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In the Classroom

The Drinking Bird Toy and its Modifications as A Means of Illustrating Thermodynamic Concepts

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The drinking bird toy is modified so that it operates using ice instead of liquids. It is shown how this and other modifications can be used in general and physical chemistry courses to illustrate a variety of thermodynamic concepts. Expressions are given for the maximum work in terms of the heat of vaporization or the heat of fusion. A sample calculation is given to compare the maximum work obtainable from equal amounts of liquid water and ice.

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The drinking bird toy, which can be purchased from novelty catalogues and variety stores, is an excellent means of illustrating many thermodynamic concepts taught in general and physical chemistry courses. Among these concepts are heat engines, thermodynamic cycles, Carnot efficiency, heat of vaporization, endothermic reactions, vapor pressure, relative humidity, radiant energy and the Clausius–Clapeyron equation.

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Several articles [1–8] show how this fascinating device can be used in the classroom to illustrate these concepts. In this article, this list is expanded to include such topics as dew points, heats of fusion, and the extraction of work from endothermic changes such as the melting of ice. We have found this inexpensive device to be a sure winner for classroom demonstrations, and it can be the focal point of any number of laboratory exercises dealing with these and other thermodynamic concepts. We show how to modify the toy to make it operate on ice instead of liquid water.

Inside the Bird

Figure 1 shows a typical configuration for the drinking bird as well as a modification, which will be discussed later. The bird operates when the temperature of its head is maintained at a lower temperature than its bottom (usually by evaporative cooling). Subsequently, the internal fluid condenses inside the cooler region of the head, thereby producing a decrease in pressure. This decrease in pressure draws the fluid up the neck, only to have the tilting action lift the tube out of the fluid in the bottom reservoir, which allows it to drain and start the cycle over again. The decrease in pressure that produces the rising action of the internal fluid is yet another way of illustrating the same principle behind the classic demonstration whereby one crushes a can by producing steam in it, capping it, and then letting it cool. The bird is one of any number of engineering devices designed to create motion from the spontaneous flow of heat from a high temperature region to a one of a lower temperature, namely a heat engine. Mentzer [1] discusses a 1946 patent that was issued for this device. A unique aspect of this heat engine is that it is designed to extract heat from the surroundings and produce work from it while dumping the residual heat into an endothermic reaction, usually the evaporation of water or some other liquid. Most often, heat engines work in exactly the opposite mode, namely extracting heat from an exothermic reaction and dumping the obligatory residual heat into the surroundings.

A good internal working fluid will have a vapor pressure that is sensitive to small temperature changes [1]. Taking the derivative of the familiar integrated form of the Clausius–Clapeyron expression for vapor pressure , $\ln P = \text{constant} - \Delta H_v/(RT)$, gives, $dp/dT = P\Delta H_v/\left(RT^2\right)$. In practice, T (in Kelvin) is not drastically different from room temperature and the heat of vaporization, ΔH_v, does not vary as much as the room-temperature vapor pressure, P, of different liquids. Hence the best internal fluids

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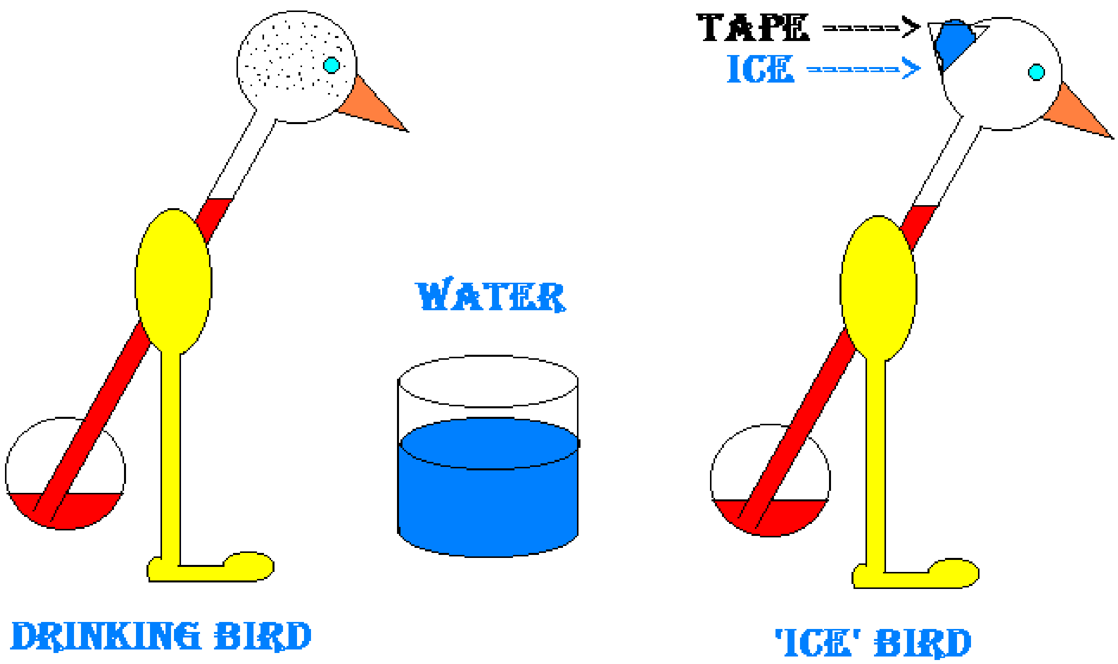

FIGURE 1. SCHEMATIC OF THE DRINKING BIRD TOY AND A MODIFICATION THAT ALLOWS IT TO OPERATE USING MELTING ICE INSTEAD OF AN EVAPORATING LIQUID AS FUEL.

are volatile ones. The fluid most commonly used inside the bird is Freon 11, CCl_3F, which has a normal boiling point of 24 °C. A more volatile liquid should work better, but would require a bird constructed of stronger materials.

