A dunking bird of the second kind

Nadine Abraham
Western Reserve Academy, Hudson, Ohio 44236

Peter Palffy-Muhoray
Liquid Crystal Institute, Kent State University, Kent, Ohio 44242

(Received 9 July 2003; accepted 13 February 2004)

The conventional dunking bird is a heat engine that relies on the temperature difference between the head and the tail of the bird for its operation. We describe a new type of dunking bird that is not a heat engine, but one that directly uses the chemical potential difference between liquid water and its vapor.
[DOI: 10.1119/1.1703543]

I. INTRODUCTION

The dunking bird is arguably one of the most successful physics toys of all time. It was invented by Miles V. Sullivan in 1945,[1] and in spite of its somewhat silly appearance, is a sophisticated and elegant device. It consists of two joined glass bulbs (see Fig. 1), containing a low boiling point fluid, such as methylene chloride. If the bottom bulb is warmer than the top, the fluid condenses in the head, making the bird top heavy. It then tips forward, dipping the beak into a container of water and wetting the head, allowing the working fluid to return to the bottom bulb. The now bottom heavy bird then rights itself and the cycle repeats. Evaporative cooling of the head results in a temperature difference between the bulbs, which drives the motion.

In addition to being a popular candidate for a perpetual motion machine and its proposed use as a device for pumping water in Egypt,[2] the dunking bird has received considerable attention in the scientific literature.[3–19] Because it relies on the temperature difference between its head and its tail for its operation, the classic dunking bird is a heat engine; we shall refer to it henceforth as a dunking bird of the first kind. In this note, we describe the results of our effort to design and build a dunking bird that is not a heat engine, and thus does not require a temperature difference for its operation. We shall refer to this device as a dunking bird of the second kind.

II. DESIGN AND CONSTRUCTION

Our goal is to create a dunking device that obtains energy from the evaporation of water, but is not a heat engine. To achieve this device, we designed a bird with a triangular ‘‘wing’’ made of a sponge. When the wing is dry, the bird is top heavy, so it tips forward and dunks its head so that the tip of the sponge comes into contact with the water. Water then permeates the sponge due to capillary action and rises. Eventually, due to the weight of water in the sponge, the bird becomes bottom heavy and rights itself. The sponge wing then dries due to evaporation, the bird tips forward again, and the cycle repeats.

Our prototype dunking bird of the second kind is shown in Fig. 2. We used simple and readily available materials for its construction: popsicle sticks, plastic drinking straws, washers and a dishwashing sponge. The details of the device are shown in Fig. 3. Large popsicle sticks were used for the legs and torso, as well as for the base. Superglue was used to fasten the sticks together in the base and to attach the legs to the base. The body of the bird consists of a portion of a plastic drinking straw, bent to form a tail in such a way as to prevent the bird from tipping too far back. The straw is glued to a piece of popsicle stick. The triangular wing was cut from a quick-drying thin ($\frac{1}{8}''$ dry) cellulose dishwashing sponge. Because gluing a sponge interferes with its capillarity, the wing was sewn to the popsicle stick using cotton thread. A second piece of drinking straw, glued transversely to the popsicle stick in the torso, served as an axle. The tops of the legs were concavely rounded slightly to help keep the axle straw in place. The curved portion of a partially straightened paper clip was inserted between the sponge wing and the popsicle stick of the torso, and the straight portion, bent upward, was used to hold small metal washers as weights.

When the wing was dry, washers were added until the bird tipped forward. The plastic glass holding the water was situated so that the tip of the sponge just dipped into the water in the tipped position. To monitor the height of the bird, a small cardboard square was glued to the torso to act as a light shutter for a photovoltaic cell. The signal from this cell indicated the orientation of the bird's torso and was continuously recorded. The water level in the glass in front of the bird was kept nearly constant by a drinking straw siphon that connected the glass to a large covered plastic container filled with water.

III. OPERATION AND PERFORMANCE

When the bird with dry wings is in the ‘‘head up’’ position, it is top heavy (primarily due to the washers), and tips forward to the ‘‘head down’’ position. In the latter position, water is drawn into the sponge due to capillary action, and, because the head is lower than the tail in the head down position, water moves up toward the broad bottom edge of the wing. As the water moves up into the wing, the bird becomes bottom heavy, and rights itself, raising its head and lowering its tail until the bottom of the straw tail contacts its supporting surface, and the bird again assumes the head up position.

