EXERGY NEEDS TO MAINTAIN REAL SYSTEMS NEAR AMBIENT CONDITIONS

GÖRAN WALL

University College of Eskilstuna/Västerås, Box 11, S-721 03 Västerås, Sweden.

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ABSTRACT

This study treats the exergy needed to maintain real systems at states near equilibrium with the environment, e. g., processes involving exergy flows at temperatures near ambient temperature. Important relations for temperate states are introduced and exemplified by analyzing a food producing industry. This shows a large amount of exergy destruction at the production of cold and heat and ways to improve the process are suggested.

KEYWORDS

Exergy, Thermodynamics, Temperate systems, Refrigeration, Heating, Food industry

NOMENCLATURE

A	Area, system boundary
COP	Coefficient of performance
c_p	Specific heat
E	Exergy
E/Q	Exergy factor
H	Enthalpy
m	Mass
n	Number of mol
p	Pressure
Q	Energy
S	Entropy
T	Temperature
t	Time
U	Overall heat transfer coefficient
V	Volume
μ	Chemical potential

Subscripts

i	Substance
0	Ambient state
d	Delivered
r	Returned
yr	Year
min	Minimal

INTRODUCTION

On the 2nd of September, 1978, an article by Hannes Alfvén was published in the Swedish daily newspaper Svenska Dagbladet. The headline of the article was "Nordic Cold instead of Fuel Oil". Alfvén suggested ways to make use of the temperature difference between the roof facing the sky (-30°C) and the ground (0°C) for space heating. He also suggested the name tepidology for the theory to describe systems close to ambient conditions. By using technology based on heat pumping, temperature potentials could be added just as electrical potentials. However, his idea to introduce tepidology has, so far, not been further elaborated.

Beside space heating many industrial processes also operate close to ambient conditions. For example, in food industries large amount of energy for both heating and cooling are used. Exergy efficiencies of these processes are generally very poor. Special relations are valid for systems which are close to equilibrium, for instance, linear relations may often be assumed. This implies a special treatment and tepidology may be an important field of further research.

ENERGY AND EXERGY

Energy is often defined as work or the ability to perform work. Energy should instead be defined as motion or the ability to produce motion. This is certainly a less specific but a more correct definition. Energy is conserved in all processes. Energy is mostly an all too hazy concept.

In 1824, Carnot published a relation between heat and work, which Kelvin later made explicit and finally resulted in formulation of the second law of thermodynamics. Gibbs expressed the general relation for work as early as 1873. But not until 1956 did Rant suggest the name exergy and a general definition was given by Baehr in 1965. These works are some of the important steps in the definition of exergy.

The energy and exergy concepts can be expressed in the following way: (1) energy is motion or ability to produce motion and (2) exergy is work or ability to produce work. The laws of thermodynamics may be formulated accordingly: (1) energy is conserved in a process (1st law, law of energy conservation) and (2) exergy is conserved in a reversible process, but consumed in an irreversible (real) process (2nd law, law of exergy).

The exergy E of a system may be written as

$$E = S(T - T_0) - V(p - p_0) + \sum_i n_i(\mu_i - \mu_{i0}). \qquad (1)$$

We clearly see that exergy approaches zero as the system approaches equilibrium with the environment, i.e., $T = T_0$, $p = p_0$ and $\mu_i = \mu_{i0}$. The effects of electricity, magnetism, gravity, radiation, etc. can also easily be added to this expression.

Analogously, the exergy of a flow can be written as

$$E = H - H_0 - T_0(S - S_0) - \sum_i \mu_{i0}(n_i - n_{i0})\,. \tag{2}$$

EXERGY OF HEAT AND COLD

Let us name the relation E/Q *exergy factor*. The exergy factor of energy transfered as heat at a constant temperature T, i.e., a heat reservoir, in an environment of temperature T_0 then becomes

$$\frac{E}{Q} = \left|\frac{T - T_0}{T}\right|, \tag{3}$$

which is represented by the black curve in Fig. 1. The ratio $|(T - T_0)/T|$ is also known as the Carnot factor. We also see that a cold system contains exergy which increases rapidly with decreasing temperature.

