IC/83/128
INTERNAL REPORT
(Limited Distribution)

International Atomic Energy Agency

and

United Nations Educational Scientific and Cultural Organization

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

SOME COMMENTS ABOUT THE COMPARISON BETWEEN A CONVENTIONAL AND A SOLAR POWERED ABSORPTION REFRIGERATION SYSTEM [+]

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MIRAMARE - TRIESTE
August 1983

[+] To be submitted for publication

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ABSTRACT

Two statements about the performance of solar refrigeration systems are discussed. First, concepts of efficiency and coefficient of performance are studied. Second, the influence of inflation and rise of fuel prices are considered, in relation to the comparison between solar and conventional refrigeration systems.

I. INTRODUCTION

When solar and conventional sources are compared for refrigeration on ice-production, two points usually arise which are against the solar system:

1) Solar systems are bad thermal machines, because they have a very low coefficient of performance (COP);
2) Solar systems are more expensive than the conventional systems.

In this paper we analyze these two statements. For the first one we discuss that the COP is not the appropriate comparison parameter; another parameter, which we have named the Performantia, must be used. With respect to the second statement, after some economical analysis, our conclusion is that it is not completely correct because in comparing prices one should take into account inflation, rise of the fuel prices and the distance between the system and the fuel supply.

II. CONCEPTS OF EXERGY, ANERGY AND SECOND LAW EFFICIENCY

Given a thermal source at the temperature T_h and another at the temperature T_c, lower than the first one, we can obtain work from a thermodynamical cycle which runs between these two sources. The maximum mechanical work we can obtain from the cycle, W_n, is

$$W_m = \eta_c E \quad , \qquad (2.1)$$

where E is the thermal energy delivered from the high temperature source, and η_c is the Carnot or ideal efficiency given, as is well known, by

$$\eta_c = \frac{T_h - T_c}{T_h} . \qquad (2.2)$$

The energy which is totally transformed in mechanical work is also called **Exergy** (see for example Ref.1), E_x, that is

$$Ex = \eta_c E . \qquad (2.3)$$

The energy which is absolutely impossible to transform in mechanical work, is called the Anergy A,

$$A = E - E_x = \frac{T_c}{T_h} E . \qquad (2.4)$$

The efficiency at the first law (efficiency of the conversion from thermal to mechanical energy) is defined as the quotient between the real or experimentally measured mechanical work W, and the total thermal energy used,

$$\eta(1st) = \frac{W}{F} \leqslant \eta_c < 1 \qquad (2.5)$$

that is, it has the Carnot efficiency as the highest limit.

The efficiency of the second law, sometimes called availability, effectiveness or exergy efficiency, is defined as:

$$\eta(2nd) = \frac{W}{Ex} \leqslant 1 \qquad (2.6)$$

and the relationship with the efficiency of the first law is:

$$\eta(2nd) = \frac{\eta(1st)}{\eta_c} . \qquad (2.7)$$

Note that in the temperature-entropy diagram of an ideal cycle, energy, exergy and anergy can be interpreted as different areas, as shown in Fig.1.

The concept of exergy is useful to precise how much mechanical work can be delivered from a thermal source which has a fixed temperature.

In order to discuss the meaning, let us take as an example the comparison between two thermal cycles producing mechanical work, characterized by the following parameters,

System 1 : $T_h = 300°C$ $T_c = 30°C$ $\eta_1(1st) = 26\%$ (measured)

System 2 : $T_h = 500°C$ $T_c = 30°C$ $\eta_2(1st) = 28\%$ (measured)

If we compare the systems taking into account only the 1st law efficiencies, we conclude that, since $\eta_1(1st) < \eta_2(1st)$, System 2 is a better thermal machine than 1. But it is wrong, this only means that if the thermal sources for the two systems can deliver the same amount of energy, we will obtain more mechanical work through System 2; but it is System 1 which is really using its source in a better way. Note that System 1 has an exergy of

$$Ex_1 = 0{,}47\ E \quad ,$$

which means that the maximum mechanical work that can be obtained from this source is 47% of the total energy, while the rest

$$A_1 = 0{,}53\ E$$

is the energy which has lost its capacity to do mechanical work. System 2 has an exergy and anergy of

$$Ex_2 = 0{,}61 E$$

$$A_2 = 0{,}39 E \quad .$$

Therefore the 2nd law efficiency for the two systems will be

$$\eta_1(2nd) = \frac{\eta_1(1st)}{\eta_{c1}} = \frac{0{,}26}{0{,}47} = 0{,}55$$

$$\eta_2(2nd) = \frac{\eta_2(1st)}{\eta_{c2}} = \frac{0{,}28}{0{,}61} = 0{,}46 \quad .$$

That means that System 1 is better than System 2 as a thermal machine, because it is able to use 55% of its exergy, while System 2 is able to transform only 46% of its exergy in mechanical work.

