The absorption refrigerator as a thermal transformer

F Herrmann

Abteilung für Didaktik der Physik, Universität Karlsruhe, Germany

Abstract
The absorption refrigerator can be considered a thermal transformer, that is, a
device that is analogous to the electric transformer. The analogy is based on the
correspondence between the extensive quantities, entropy and electric charge
and the intensive variables, temperature and electric potential.

1. Introduction

The absorption refrigerator—best known as a means for food storage in recreational vehicles—
is driven by a heat source unlike the compression cooling machine which is driven by an
electrical motor. We examine the absorption refrigerator not for its practical importance[1] but
because it is a prototypical device, as is the Carnot engine.

One way of looking at the absorption refrigeration cycle is to compare it with the vapour
compression cycle (Van Wylen and Sonntag 1965, Holman 1969). In the latter the gas is
compressed, in contrast to the absorption refrigerator in which a liquid is brought from low to
high pressure, which requires much less energy. Although this description is correct, it does
not illustrate one aspect which might be helpful for understanding the absorption cycle. As
for the Carnot cycle, the description of the absorption refrigeration cycle becomes particularly
simple when looking at the entropy balance, where we can see that the absorption refrigerator
is the thermal analogue of the electric transformer.

In section 2, we will bring to mind how balances of thermal engines can be formulated
by means of flow diagrams. Section 3 introduces the essential aspects of the absorption
refrigerator. It will be seen that, within the machine, one entropy current flows from a place
of high to a place of low temperature, thereby 'pumping' another entropy current from low to
high temperature.

The paper is intended for the undergraduate level.

---

[1] The absorption refrigerator has several advantages compared to the more common compression cooling machine.
It can run where no electrical energy is available, it can use the exhaust heat from thermal engines or other industrial
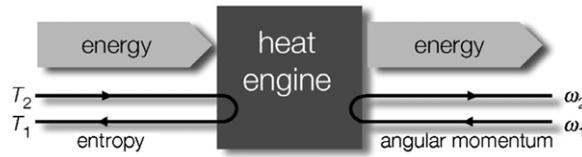processes, and it does not produce noise.

Figure 1. Flow diagram of a heat engine.

2. Flow diagrams

To define what a heat engine is, it suffices to say what the engine is doing. It does not matter how the engine is doing it. An easy way to do so is by drawing a flow diagram (figure 1). The flow diagram shows the currents that enter and the currents that leave the machine. In addition, it shows the values of the intensive quantities corresponding to the flowing extensive quantities. In the following, we always suppose that our machines work reversibly, i.e. without entropy production. This can be achieved in principle to any degree of approximation.

Let us have a closer look at figure 1. A thermal energy flow enters the machine at the left-hand side and a mechanical energy flow leaves it at the right-hand side.

Let us consider these flows separately.

1. An entropy current I_S enters the machine at high temperature T_2 and leaves it at low temperature T_1. Within the machine, the entropy 'falls' from T_2 to T_1. Thereby, a net thermal energy current

$$P_{\text{therm}} = (T_2 - T_1)\, I_S$$

   is delivered to the machine. We say that at the entrance of the machine, the entropy is the energy carrier (Falk *et al* 1983).

2. An angular momentum current M (usually called a torque) enters the machine through the mounting at the low angular velocity $\omega_1 = 0$ and leaves it at high angular velocity ω_2 through the engine shaft. Within the machine, the angular momentum is 'lifted' from ω_1 to ω_2. Thereby, a mechanical energy current

$$P_{\text{mech}} = (\omega_2 - \omega_1)M$$

   is delivered by the machine. The energy carrier at the exit of the machine is angular momentum.

Since the energy inflow must equal the outflow, we have

$$(T_2 - T_1)\, I_S = (\omega_2 - \omega_1)\, M. \tag{1}$$

Instead of considering a pure thermal engine, we can use the same argument for a thermal power plant, i.e. a thermal engine plus an electric generator. Figure 2 shows the corresponding flow diagram. Instead of equation (1), we now have

$$(T_2 - T_1)\, I_S = (\varphi_2 - \varphi_1)\, I,$$

where I is the electric current and φ is the electric potential.

Let us summarize in words what the flow diagram describes pictorially: an entropy current enters the power plant at a high temperature (at high 'thermal potential') and leaves it at a low temperature (at low 'thermal potential'). By doing so, it raises the electric charge from a low to a high electric potential (or angular momentum from a low to a high angular velocity).
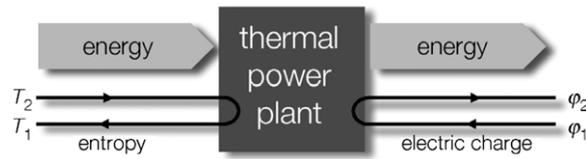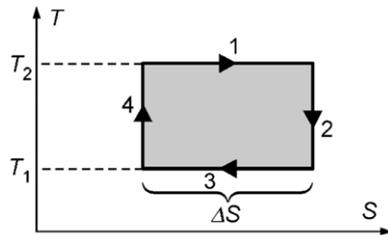
Figure 2. Flow diagram of a thermal power plant.