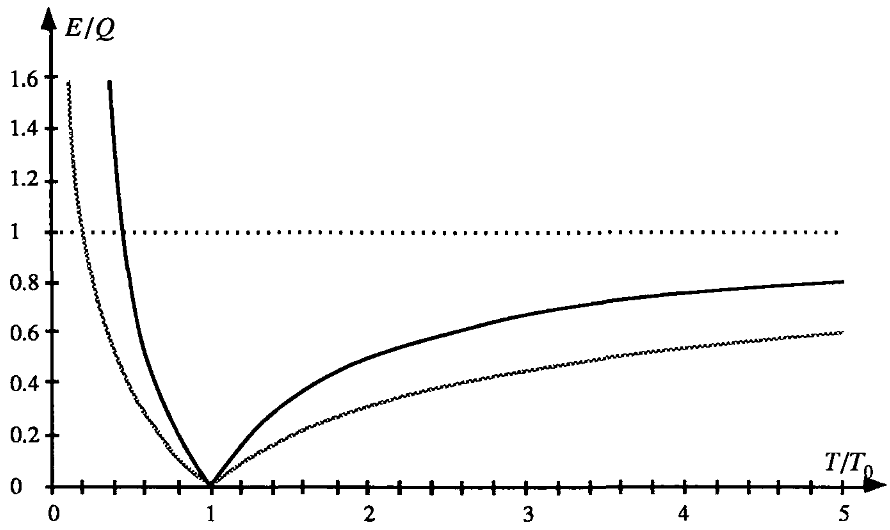

Fig. 1. Exergy factor of heat and cold as a function of ratio of temperature to environment temperature.

The exergy factor of energy transfered as heat from a limited system at temperature T, e. g., a substance m with specific heat $c_p(T)$, becomes

$$\frac{E}{Q} = \left|\frac{\int_{T_0}^{T} \frac{T - T_0}{T}\, m c_p(T')\,\mathrm{d}T'}{\int_{T_0}^{T} m c_p(T')\,\mathrm{d}T'}\right|. \tag{4}$$

If we assume that the specific heat is a constant this becomes

$$\frac{E}{Q} = \left| 1 - \frac{T_0}{T - T_0} \ln \frac{T}{T_0} \right|, \tag{5}$$

see the shadowed curve in Fig. 1.

In Sweden space heating based on district heating, a network of hot water distribution for several houses, is common. The exergy factor of district heat becomes

$$\frac{E}{Q} = 1 - \frac{T_0}{T_d - T_0} \ln \frac{T_d}{T_0}, \tag{6}$$

where T_d is the temperature of the delivered heat, i.e., the temperature of the hot water used by the consumer for space heating. This temperature is maintained at about 85°C (T_d = 358.15 K) at outdoor temperatures above +2°C (T_0 = 275.15 K) and is subsequently raised in inverse proportion to the outdoor temperature, up to 120°C (T_d = 393.15 K) at an outdoor temperature of –20°C (T_0 = 253.15 K). The exergy factor will thus vary with the outdoor temperature according to the shadow curve in Fig. 2. But, since only a part of the delivered heat is used by the consumer, i.e., the water is returned at a temperature above the outdoor temperature, the exergy factor of the actually used heat becomes

$$\frac{E}{Q} = 1 - \frac{T_0}{T_d - T_r} \ln \frac{T_d}{T_r}, \tag{7}$$

where T_r is the temperature of the returned water. When this is 55°C (T_r = 228.15 K) we instead get the black curve in Fig. 2, which is, of course, above that of the delivered heat.