Another example which clarifies that concept of exergy and anergy is the following. Let us suppose that in the former example thermal energy is dissipated to a reservoir of constant temperature of 30°C, with anergies A_1 and A_2. If we dispose of another reservoir at 25°C and we want to get mechanical work with a thermodynamical cycle between these reservoirs, the new system should have an exergy of 1,6% of the total energy, $E' = A_1 + A_2$.

Then, the exergy gives a hierarchical order of thermal sources related to their capacity in producing mechanical work, and the 2nd law efficiency allows us to distinguish the quality of real systems to produce mechanical work, independently of the source, in contrast with the 1st law efficiency concept.

III. REVERSE CYCLE CONCEPT OF PERFORMANTIA. COMPARISON BETWEEN SOLAR AND CONVENTIONAL THERMAL BEHAVIOUR

Reverse cycles, instead of producing work, consume mechanical or thermal energy to produce heat (heat pumps) or to extract heat (refrigeration). Here a different criteria is used to categorize thermal system, not the efficiency but the COP (Coefficient of Performance) defined as

$$COP = \frac{\text{Thermal energy transferred}}{\text{Thermal or Mechanical energy used}}$$

For an ideal reverse cycle such as shown in Fig.2, we have

$$COP(REF,COM,CAR) = \frac{A}{Ex} = \frac{T_c}{T_h - T_c} \qquad (3.1)$$

and

$$COP\ (HEAT,COM,CAR) = \frac{E}{Ex} = \frac{T_h}{T_h - T_c} = \frac{1}{\eta} \ , \qquad (3.2)$$

where

COP(REF,COM,CAR) is the COP for refrigeration by vapour compression ideal or Carnot cycle,

COP(HEAT,COM,CAR) is the COP for heating by vapour compression ideal or Carnot cycle,

η is the 1st law efficiency for the equivalent direct cycle between the same thermal sources.

For ideal absorption systems (negligible pumping work or running by thermosyphon), in which the heating source is at temperature T_h, the COP is given (see for example Ref.2) by

$$COP(REF,ABS,CAR) = \frac{T_c \quad (T_h - T_a)}{T_h \ (T_a - T_c)} \quad , \qquad (3.3)$$

where ABS = absorption cycle

T_a = ambient temperature

T_c = refrigerator temperature .

In the practical realization of the reverse cycles, the thermal or mechanical energy actually used by the device is much more than the theoretical one because of the irreversible phenomena involved, thermal losses, etc.

Then

$$COP\ (EXP) < COP\ (CAR) \quad . \qquad (3.4)$$

We shall discuss here that, such as the 1st law efficiency concept cannot be employed to compare two systems acting between two different thermal sources, the COP, as defined, is not able to give a quality criterion to distinguish two systems whose thermal sources have different temperatures.

Then, as done in the direct cycle, we define a parameter similar to the 2nd law efficiency, which could be called Performantia, as

$$Per = \frac{COP\ (EXP)}{COP\ (CAR)} \qquad (3.5)$$

parameter that will give us the quality of the device, that is its relationship with the ideal one.

In the following we analyze this parameter with an example. Let us suppose we have to compare two absorption systems, characterized by

System A – Absorption refrigerator with a solar energy source

T_h (produced by the collectors) = 120°C T_a = 25°C

T_c (in the refrigerator) = -5°C $COP_A(EXP)$ = 0,5

[illegible] refrigerator with a fossil fuel source

T_h [illegible] measured 1000°C T_a = 25°C

T_c [illegible] 5°C $COP_B(EXP)$ = 2 ,

where T_a is the ambient temperature.

Usually, a refrigerator engineer concludes that System B is four times better than A, because for each kWh used, System B removes 2 kWh from the refrigerator, whereas System A removes only 0,5 kWh. However, the sources are essentially different, because for System A it could be a set of flat plate collectors (evacuated tube selective surface collectors) or CPC collectors, whereas in B it is a flame produced by the fuel oxidation.