The motion of the bird was monitored by recording the output of a photovoltaic cell that was illuminated by a table lamp in such a way that the shutter on the bird's tail covered the cell when the bird was in the head up position. The number of dips as a function of time is shown in Fig. 4. The symbols indicate times when the bird assumes the head up position. The average time between dips is 442 min, with an average time of 405 min in the head up position and 37 min

Fig. 1. A classic dunking bird of the first kind.

in the head down position. As can be seen in Fig. 4, the interval between dips varied with time, probably due to changes in the relative humidity. The bird is capable of doing work during its motion from head up position to head down position as well as during its motion from head down position to head up position. Therefore these may both be regarded as power strokes.

IV. PRINCIPLES OF OPERATION

Although the operation of the device is relatively simple, it is interesting to consider the relevant underlying processes. The idealized operation of the bird consists of four steps:

(1) drinking process in the head down position;
(2) rising stroke, as the bird moves from the head down to the head up position;
(3) drying process in the head up position;
(4) dunking stroke, as the bird moves from the head up to the head down position.

In the first step, drinking water is drawn into the sponge via capillary action. Cellulose sponges are made from compressed wood fibers reinforced ith nylon fibers. Capillary action is caused by the relatively high cellulose/nylon-air interfacial energy, γ_{sa}, of the sponge. This interfacial energy is reduced when water is drawn into the sponge. Capillary rise measurements suggest that the sponge may be thought of as a collection of capillary tubes with characteristic lengths of the order of microns. An interesting project would be to study the height of water drawn into a sponge by capillary action as a function of time, and compare this height with the results for capillary tubes.[20,21]

If we assume that water completely wets the sponge, Young's law gives $\gamma_{sa} = \gamma_{sw} + \gamma_{wa}$ where γ_{sw} and γ_{wa} are the interfacial energies of the sponge-water and water-air interfaces. The energy gain/area when water wets the sponge is $\gamma_{wa} = 7.28 \times 10^{-2}$ N/m at 20 °C.[22] Some of this energy (one-half, for the case of vertical rise in a uniform capillary[23]) is

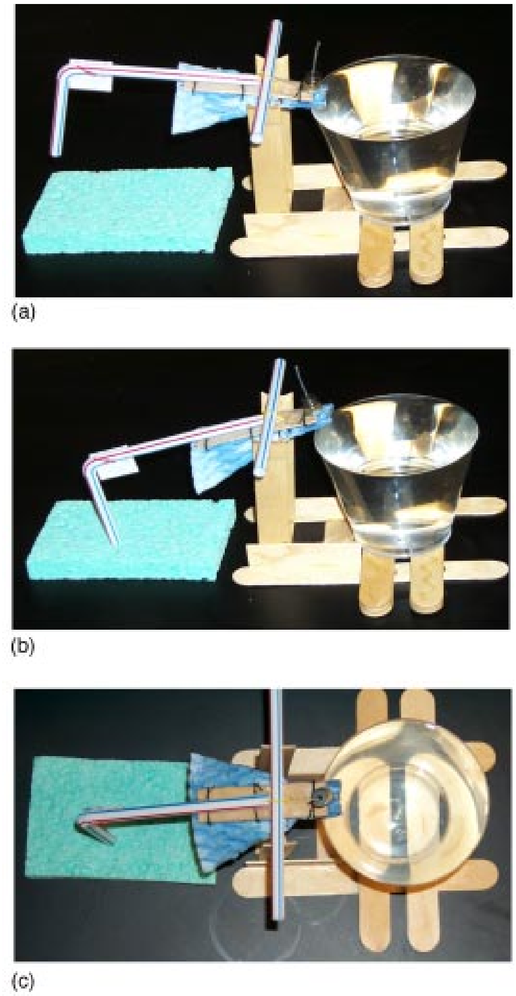

Fig. 2. Photograph of our prototype dunking bird of the second kind; (a) starting to drink; side view; (b) finished drinking, side view; (c) finished drinking, top view.

dissipated by viscous shear. The portion that is not dissipated is available for lifting the water and, at the end of the drinking step, is stored as gravitational potential energy of the water in the sponge.