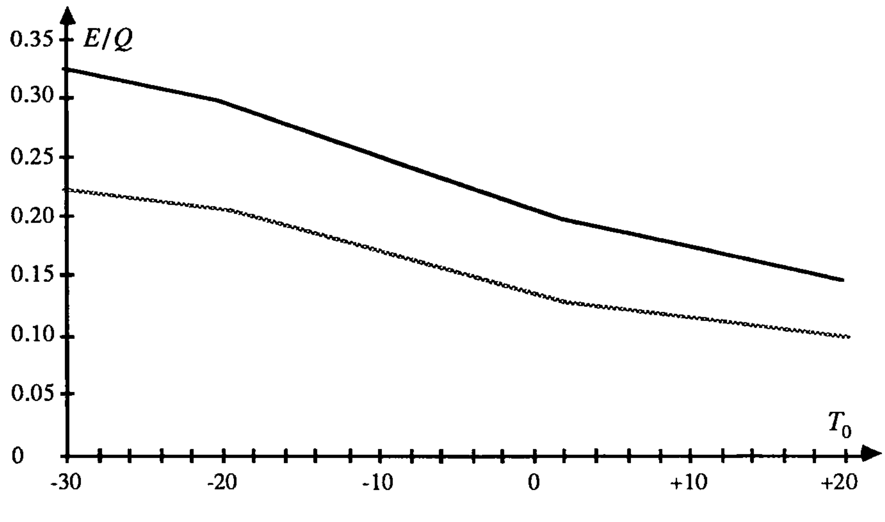

Fig. 2. Exergy factor of district heat.

TO MAINTAIN A CONSTANT TEMPERATURE OF A REAL SYSTEM

In order to maintain a real system at a specific temperature in an environment of a different temperature we need to compensate for the spontaneous energy transfer across the system boundary A. For a real system, a building or a cold-storage room, this boundary may consist of several layers of different thickness and materials. In practice, this energy transfer (leakage) can be regarded as (1) energy transferred as heat owing to a temperature difference (non matter)Q_h and (2) energy transfer involving bulk flow of matter Q_m , e.g. ventilation and hot water usage,

$$Q = Q_h + Q_m \tag{8}$$

At small temperature differences the transfer of energy as heat may be calculated by an *overall heat transfer coefficient U*, which is usually empirical, and we may write

$$Q_h = UA\left|T - T_0\right|t, \tag{9}$$

which is equivalent to the need of energy to compensate for this leakage. Similarly, the need of exergy becomes (from Eqs. 3 and 9)

$$E_h = \frac{UA(T-T_0)^2 t}{T}. \tag{10}$$

As we see, the exergy need varies quadratically with the temperature difference $T-T_0$, whereas, the energy need only varies linearly with the temperature difference $T-T_0$.

The energy transfer related to a bulk flow of matter may be defined as

$$Q_m = \left|\int_{T_0}^{T} mc_p(T')\mathrm{d}T'\right|. \tag{11}$$

At small temperature differences, i.e., c_p assumed constant, this becomes

$$Q_m = mc_p\left|T - T_0\right|. \tag{12}$$

The relating exergy loss becomes

$$E_m = mc_p\left|T - T_0 - T_0 \ln \frac{T}{T_0}\right|. \tag{13}$$

Note, for phase change we calculate the exergy change from

$$E_{phase} = \left|\frac{T_{phase} - T_0}{T_{phase}}\right| Q_{phase} \tag{14}$$

Let us now consider the variation of exergy with regard to the outdoor temperature. Figure 3 below shows the exergy factor (Q_m=0) based on the monthly average outdoor temperature for systems at different temperatures.

As we can see the exergy factor is lower in the summer for warm systems. For a freezer at –20°C, though, it is fairly high every month.

In Fig. 4 below we have calculated the exergy need to maintain a constant temperature of different systems according to Eq. 10. We see that to maintain the temperature of a cold store at –20°C in a temperate premises at +16°C, e.g., an indoor cold-storage room, requires 6.6 times the exergy (per m^2 wall) needed to keep a house warm (+20°C) in Sweden.