Figure 3. *T–S* diagram of the Carnot cycle.

There is a similarity between a heat engine and a water wheel. Whereas within the heat engine entropy falls from high to low temperature in order to drive something ('to do work'), in a water wheel water goes from a greater to a smaller height or, expressed in more physical terms, mass goes from a higher to a lower gravitational potential. The foregoing description of a heat engine, as well as the comparison with a water wheel, is due to Carnot (1953).

So far, nothing has been said about the realization of the thermal engine. One realization, which is possible in principle but impractical, has been proposed and discussed by Carnot: a cyclic process consisting of four steps, which today is called the Carnot cycle. The corresponding machine is called the Carnot engine.

The Carnot cycle is most easily characterized by its *S–T* diagram, figure 3. According to the direction of the cyclic process, the engine works as a thermal motor or as a heat pump. Here, we describe it as a motor. In the first step, an amount of entropy ΔS enters the engine at high temperature T_2. In the second step, the temperature is lowered from T_2 to T_1, while the entropy remains constant. In the third step, the engine releases the entropy ΔS while the temperature remains constant. In the fourth step, the temperature increases to T_2 while the entropy is held constant.

The net amount of energy that is supplied thermally to the machine can be read from the *T–S* diagram. It is given by the area enclosed within the rectangle.

3. The absorption refrigerator as a thermal transformer

The absorption refrigerator consists of four interconnected heat exchangers, as shown in figure 4: the condenser, the evaporator, the absorber and the generator. The working fluid is ammonia. The ammonia flows through the four heat exchangers in the following order: condenser → evaporator → absorber → generator → condenser → .... The condenser and the absorber are at ambient temperature T_{amb}. The evaporator is at low temperature T_{low} and the generator is at high temperature T_{high}.
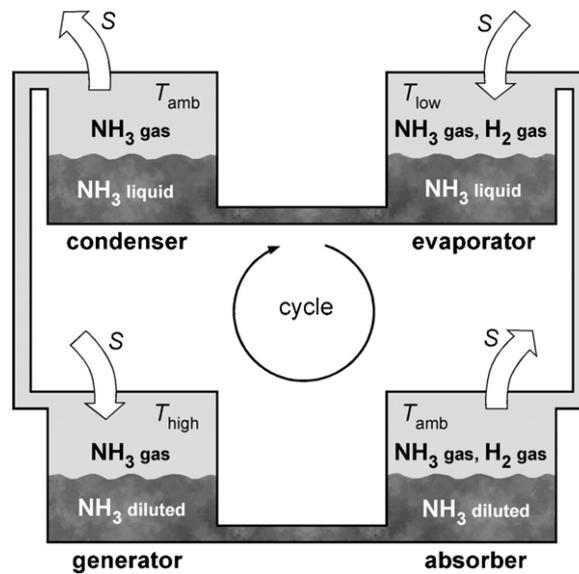
Figure 4. Schematic arrangement of the absorption refrigerator.

The ammonia exists in two different phases inside each of the four heat exchangers. Liquid and gaseous ammonia coexist in the condenser and the evaporator. There is gaseous ammonia and ammonia in a hydrous solution in the absorber and the generator.

In addition to the ammonia, the gaseous phase in the evaporator and in the absorber also contains hydrogen. The hydrogen does not participate in the cyclic process. It only ensures that the total pressure in the evaporator is the same as in the condenser.

The transport of ammonia from the absorber to the generator could in principle proceed via diffusion. Because diffusive processes are slow, the ammonia is more effectively transferred by means of the so-called absorption circuit. The liquid ammonia–water mixture circulates in such a way that the ammonia proceeds convectively from the absorber to the generator. This liquid current is driven either by a pump or by natural convection. In the present context, the absorption circuit is no more than a technical trick that accelerates the flow of the working fluid. Because we are interested only in understanding the basic principles of the machine, we omit the absorption circuit and assume that the ammonia transport from the absorber to the generator occurs by diffusion.

We are now prepared to understand the principle of the absorption machine. We follow a portion of ammonia on its way through the four stations of the machine. It is essential to consider the entropy balance: where, and at what temperature, does the portion pick up entropy, and where does it release entropy? We consider the process in a *T–S* diagram (figure 5).

We begin with the gaseous phase of the condenser. Within the condenser, the gaseous ammonia portion changes into the liquid phase. Because the entropy content of a given amount of the liquid is much lower than in the gaseous phase, the ammonia has to release entropy. This entropy leaves the machine at ambient temperature. The liquid ammonia portion next proceeds to the evaporator.

