

The object of this column is to enhance our readers' collection of interesting and novel problems in chemical engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class, or in a new light, or that can be assigned as a novel home problem, are requested, as well as those that are more traditional in nature and which elucidate difficult concepts. Please submit them to Professors James O. Wilkes and Mark A. Burns, Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.

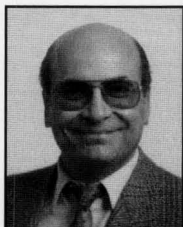
# MAGIC UNVEILED THROUGH THE CONCEPT OF HEAT AND ITS TRANSFER

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Everyday common experiences help us understand the fundamentals of nature and how things function. We all tend to relate our new knowledge to what we already know and to make connections that create a bridge between the two. When these bridges are sound, not only do we understand the new information better and faster, but we also retain the details in our long-term memory.

The following are some examples I have used in my quest to get through to the students the concept of heat capacity and heat transfer. Since students are familiar with these events in their everyday life, they tend to be more interested in the relationship between the new concepts being presented to them and their own experiences. Quite often, this generates classroom discussion, another *raison d'être* to learn and retain the information.



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## PROBLEMS

1. We often hear mothers talk about their babies at length (what mother doesn't?), and one frequent comment they make is that babies must be well wrapped up. Is there a good reason for this? If there is, why would babies lose more heat compared with older children and adults?
2. Why should there be a minimum amount of wood to light up a camp fire and sustain it?
3. Why is fire-walking possible on a red hot bed of coals which may have a temperature of around 1000°C? What limitations can you think of to prevent severe burning?
4. Why do you not burn your hand inside an oven at 300°C, but burn it on a metal tray taken from the same oven?
5. Why don't you burn your mouth trying to sample a hot jam tart or slice of pizza straight from the oven until you bite into the portion containing jam or sauce?
6. Oceanic climate of coastal areas and of islands tends to be milder than it would otherwise be. Why does the nearby ocean exert a moderating influence on the land's temperature?
7. Defending soldiers of castles in the middle ages used to pour down boiling oil on the attacking enemy soldiers. Why did the defenders go to all the trouble and expense

of using oil, especially when the heat capacity of oil is less than half of that of water? You may use the following data for illustration:

	Heat capacity (kJ/kg·°C)	Boiling Point (°C)	Density (kg/m <sup>3</sup> )
Water	4.20	100	958
Oil	2.00	300	800

8. If you want to drink a very hot cup of coffee in a hurry, do you pour the cold milk into the coffee first and then wait a while, or do you wait first and then pour in the milk? Explain.
9. A Chinese restaurant offers noodles which vary in diameter from about 1 mm to 8 mm. Which size should a Westerner choose if he is in a hurry during the lunch hour and wants to avoid a burned tongue? Assume that the food is already cooked and ready to eat.
10. Give two reasons why an increase in temperature causes a worldwide rise in sea levels.
11. In the winter, why does an outdoor metal door handle feel much colder than a wooden one?
12. Why is it desirable to paint steam and hot-water pipes with aluminum paint?
13. A hen's egg of mass 50 grams requires 5 minutes to hard boil. How long will it take to hard boil an ostrich's egg of mass 3 kg? State your assumptions.
14. Someone recommends a cold-water diet to lose weight. You are asked to drink ice cold water at 0°C to shed 2000 calories (8.4 kJ) per day. Can you do it?
15. Why is it easy to burn toast in a toaster or oven?
16. Explain why many swimming pools are in the hot sun all day but never get really warm. What can you suggest to overcome this?
17. What would be the temperature at the bottom of a 50-m deep freshwater lake in Canada in the winter and the summer?

## SOLUTIONS

1. A baby has a larger surface area per unit mass compared with adults. Since heat loss is directly proportional to the area (everything else being equal, such as body and room temperatures) the heat loss by babies is greater and needs to be reduced by extra layers of clothing. Incidentally, thin layers of clothing are more effective than one thick layer since the air trapped between the layers acts as an insulator due to poor thermal conductivity of gases.
2. This situation is similar to that of the heat loss by

babies presented above. If the heat generated by burning wood cannot compensate for the heat lost from the surface of the pile, then the fire will extinguish itself. Therefore, there must be sufficient wood in the fire to sustain the burning and to minimize the surface area of the pile through which heat is lost. Of course, one needs to ensure that the fire is not suffocated by a lack of oxygen (air) as the wood pile is stacked up to reduce its surface area per unit mass.

3. There are three factors to consider here:

a) In the general heat equation,  $Q = mC_p\Delta T$ , although the temperature difference,  $\Delta T$ , between the hot charcoal and the surface of the feet is very large,  $mC_p$  is very small as the charcoal is very light in mass and its specific heat capacity is about 1.01 kJ/kg·°C.

b) In the heat conduction equation,  $q = -kA(dT/dx)$ , the temperature gradient is very high, but the points of contact A between the feet and charcoal is small and so is the conductivity, k, due to the formation of steam under the feet; steam as a gas is a poor conductor.

c) The time of contact is important since q times the contact time is the amount of heat transferred to the feet. Although 1 or 2 seconds may not be long enough to burn the feet, anything longer may cause severe burns.

In the fire-walking scenario, the people taking part are usually "hyped" up by pep talks. They tend to sweat—and they also tend to walk on the wet evening grass with bare feet. These factors may help create that insulating layer of steam under the feet. Again, this steam will only be there temporarily and may disappear after the first few steps.

