of fusion, $L_f$,* is associated with freezing and melting, and the *latent heat of vaporization, $L_v$,* is associated with boiling and condensing. They have a good intuitive sense that there is energy involved in each of these changes, so this is just a matter of connecting that intuition with these quantities.

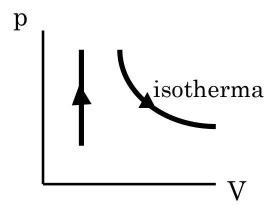
## SAMPLE MINI-LECTURE AND BOARD SUMMARY

When I used to mini-lecture on this material, I always began with a question that may seem odd at first. I used to ask,

**When you add heat to a gas, does the temperature go up?**

*Take a vote on this question.* You might be surprised at your students' answers! (Of course, you and I know that the answer to this question is "it depends." The temperature could even go down.)

After the vote, without giving the correct answer, I like to draw a p-V diagram like so:




This shows two of the possibilities: adding heat with an increase in temperature, and adding heat with no increase in temperature. (The third possibility, adding heat with a *decrease* in temperature, could be illustrated by a transformation intermediate between an isotherm and an adiabat. But this will be harder for the students to see.)

By now everyone should see that adding heat to a gas does not always make the temperature go up. So next to the original question, I write the answer:

**When you add heat to a gas, does the temperature go up? It depends.**

The fact is, (I continue), there is no fundamental relationship between heat and temperature---or, better yet, between heat and internal energy. So what are we missing here? What's the missing ingredient that goes along with *heat* and *internal energy*?

The students eventually answer "Work!", at which point I write down the First Law. The reason that adding heat may or may not make the temperature rise is that this third term, work, can be just about anything, depending on the transformation. (Explain this with reference to the examples shown on your p-V diagram.) We'll spend the next session, and next week's lab, thinking a lot more about the First Law and its consequences.

But now we finally get to the subject at hand. What if you had a material that *couldn't expand*? When you add heat to a solid or a liquid, it doesn't expand very much at all. What does that mean for the First Law? The students should be able to see that when a material doesn't expand, it can't do any work against its environment. So any heat you add goes directly into raising the internal energy---that is, the temperature.

The upshot (and now we've finally gotten to the point) is that for solids and liquids, adding heat *does* raise the temperature. This is reflected in the formula

$$\mathbf{Q = mc\Delta T.}$$

And then I just explain what the terms are.

At this point the students still have to realize that if a solid is at its melting point, or if a liquid is at its boiling point, then adding heat will not raise the temperature. But you can leave them to deal with this in Discussion Question 2.

This class discussion may seem like the long way around, and I suppose it is. If you don't want to go into the whole *spiel*, then I would recommend doing this much at least: After working with $Q = mc\Delta T$ for a while, ask why this formula only works for solids and liquids. "In other words, how come we don't have a formula relating Q and $\Delta T$ for ideal gases?"

## REMARKS ON THE DISCUSSION QUESTIONS AND PROBLEMS

*Discussion Question 1*

We all know that "the freezing point of water is $0^0$C." For many people, this piece of common knowledge translates into the belief that if you cool water to $0^0$C, it freezes. (False!) The goal of this question is to establish that $H_20$ can be in liquid form *or* solid form at $0^0$C, and in any proportion. This is a first step towards understanding the energetics of phase transitions.

*Discussion Question 2*

This question helps students to visualize what happens during a phase transition, so that latent heats of fusion and vaporization make intuitive sense. Draw some pictures here: a puddle of water labeled $0^0$C, then an arrow labeled "draw heat out," and then a puddle of water with ice cubes in it, still at $0^0$C. (Underneath the first arrow you can then put a second arrow, pointing in the opposite direction, labeled "add heat.")

*Discussion Question 3*

This question ties in well with the previous one, because it gives the latent heat of vaporization an everyday significance.

*Discussion Question 4*

I would save this question for after the students have solved several calorimetry problems. The explanation hinges on the large specific heat of water, and this will make more sense after the students have worked with specific heats for a while.

*Problem 1*

As usual, encourage the students to draw a picture. If they don't know where to start, you might mention that "no heat is lost to the surroundings." This may remind them of the standard strategy—outlined above—or you may lead them to discover it for themselves.

*Problem 2*

This involves a phase change, so if possible don't neglect it.

As usual, encourage the students to draw a picture. If they don't know where to start, you might underline the words "thermally insulated" in the statement of the problem. This may remind them of the standard strategy—outlined above—or you may lead them to discover it for themselves.

# Answers to Problems

**1.** 19.6 C

**2.** 34.4 g