Outside the Bird

The maximum work, w, one can obtain from extracting a quantity of heat, Q_H, from a high-temperature reservoir at temperature T_H and releasing it to a low temperature, T_L, is given by the well-known Carnot efficiency formula, $w = Q_H(1 - T_L / T_H)$. For the drinking bird, Q_H comes from the room and is partitioned among the work required to produce the bobbing motion, w, and the heat used to evaporate n moles of the water from its head. Replacing Q_H with $w + n\Delta H_v$, where ΔH_v is the molar heat of vaporization, the maximum work can now be written as:

$$w = n\Delta H_v(T_H / T_L - 1) \quad (1)$$

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When the bird is drinking water, its head is cooled by the evaporation of the water from a porous coating. The lowest temperature that one can obtain for the head of the bird can be identified as the dew point of the surrounding air [2]. The dew point is defined as the temperature at which air becomes saturated with water vapor, hence it is the temperature where the vapor pressure of water is the partial pressure of the vapor in the air. One can use the Clausius–Clapeyron equation at two different temperatures to rewrite equation 1 in a different form [2].

$$w = -nRT_H \ln\left(P / P_{sat}\right) = -nRT_H \ln\left(\text{relative humitity} / 100\right) \qquad (2)$$

Equations 1 and 2 are equivalent insofar as the heat of vaporization is independent of temperature. Equation 2 verifies the somewhat obvious fact that the bird refuses to function as the relative humidity approaches 100% (i.e., $w = 0$). The bird stops in a matter of minutes when placed in a closed container such as a bell jar or a covered chromatographic cell [3]. One might suggest to the class that it suffocated, and observe the response!

An alternative way of looking at the drinking bird is that it is a means of extracting work from a spontaneous process, the evaporation of water, just as a gasoline engine extracts work from the spontaneous combustion of hydrocarbons in air. One reason the bird-engine is so intriguing is because it is able to utilize an endothermic fuel. The bird can be made to operate as the usual type of heat engine by placing a small burning candle near its defeathered tail. However, care must be exercised since most toy birds cannot withstand the high internal pressure that can be produced! The bird can also be modified to operate on radiant energy. Painting its bottom black and its head silver [5] allows it to operate in sunlight or near a light bulb.

Work from Melting Ice

Another interesting modification, which to our knowledge has never been discussed, is to strap a bit of ice on the bird's head. This can readily be done with tape, as is shown in Figure 1, or more permanently by gluing a cut-off portion of a plastic cylinder. The porous felt, along with any decorative hat or feathers on its head, can be removed with a solvent such as acetone. Leaving the felt on lets the device operate longer, as it then can utilize both melting of the ice and evaporative cooling of any residual liquid. In classroom demonstrations, our experience is that the ice-fueled bird immediately

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begins to perform its bobbing motion whereas the drinking bird is often reluctant to start, especially in humid air. This modification of the bird illustrates how one can extract work from another spontaneous endothermic process, namely the melting of ice. Using the same arguments that led to equation 1, the expression for the maximum work obtainable from melting *n* moles of a solid is readily seen to be:

$$w = n\Delta H_m \left(T_H / T_m - 1 \right) \quad (3)$$

where ΔH_m is the molar heat of fusion, T_H is the temperature of the room, and T_m is the melting point of the solid.

An interesting exercise is to compare the maximum amount of work that the drinking bird can extract from one gram (1/18 mol) of liquid water to what the ice-fueled bird can extract from the same amount of ice. At room temperature (22 °C) and a relative humidity of 40%, Lange's *Handbook of Chemistry* [9] gives the dew point of air as 7.9 °C. Using 41.4 kJ mol^{-1} as the heat of vaporization, both equation 1 and equation 2 give a maximum of 110 joules of work that can be extracted from evaporating one gram of water. However, for the ice-fueled bird (using a heat of fusion of 5.94 kJ mol^{-1}) equation 3 gives a maximum of only 27 joules of work that can be extracted from melting one gram of ice. Since the efficiency of the drinking bird is quite sensitive to the relative humidity, it is informative to calculate the relative humidity above which the ice-fueled bird can become more thermodynamically efficient than the drinking bird. Eliminating *w* from equations 2 and 3, one calculates that evaporating water in 22 °C air at a relative humidity of 81% yields the same value for the maximum work as that which would result from melting ice (This corresponds to a dew point of 18 °C). Therefore, the ice-fueled bird is capable of extracting more work from water than the drinking bird when the relative humidity is greater than 81%.

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