4. There are two important reasons. First, the mass of air surrounding the hand is very small (the density of air at 300°C and 1 atm is 0.615 kg/m<sup>3</sup>), and hence its heat content is small despite the high oven temperature. Second, the air is a poor conductor and the relatively still hot air will not burn.

The metal oven tray, on the other hand, has a much larger mass and hence contains much more heat than the air. In addition, the metals are better conductors of heat. Therefore, a good conductor coupled to a large reservoir of heat will relay large quantities of heat at a faster rate than blood can take it away from the fingers.

5. Jam and sauce contain water, and water has the highest specific heat among the common substances. Therefore, the jam and sauce portions have a higher heat content than the mostly bread portions despite their being at the same temperature. (Now that you know the

theory as well as having had the experience, you have no excuse for burning your tongue!

6. Water has a higher heat capacity. For the same temperature rise, water will hold more heat than land. When weather gets cold, water gives up heat, dropping to a lower temperature. Land gives up the *same* amount of heat in dropping to a lower temperature, however—this results in the ocean being warmer than the neighboring land in cold weather and colder than the neighboring land in warm weather. The ocean, when near by, therefore exerts a moderating influence on the land's temperature. Land that is far from the ocean does not enjoy the same advantage.

7. Taking a basis of 1 m<sup>3</sup> of oil and 1 m<sup>3</sup> of water, we can estimate the heat content of each as

$$Q(\text{water}) = 958 \text{ kg} \times 4.2 \text{ kJ/kg} \cdot ^\circ\text{C} \times (100-20)^\circ\text{C} = 321888 \text{ kJ}$$

$$Q(\text{oil}) = 800 \text{ kg} \times 2.0 \text{ kJ/kg} \cdot ^\circ\text{C} \times (300-20)^\circ\text{C} = 448000 \text{ kJ}$$

assuming a skin temperature of 20°C. Hence, the ratio Q(oil) to Q(water) is 1.4. This means oil has 40% more burning power. (Those clever soldiers knew what they were doing!)

8. Newton's law of cooling states that the rate of heat loss is proportional to the temperature difference between the hot coffee and the surrounding air. Therefore it may be desirable to let the hot coffee cool and then add milk for additional cooling.

There is something, however, to be said about the option of adding milk first since this increases the volume of liquid and hence the surface area through which heat escapes (as well as the additional cooling obtained from the milk).

9. The thin noodles will cool quicker because of their larger surface area per unit mass; this will help when eating *individual* noodles. On the other hand, for a given *pile* of noodles, thin ones have smaller spaces between them (small porosity), cutting off the cooling ambient air while on the plate.

10. Rising temperature will melt some of the ice caps in the poles and the sea water will thermally expand. The thermal expansion of the land may be considered negligible.

11. Metals are much better conductors of heat than wood and therefore conduct heat away from hand more rapidly. For example, the thermal conductivity of carbon steel is 43 W/m °C and that of maple or oak is 0.17 W/m °C. This means that carbon steel will conduct heat at a rate 250 times faster than wood.

12. This is because of the principle that a poor absorber of

radiative heat is also a poor emitter of the same. A brightly painted pipe radiates heat at the minimum rate.

13. Assume the eggs are spherical with a radius  $r$  and are similar chemically. The mass of each egg is proportional to  $r^3$  and the surface area through which the heat transfer takes place to  $r^2$ . The rate of heat transfer by conduction is proportional to the temperature gradient inside the eggs, which itself is proportional to  $1/r$ . Therefore the cooking time is proportional to  $r^2$ , or to  $m^{(2/3)}$  where  $m$  is the mass. It follows then that the time to cook the larger egg is

$$(5 \text{ min})[(3000/50)^{(2/3)}] = 76.6 \text{ minutes}$$

(You have to get up early to prepare your breakfast if you want to feast on one of these delicacies!)

The same result may be obtained by using the analytical solution to the unsteady-state heat conduction equation for one dimension.

14. Water is heated from 0°C to the body temperature of 37°C and therefore requires

$$4.2 \text{ kJ/kg} \cdot ^\circ\text{C} \times (37-0)^\circ\text{C} = 155.4 \text{ J}$$

of energy for each kilogram. Using up 8400 J body energy then requires 54 kg of ice-cold water. (Good luck!)

15. As the toast starts to get brown it absorbs more of the radiant heat energy falling on it and rapidly burns. Next time your spouse burns your toast, be kind to him or her. (Also see question 12.)

16. As soon as the top layer of water gets hot, it evaporates and cools the remaining water. A very thin layer of a special liquid spread over the water surface will prevent evaporation. This liquid should have a high heat capacity and high latent heat of evaporation.

17. Since the density of water is highest at 4°C, the bottom of the lake will remain at 4°C irrespective of seasons. In winter the surface water becomes colder and more dense than the water beneath it and is replaced by the warmer water. This continues until all the deep water is at the temperature of maximum density (*i.e.*, 4°C).

Further cooling of the surface water forms ice, and the water just below the ice will be at 0°C. The water at the bottom of the lake remains at 4°C. It would take many years for the bottom water to be cooled to 0°C by conduction through 50 m of water since the conduction process is very slow. When spring arrives, the ice melts and the surface water warms up. The bottom water remains undisturbed, however, being at the maximum density. □