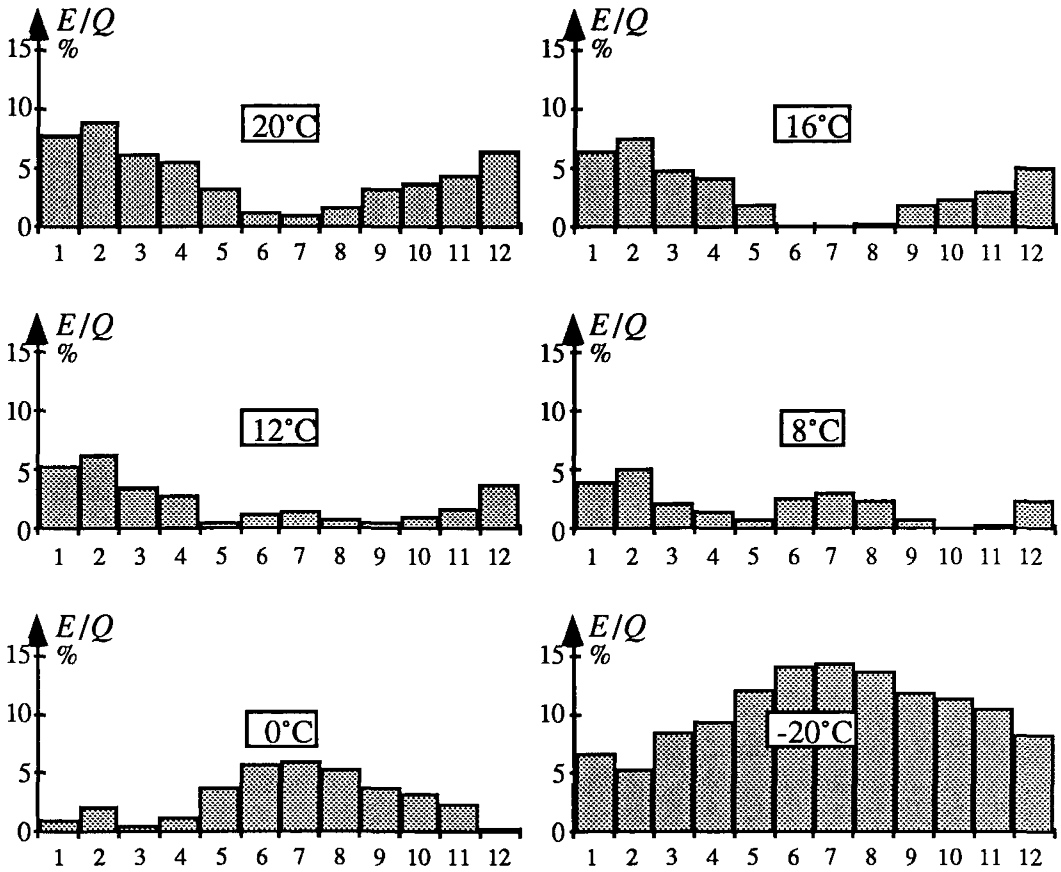

Fig. 3. Exergy factor *E/Q* of systems at different temperature in Göteborg at the west coast of Sweden, during year 1986, monthly average outdoor temperature (°C): Jan. -3.1, Feb. -6.2, March 1.7, April 3.9, May 10.4, June 15.8, July 16.5, Aug. 14.8, Sep. 10.2, Oct. 8.9, Nov. 6.8 and Dec. 1.1, annual average outdoor temperature: 6.7. (January is marked 1, etc.).