The second step is the rising stroke. Here, the center of mass shifts as water is absorbed, and when it has moved to the other side of the axle, the bird tips, lifting its head. The gravitational potential energy of the system (water in the sponge and the bird) is reduced as the center of mass is lowered. All of this energy is available to do mechanical work.

The third step is the drying process, where the liquid water in the sponge evaporates. This process is driven by the chemical potential difference between the liquid water in the sponge and the water vapor at the corresponding height.

The fourth step is the dunking stroke, when the bird, now top heavy because the sponge is dry, lowers its head. Here, again, the gain in gravitational potential energy due to the lowering of the center of mass of the system is available to do mechanical work.

In principle, the four processes can take place isothermally. In practice, there may be small temperature differences due to evaporative cooling, viscous dissipation, and thermo-capillary effects, but these may be made vanishingly small and are not essential to the operation of the device.

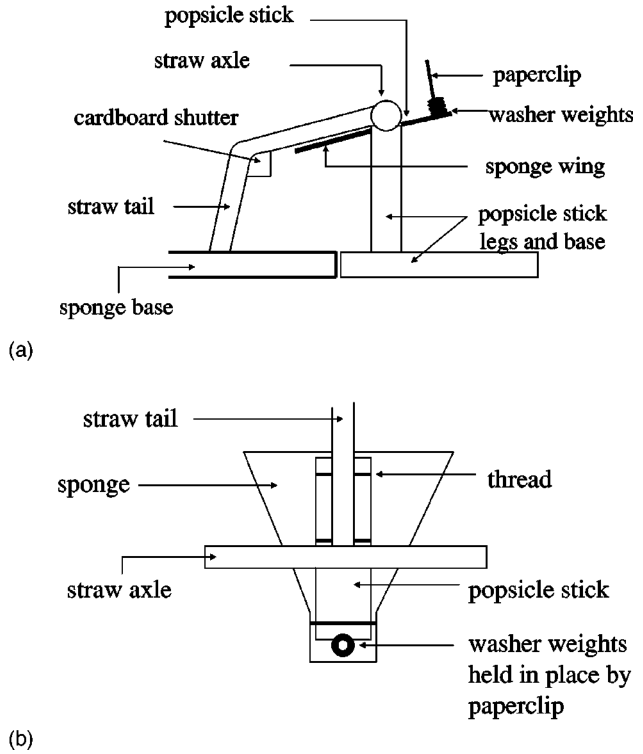

Fig. 3. Schematic drawing of our prototype dunking bird of the second kind; (a) side view and (b) top view. The width of the 7 mm outside diameter drinking saw indicates the scale.

Also, in practice the four steps are not clearly separated, but overlap. For example, the center of mass of the water in the sponge continues to move due to capillary action even after the rising stroke, and the drying process continues through the dunking and drinking stages.

Step 3, the drying process in the head up position, may be thought of as the recharging stage; due to evaporation, the surface energy of the sponge is increased again to γ_{sa}, and the system is again capable of doing mechanical work. The dynamics of wetting and de-wetting is a fascinating but complex subject[24,25] and will not be treated here.

After one cycle, the bird is again in its initial state. During a cycle period, some water has evaporated, and some mechanical work has been done. The free energy change associated with evaporation is the maximum work that the system is capable of doing. The total chemical potential gain—or free energy change—must therefore be greater than the mechanical work done by the system.

The four processes describe the oscillations of the bird between the stable states of head down and head up. The bistability arises as a result of friction, which must be overcome before motion can start, and as a result of nonuniform water absorption in the sponge, which causes the center of mass to shift well beyond the axle during the first (drinking), second (rising) and even third (drying) steps. The period of oscillation is dominated by the drying time, until the center of mass moves back over the axle far enough to overcome friction. We therefore expect the period to be inversely proportional to the evaporation rate.