Let us calculate the performantia of the two systems

$$Per_A = \frac{0,5}{2,16} = 0,231$$

$$Per_B = \frac{2}{6,84} = 0,292 \quad .$$

From these figures we can see that System B continues to be the better one but now with only a slight advantage over System A. The performantia tells us that System A is able to work at 23% of an ideal system, whereas System B is able to work at 29%. Therefore, if we are able to improve experimentally the solar system, such as the

$$COP_A\ (\ EXP\ ) = 0,65$$

the performantia will move to

$$Per'_A = 0,300$$

given a system that is better than B.

That is, even though System A has a COP three times lower than System B, from the point of view of a thermal machine, it is better than System B, because it has a performantia 0,30 vs 0,29 of System B.

Then we conclude that in order to make a comparison between a conventional and a solar powered system we have to compare their Performantia and not their COP.

IV. COST COMPARISON BETWEEN SOLAR AND CONVENTIONAL SYSTEMS

Solar systems have higher commercial prices than conventionals ones; however when we make comparison fuel and transportation charges must be included. These two points will be discussed here. For rural and remote implantations we should also consider the availability of conventional fuels: In many places it is a usual problem that communications and fuel provision fail due to weather or management troubles. We will not consider this factor which depends critically on local conditions.

Fuel transportation requires two types of investments:

a) Carrier costs (according to the fuel considered;it could be a high voltage electricity transmission line,truck for fossil fuel or a gas pipeline): Represent an immediate investment which has to be added to the price of the conventional energy system.

b) Running charges, which can be classified in two types:

1) Carrier efficiency. Ohmic losses in electricity lines have a relative large variation, from 0,1% per kilometer for high voltage overhead lines up to 1-1,5% for poorly isolated low potential branches. Fuel consumption represents the losses in fuel truck transportation and can be estimated in 0,1-0,3% per kilometer. Wide pipelines have a very small pressure drop per kilometer of horizontal transfer requiring small expenses in pumping energy , Costs are large for distribution networks.

2) Maintenance.

We have carried out the evaluation using a unit, that we call "u", representing the present price of the energy unit involved kWh or kg of fossil fuel. In this way we intended to be independent of variations of local currency and prices.

Let us introduce the following notation:

v = present value of the carrier per unity of transportable energy
= share of the carrier used to transport the energy required for the conventional machine used.
f = fuel consumption in the transport process, per kilometer, unity of energy transported and year.

m = maintenance cost of the transportation system, per kilometer unity of energy
d = distance between the source of the fuel and the machine
n = mean life of the carrier (years)

We shall assume that transportation cost is a linear function of the distance (see for example ref.3). This means that to provide one unity of energy to the machine we have to deliver

$$q_0 = 1 + (f + m) d \tag{4.1}$$

units of energy from the source. Let us assume that the price of the fuel grows steadily each year at a rate of e. So

$$q_i = (1 + e) q_{i-1} \tag{4.2}$$

i.e. the price q_i in the year i, is eq higher than the price in the year i-1 (u - unity). We call r the current rate for investment, and define

$$X_q = \frac{1 + e}{1 + r} \tag{4.3}$$

The present value of the energy required for each unity of energy to be consumed is

$$Q = q_0 \; X_q \frac{X_q^n - 1}{X_q - 1} = q_0 \; \gamma \tag{4.4}$$

where γ is a purely financial quantity. Then the present price of fuel and transportation is

$$P = p \quad v + Q \; . \tag{4.5}$$

We note that this is a linear function of the distance d, and allows us to determine the distance after which a solar system becomes convenient.

A CASE SITUATION: Let us consider a fishing village on the Brasilian coast for which a refrigeration machine is required. We have to compare a gas-oil absorption system to a solar powered one Gas -oil is carried by truck.

Present prices of fuel and truck are $u = 0.3$ \$ and $v = 8$ \$/kg $= 26{,}7\ u$ (in u unity). We will assume a) $p=0.3$, that is the truck is employed at 10% for fuel transport; b) the mean life of a truck is 10 years. Since the mean life of a solar system is 20 years we have to buy a new truck after the first 10 years. This difference in life duration could be taken into account by doubling the value of v. This is equivalent to assuming that truck prices will increase at a rate of r. Therefore $n = 20$ in Eq. (4.4).

In a standard case, fuel consumption gives $f = 0{,}13$ ‰ and assuming maintenance will be about 30% of that consumption, we get $f+m = 0.18$ ‰. The value of γ is 1 when we assume $r=e$. However the most probable trends indicates $e > r$.

Then, from Eq. (4.5) we get

$$P = 2 \times 2.67 + \gamma\,(1 + 0{,}00018\ d)\ ,$$

In figure 3 we represent this quantity as a function of d for different values of γ. Of course the expected value of γ depends on local conditions.