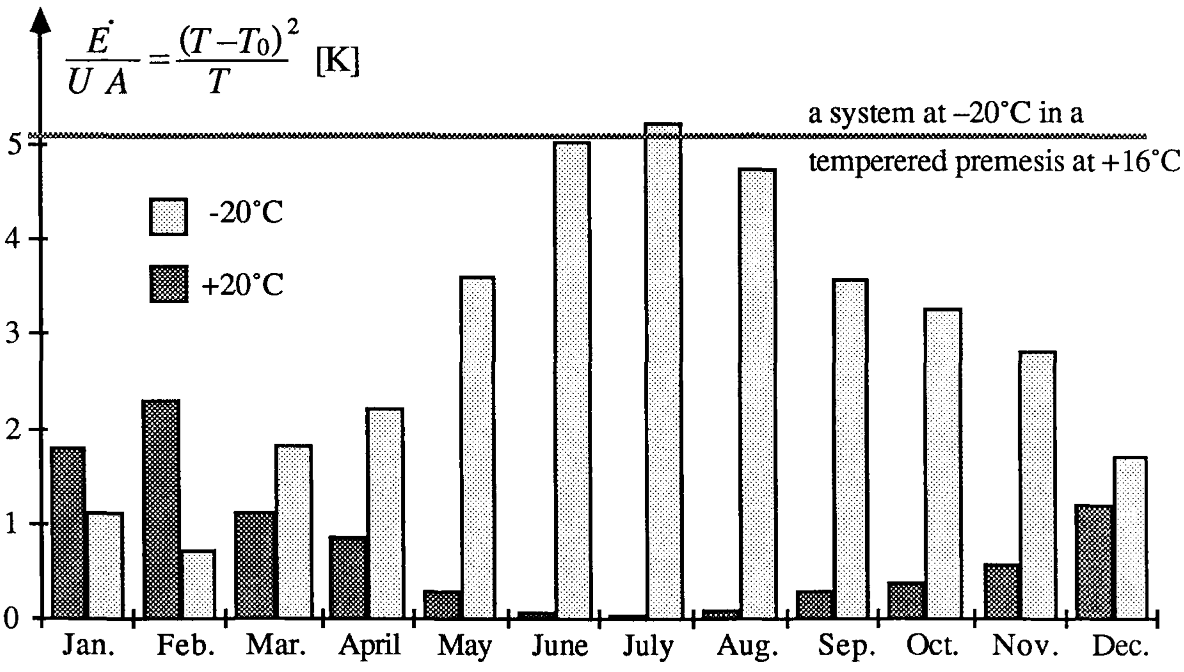

Fig. 4. Exergy need to maintain a system at -20°C and +20°C based on monthly variations of the outdoor temperature and a system of -20°C in a temperate premises at +16°C.

We may also calculate the exergy factor of the system based on a simple model of the outdoor temperature. Let us assume that

$$T_0(t) = T_{yr} + (T_{yr}-T_{min}) \cos\left(\frac{2\pi t}{365}\right) + \frac{T_{day}-T_{night}}{2\cos(2\pi t)} . \tag{15}$$

where T_{yr} is the annual average outdoor temperature, T_{min} is the minimum five-day mean temperature and $(T_{day}-T_{night})/2$ is the diurnal amplitude. Then the exergy factor becomes

$$\frac{E}{Q} = \frac{\left(a^2 + \frac{b^2}{2} + \frac{c^2}{2}\right) d + \frac{b}{\omega}\left[\frac{b}{2}\sin(\omega d) - 4(a-c)\sin\left(\frac{\omega d}{2}\right)\right]}{T\left[ad - \frac{2b}{\omega}\sin\left(\frac{\omega d}{2}\right)\right]} \tag{16}$$

where $a = T-T_{yr}$, $b = T_{yr}-T_{min}$, $c = (T_{day}-T_{night})/2$, d = number of days per year in operation and $\omega = 2\pi/365$.

By combining this equation with Eq. 9 the exergy factor of the space heating system of Sweden is calculated to about 4% (Wall 1987).

ENERGY AND EXERGY FLOWS IN A FOOD PRODUCING INDUSTRY

The importance of a careful study of the exergy needs is exemplified by studying the energy and exergy flows, Figs. 5 and 6 below, of a typical food industry (Wall *et al.*, 1988). In this case the products are cured meats and provisions†. Heating is based on fuel oil and cooling is provided from electricity used in vapor-compression systems, thus, two completely separated systems.

From Figs. 5 and 6 we see important differences. From the energy flow we see that a large amount of heat from the refrigeration machinery is not being used today. The exergy flow shows a large amount of destruction at the production of cold and heat. From a careful analysis of the boiler plant and the actual food production one can show that only 10% of todays energy supply is actually motivated (Wall *et al.*, 1988).

The major losses in the energy case seem to be waste heat, whereas, the exergy losses are concentrated to the production of heat and cold. The situation becomes even more serious when we consider the interaction between the need of heat and cold in the process. All cold-storage rooms are placed in temperate premises which means that the heat losses imply both additional heating and cooling. Ways to decrease the energy transfer between systems of different temperature, thus, becomes very profitable. This was found by using simple algorithms based on a "spreadsheet" program (Excel™).

† "Slakthusets industriområde" in Göteborg, Sweden. All data refers to year 1986.