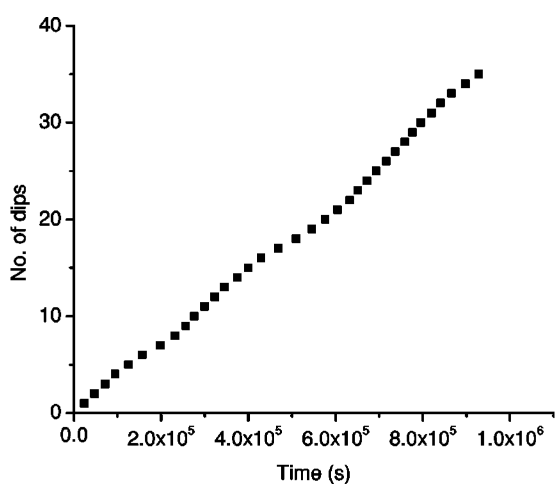

Fig. 4. Number of dips as a function of time. The points indicate times when bird stops.

V. THE FREE ENERGY OF EVAPORATION

At constant pressure, the maximum mechanical work that evaporating water molecules are capable of doing is equal to the change in their chemical potential. The chemical potential in the liquid and vapor phases can be estimated from the Helmholtz free energy density given by the van der Waals model[26]

$$F=-\frac{9}{8}\rho_c kT_c\left[\frac{\rho^2}{\rho_c^2}+\frac{8}{9}\frac{\rho}{\rho_c}\frac{T}{T_c}\ln\left(\frac{3\rho}{\rho_c}-1\right)\right], \tag{1}$$

where ρ and T are the number density and temperature, and the subscript c indicates critical values. The chemical potential $\mu(\rho,T)=\partial F/\partial\rho$, and, because $P_c=3/8\rho_c kT_c$, the chemical potential difference between the liquid water and water vapor, $\Delta\mu=\mu(\rho_l,T)-\mu(\rho_v,T)$, can be written as

$$\Delta\mu\frac{\rho_c}{P_c}=-6\left(\frac{\rho_l-\rho_v}{\rho_c}\right)-\frac{8}{3}\frac{T}{T_c}\ln\left(\frac{3\rho_c/\rho_l-1}{3\rho_c/\rho_v-1}\right)+\frac{8}{3}\left[\frac{1}{1-\rho_l/3\rho_c}-\frac{1}{1-\rho_v/3\rho_c}\right], \tag{2}$$

where the subscripts l and v denote the liquid and vapor. In equilibrium, the water vapor is saturated, $\rho_v=\rho_v^{\mathrm{sat}}$, the two phases coexist, and the chemical potential difference is zero. If we write the relative humidity as $x=\rho_v/\rho_v^{\mathrm{sat}}$, and assume that $\rho_v\ll\rho_c$, the chemical potential difference is given by

$$\Delta\mu\frac{\rho_c}{P_c}\simeq-6\frac{\rho_l}{\rho_c}-\frac{8}{3}\frac{T}{T_c}\ln\frac{x\rho_v^{\mathrm{sat}}}{\rho_l}\left(1-\frac{\rho_l}{3\rho_c}\right)+\frac{8}{3}\left(\frac{\rho_l/3\rho_c}{1-\rho_l/3\rho_c}\right)=-\frac{8}{3}\frac{T}{T_c}\ln x, \tag{3}$$

or

$$\Delta\mu=-kT\ln x. \tag{4}$$

Equation (4) gives the free energy per molecule available for work from evaporation, in agreement with the elegant result of Ref. 15 obtained by different considerations. At a relative humidity of 50%, the corresponding free energy density of water at room temperature is a considerable 96 kJ/kg, approximately one-half of the 50 Wh/kg energy density of a fully charged Ni–Cad battery.

Because the evaporation rate is proportional to the chemical potential difference between the liquid and the vapor, Eq.

(4) suggests that the frequency of dunking is proportional to the logarithm of the relative humidity. An interesting project would be to study the accuracy of this prediction, and the usefulness of dunking birds as hygrometers.