Now we can perform a cost comparison between solar and conventional systems. We have to evaluate the difference between present prices of both systems for each unity of energy necessary to run the absorption refrigerator. This difference is independent of d, and in figure 3 is represented by a straight horizontal line. . It has to be compared with present prices of fuel and transportation. There will be a crossing between the lines, which determines after which distance (between energy source and machine) the solar system will be more convenient than the conventional one.

As an example let us consider an absorption machine producing 250 kg of ice per day. This will require an energy input of about 10^7 Kcal per year, equivalent to 1100 Kg of fuel. The current commercial prices give a cost difference of about 10000 \$ between a solar CPC system and a fuel boiler. This requires an extra-investment in the solar system of about 28,8 Kg of fuel per unity of energy to be produced. This is represented in figure 3 as a flat line. We observe that depending on the e/r relation the solar system would not be convenient. In particular for $e/r = 1.1$ the solar array will be appropriate when the distance between source and machine is larger than 360 Km. For expected values of e/r larger than about 1.18 the solar system will always be the more appropriate choice.

ACKNOWLEDGEMENT

The authors wish to thank Professor Abdus Salam, the International Atomic Energy Agency and UNESCO for hospitality at the International Centre for Theoretical Physics, Trieste.

REFERENCES

1) Gardel A. Energy, Economy and Prospective (Pergamon Press 1981).
2) Rogers G.F.C. and Mayhew Y.R. Engineering Thermodynamics Work and Heat Transfer. (Longaman, 1967)
3) Sorensen B. Renewable Energy (Academic Press. 1979).

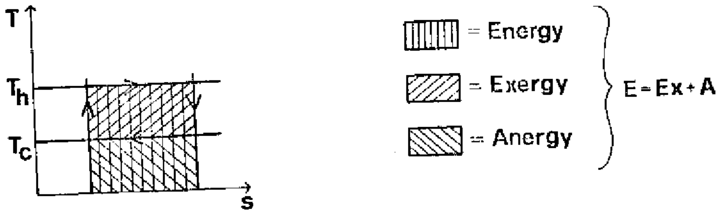

Fig.1 Interpretation of E, Ex and A for a termodynamic cycle in the temperature entropy diagram.

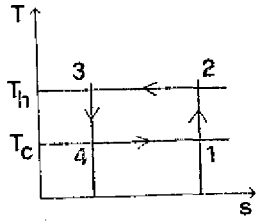

Fig.2 Ideal reverse cycle for refrigeration.

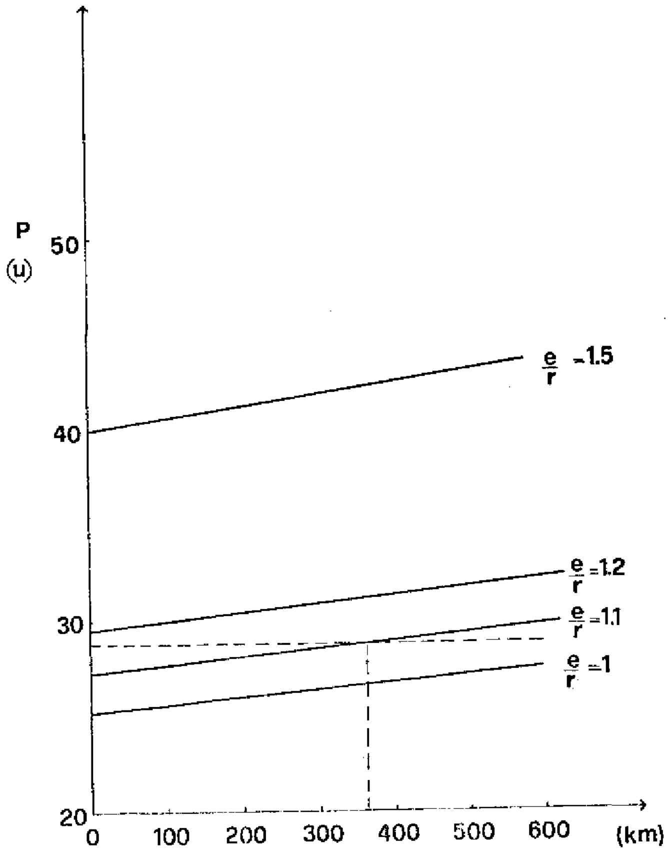

Fig.3 Present prices for fuel and transportation vs. distance from energy source to refrigerator.