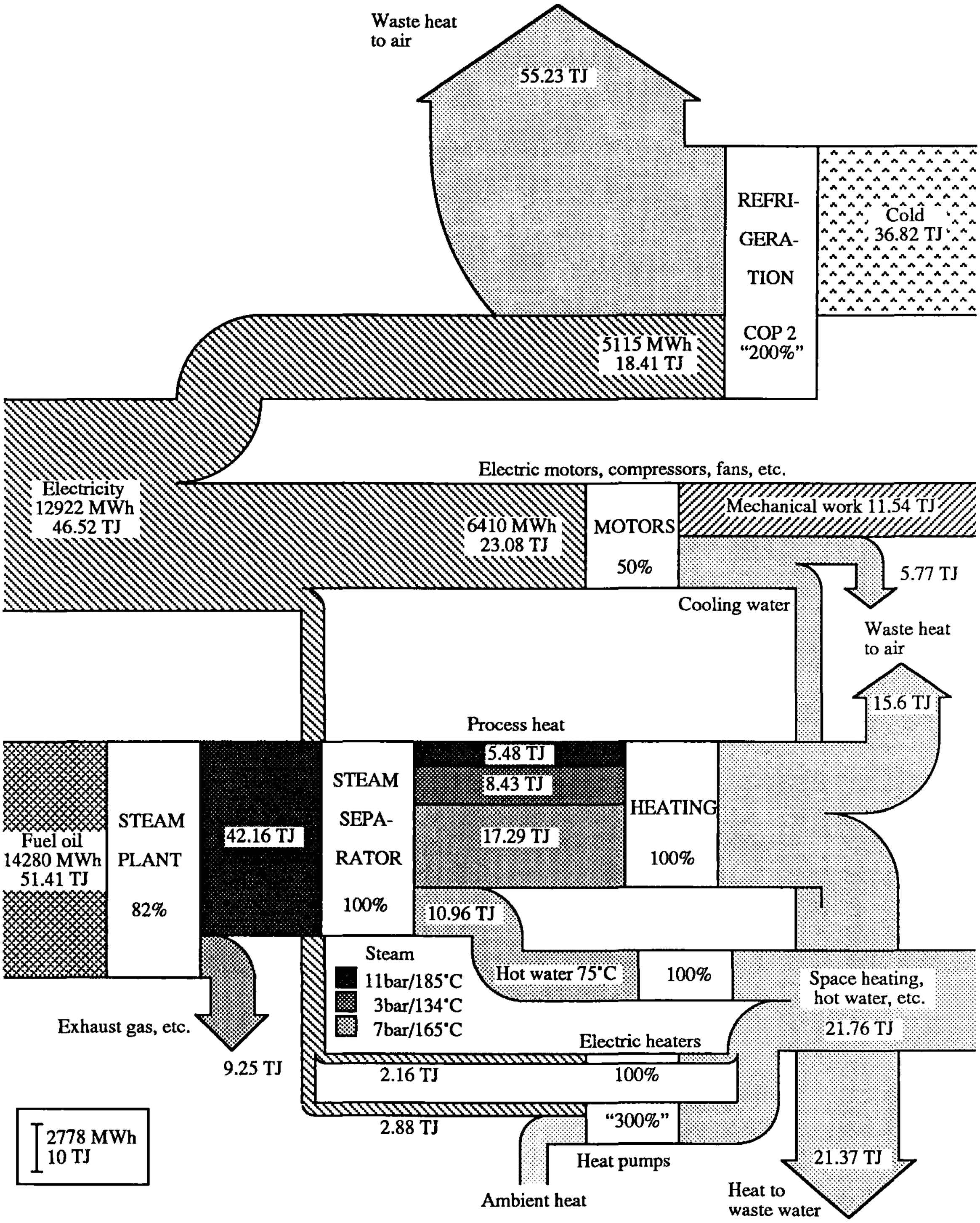

Fig. 5. Energy flow of a food producing industry.

One major problem, though, is the different cost of exergy. The cost of energy varies slightly between different energy commodities, but, the cost of exergy in district heat is about five times higher than that of other exergy commodities, e.g., electricity and fuel oil [Wall 1986]. By this discrepancy efficient use of exergy is sometimes not motivated. For instance, in this case a connection of the food producing plant to the local district heating network is not economically motivated even though it implies exergy savings.