VI. SUMMARY

We have designed and constructed a dunking bird of the second kind that is not a heat engine. The device uses readily available materials in its construction and is simple to make. Experiments with our prototype indicate that, with an adequate water supply, such a dunking bird is able to do work indefinitely. Our device is slower than dunking birds of the first kind, with a period of hours rather than seconds. It nonetheless demonstrates the possibility of extracting mechanical work from water in an environment where the relative humidity is less than 100% without using a heat engine.[27]

ACKNOWLEDGMENTS

We acknowledge useful discussions with Tamas Kosa and Bahman Taheri. One of us (N.A.) acknowledges the support and encouragement of Western Reserve Academy.

[1]U.S. Patent 2,402,463 (1946).

[2]Richard B. Murrow, ''A simple heat engine of possible utility in primitive environments,'' August 1966, RAND Corporation.

[3]The ''drinking bird'' can be purchased from Edmund Scientific, ⟨http://scientificsonline.com/⟩.

[4]Jearl Walker, *The Flying Circus of Physics* (J Wiley, New York, 1975).

[5]J. S. Miller, ''Physics of the dunking duck,'' Am. J. Phys. **26**, 42 (1958).

[6]J. L. Gaines, ''Dunking duck,'' Am. J. Phys. **27**, 189–190 (1959).

[7]H. E. Stockman, ''Dunking duck without liquid,'' Am. J. Phys. **29**, 335–336 (1961).

[8]H. E. Stockman, ''Secret of the dunking duck,'' Am. J. Phys. **29**, 374–375 (1961).

[9]K. B. Kolb, ''Reciprocating engine,'' Phys. Teach. **4**, 121–122 (1966).

[10]''Drinking duck shutter,'' Announcements and News, Phys. Teach. **5**, 342 (1967).

[11]D. L. Frank, ''The drinking bird and the scientific method,'' J. Chem. Educ. **50**, 211 (1973).

[12]R. Plumb, ''Physical chemistry of the drinking duck,'' J. Chem. Educ. **50**, 212 (1973).

[13]R. Plumb, ''Footnote to the drinking duck exemplum,'' J. Chem. Educ. **52**, 728 (1975).

[14]H. Bent and H. Teague, ''The hydro-thermal-dynamical duck; A sketch of his uses in the classroom and the laboratory,'' J. Coll. Sci. Teach. **8**, 18–28 (1978).

[15]C. Bachhuber, ''Energy from the evaporation of water,'' Am. J. Phys. **51**, 259–264 (1983).

[16]S. A. Bowling, ''The dunking bird,'' The Alaskan Science Forum, ⟨http://www.gi.alaska.edu/ScienceForum/ASF8/854.html⟩, Article #854 (1988).

[17]D. Rathjen, ''Duckpower,'' Exploring **18** (4), 7–8 (1994).

[18]H. D. Gesser, ''The bobbing (drinking) bird,'' J. Chem. Educ. **73**, 355 (1996).

[19]J. Guemez, R. Valiente, C. Fiolhas, and M. Fiolhas, ''Experiments with the drinking bird,'' Am. J. Phys. **71**, 1257–1263 (2003)

[20]E. Schäffer and Po-zen Wong, ''Dynamics of contact line pinning in capillary rise and fall,'' Phys. Rev. Lett. **80**, 3069–3072 (1998).

[21]B. V. Zhmud, F. Tiberg, and K. Hallstensson, ''Dynamics of capillary rise,'' J. Colloid Interface Sci. **228**, 263–269 (2000)

[22]J. B. Marion and W. F. Hornyak, *Physics for Science and Engineering* (Saunders, Philadelphia, 1982).

[23]É. Lorenceau, D. Quéré, J.-Y. Ollitrault, and C. Clanet, ''Gravitational oscillations of a liquid column in a pipe,'' Phys. Fluids **14**, 1985–1992 (2002).

[24]Pierre Gilles de Gennes, *Soft Interfaces* (Cambridge U. P., Cambridge, 1997).

[25]Jacob Israelachvili, *Intermolecular and Surface Forces* (Academic, New York, 1992).

[26]E. S. R. Gopal, *Statistical Mechanics and Properties of Matter* (J. Wiley, New York, 1974).

[27]Additional information on dunking birds is provided at ⟨http://www.dunkingbird.org⟩.