Because the evaporator is at a lower temperature than the condenser, the portion of ammonia has to release entropy on its way from the condenser to the evaporator. We suppose
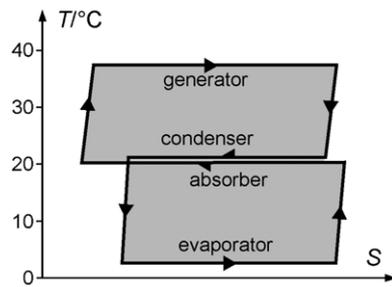
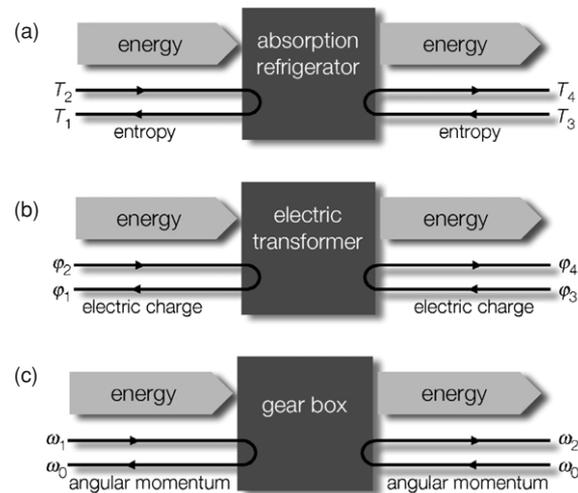**Figure 5.** *T–S* diagram of the absorption refrigerator.

Figure 6. Flow diagrams of (a) absorption refrigerator, (b) electric transformer and (c) gear box.

that it does so via the walls of the pipe that connects both heat exchangers. This amount of entropy is small compared with the entropy exchanged in any of the four heat exchangers and can be neglected for our purposes.

In the evaporator, the ammonia portion again changes into the gaseous phase. For that purpose, it has to absorb entropy at low temperature T_{low}.

From the evaporator, the ammonia portion proceeds to the absorber where it dissolves in the ammonia–water solution, thereby releasing entropy at ambient temperature.

From the absorber, the ammonia portion proceeds to the generator where it transforms from the solute into the gaseous phase, thereby absorbing entropy at T_{high}.

After this somewhat laborious step-by-step description, let us consider the entire cycle in the *T–S* diagram in the whole (figure 5). We no longer ask what the ammonia portion is doing; we only ask for the entropy exchanges. Because the entire cyclic process is a steady-state process, figure 5 also tells us how much entropy is exchanged in each of the four exchangers in a given time interval. It is seen that within the machine, a certain amount of entropy proceeds

from the high temperature T_{high} to the intermediate temperature T_{amb} whereby another entropy portion is 'pumped' from the low temperature T_{low} to the intermediate temperature T_{amb}.

The T–S diagram also displays the energy balance. The cycle consists of two loops. As the ammonia portion makes a complete cycle, it passes clockwise through one of these loops and counterclockwise through the other. The area of the upper loop corresponds to the energy absorbed by the ammonia portion; the lower loop corresponds to the released energy. Because the total amount of energy exchanged by the refrigerator in a given time interval is zero, the absolute values of the areas of the two loops must be equal. If we take into account that the process runs through the loops in opposite directions and accordingly attribute opposite signs to the areas of the two loops, we can also say that the total area is zero.

Figure 6(a) shows the flow diagram of the absorption refrigerator. When comparing it with the flow diagram of the electric transformer, figure 6(b), we see that these devices display a great similarity (Fuchs 1996). (The fact that an electric transformer only works with alternating electric currents is not important in this context.)

Let us remind ourselves that the mechanical analogue of the electric transformer (and the absorption refrigerator) is the gear box. An angular momentum current enters it via the input shaft. In the gear box, this current flows from the high angular velocity of the shaft to the angular velocity 0 of the mounting. Simultaneously, another angular momentum current is 'pumped' from a lower to a higher angular velocity. This is the current that leaves the gear box via the output shaft. Figure 6(c) shows the corresponding flow diagram.

References

Carnot S 1953 *Réflexions sur la Puissance Motrice du Feu et sur les Machines Propres à Développer cette Puissance* ed A Blanchard (Paris: Librairie Scientifique et Technique) p 28 (Nouvelle édition)
Falk G, Herrmann F and Schmid G B 1983 Energy forms or energy carriers? *Am. J. Phys.* **51** 1074–7
Fuchs H 1996 *The Dynamics of Heat* (New York: Springer) pp 553–4
Holman J P 1969 *Thermodynamics* (New York: McGraw-Hill) p 361
Van Wylen G J and Sonntag R E 1965 *Fundamentals of Classical Thermodynamics* (New York: Wiley) p 288