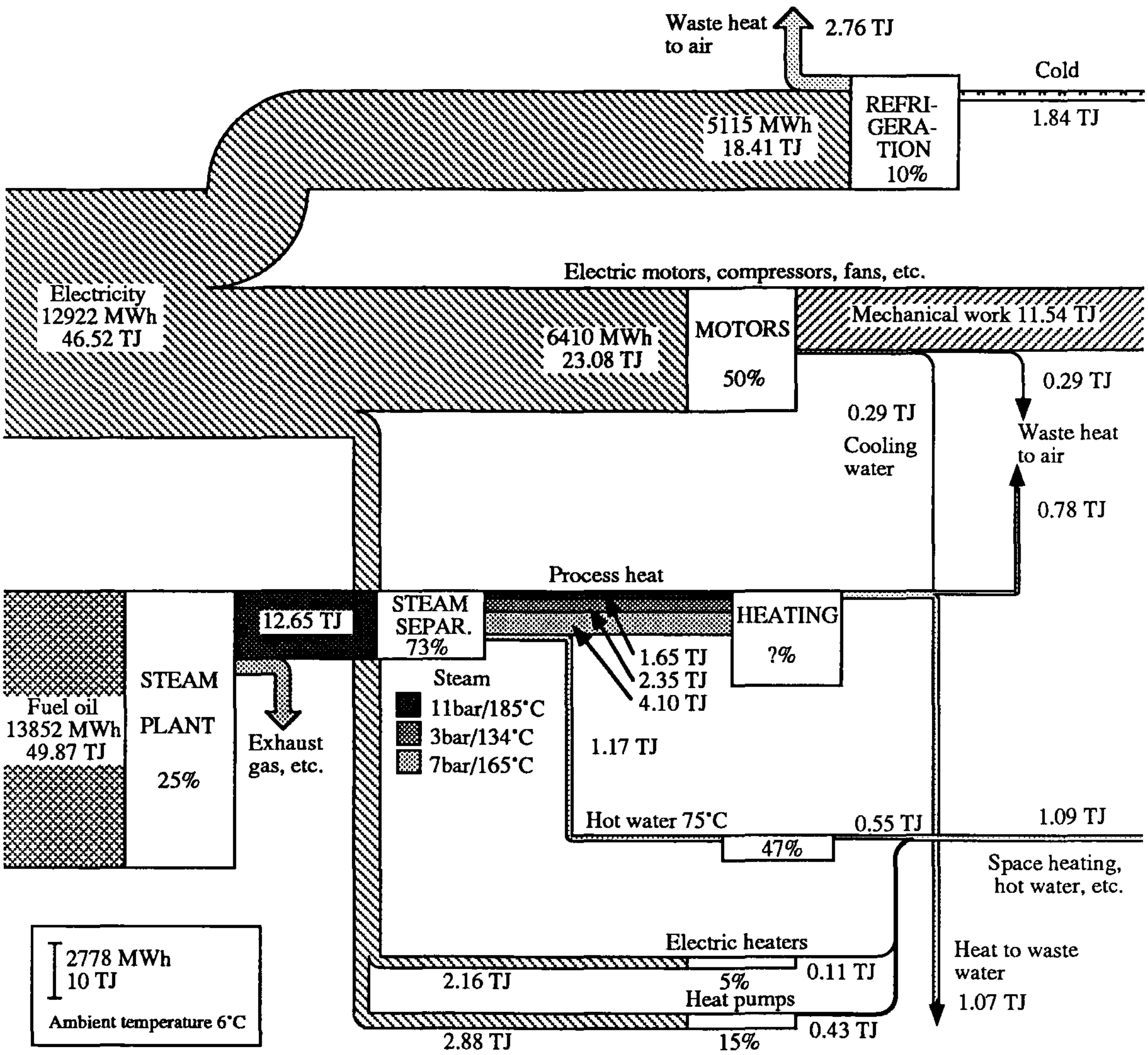

Fig. 6. Exergy flow of a food producing industry.

CONCLUSIONS

Careful exergy studies is shown to be an important tool to improve industrial processes by studying a food industry. Important areas of improvement are discovered.

The exergy needs to maintain a constant temperature of different systems shows that cold-storage rooms usually require far more exergy than space heating. Cold-storage rooms in industry should therefor be more carefully designed and systems based on simultaneous production of heat and cold should also be developed.

The energy and exergy needs at the plant of study show that sealing and heat insulation of cold-storage rooms are important ways to improve the plant. However, todays pricing of energy makes it hard to motivate efficient exergy use.

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