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ENERGY AND EXERGY ANALYSIS OF DISTRICT HEATING SYSTEMS

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ABSTRACT

The concept of exergy is defined and applied to district heating systems. The influence from different reference state conditions and system boundaries are explained in some detail. The aim is to show the simplicity and value of using the concept of exergy when analyzing district heating processes. The exergy factor is introduced and applied for a number of Swedish and Danish district heating systems. This varies from 14.2% to 22.5% for Swedish district heating systems. The higher the exergy factor, the more the exergy losses in the passive conversion towards space heating. Large losses revealed in an exergy treatment of a process should be seen as a challenge to achieve technical improvements of the system.

INTRODUCTION

The exergy concept is of essential importance to engineering in the design of energy systems and in order to meet environmental constraints. A thorough understanding of exergy, providing valuable insights into the concepts of efficiency, environmental impact and sustainability of energy systems are required by any engineer or scientist working in the area of energy systems and the environment [1].

Energy is related to the first law of thermodynamics, and exergy is related to the second law of thermodynamic. Energy is neither produced nor consumed; it is only converted from one form to another. Energy is always conserved and balanced in accordance with the first law of thermodynamics. In real processes exergy is always partly destroyed, the total exergy input always exceeds the total exergy output, this imbalance is due to exergy destruction, which is also called availability destruction, irreversibility, and lost work.

The exergy method is a useful tool for furthering the goal of more efficient energy-resource use, for it enables the locations, types, and true magnitudes of wastes and losses to be determined. The applications of exergy method are applied in a wide field. It covers society (e.g. [2-4]), industry (e.g. [2, 5]) as well as biological processes (e.g. [6]) and ecosystems (e.g. [7]).

District heating system is a system to distribute hot water to a number of buildings for space heating and hot water services. Earlier studies were dealing with energy, and rarely using exergy analysis. Only some studies of district heating system based on geothermal heat have used exergy analysis [8-14]. These studies focus on exergetic and exergoeconomic analysis of different geothermal district heating systems in Turkey.

EXERGY

Energy is sometimes defined as work which is not correct. Work is but a form of energy. Energy should instead be defined as motion or the ability to produce motion. [2] This is certainly a less specific but a more correct definition. Energy is also conserved in all processes.

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 [15]. Gibbs expressed the general relation for work as early as 1873 [16]. But not until 1956 did Rant [17] suggest the name exergy and a general definition was given by Baehr [18] in 1965. These works are some of the important steps in the definition of exergy.

Exergy is the maximum amount of work that can be extracted from a system [6]. If exergy is defined as the maximum work potential of a material or of a form of energy in relation to its environment, then the environment must be specified, i.e. a reference environment. Usually average values of the earth are selected, i.e. reference temperature T_0 is 298.15 K and the reference pressure P_0 is 1 atm. However, the earth is not in equilibrium, actually it is far from equilibrium. The temperature varies from place to place. In some cases a local temperature should be used as reference temperature, e.g. when considering space heating or air-conditioning systems [6].

Thus, 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 (ordered motion) or ability to produce work [2]. 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 is expressed by:

$$E = U - P_0V - T_0S - \sum_i \tilde{\mu}_{i0} n_i \qquad (1)$$

where *U*, *V*, *S*, and n_i denote extensive parameters of the system (internal energy, volume, entropy, and the number of moles of different chemical materials *i*) and P_0, T_0, and $\tilde{\mu}_{i0}$ are intensive parameters of the environment (pressure, temperature, and generalized chemical potential). These terms may be described accordingly: *U* is the energy carried within the system itself, part of this energy is used as work, i.e. exergy. This part is defined by the last two terms. P_0V is the work captured as a volume *V* that occupies a space of the environment of pressure P_0. This is pure work. T_0S is the part of the energy *U*, which is useless due to lack of order *S*, or heat at ambient temperature T_0. Similarly, the last term is another useless part of the energy *U*. In this case it is as substances at ambient states. The energy that is carried by substances can only be used “down to” the level that is given by the environment. This is similar to the available potential energy of a waterfall or the carrying capacity of a ship, which is the total capacity minus the ballast. The exergy *E* of a system may be written as:

$$E = S(T - T_0) - V(P - P_0) + \sum_i n_i(\mu_i - \mu_{i0}) \quad (2)$$

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:

$$E = H - T_0 S - \sum_i \tilde{\mu}_{i0} n_i \quad (3)$$

where *H* is the enthalpy, which captures the internal energy *U* and the external energy P_0V in a way that simplifies calculations.

Reference temperature

It is important that the reference state is fully specified completely for an exergy analysis. This includes the temperature, pressure and chemical composition of the reference environment. Consequently, the results of exergy analyses are relative to the specified reference environment. In this paper exergy is only related to temperature which is modelled after the actual local environment, i.e. the outdoor temperature. The heat loss and temperature drop along the district heating pipe is neglected in this study; and the phase of hot water is not changed.

Exergy factor

Exergy factor is defined as the relation between exergy and energy, i.e. *E*/*Q*, where *E* is the exergy and *Q* is thermal energy or heat.

The exergy factor of energy transferred as heat at a constant temperature *T*, i.e., a heat reservoir, in an environment of temperature T_0 then becomes

$$\frac{E}{Q} = \left| \frac{T_0 - T}{T} \right| \quad (4)$$

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

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

$$\frac{E}{Q} = \frac{\int_{T_0}^{T} \frac{T - T_0}{T} m c_p(T) dT}{\int_{T_0}^{T} m c_p(T) dT} \quad (5)$$

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

$$\frac{E}{Q} = 1 - \frac{T_0}{T - T_0} \ln \frac{T}{T_0} \quad (6)$$

see the lower grey curve in Fig.1

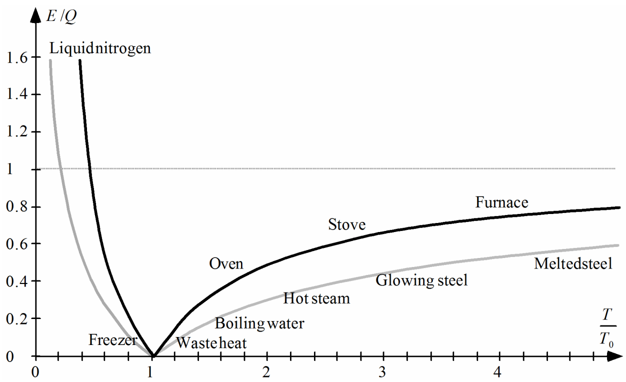


Fig. 1 Exergy factor (E/Q) of heat and cold as a function of ratio of temperature to environment temperature.

Space heating based on district heating, a network of hot water distribution for several houses and regions, is common in many colder parts of the world. The exergy factor of district heat becomes

$$\frac{E}{Q} = 1 - \frac{T_0}{T_s - T_0} \ln \frac{T_s}{T_0} \quad (7)$$

where T_s is the temperature of the supplied heat, i.e., the temperature of the hot water used by the consumer for space heating. This supply temperature in the distribution system varies from 55 ℃ to 200 ℃ [19] on different distribution systems. For a system the temperature maintained at about 85 ℃ (T_s = 358.15 K) at outdoor temperatures above +2 ℃ (T_0 = 275.15 K) and is subsequently raised in inverse proportion to the outdoor temperature, up to 120 ℃ (T_s = 393.15 K) at an outdoor temperature of below -20 ℃ (T_0 = 253.15 K). The exergy factor will thus vary with the outdoor temperature according to the lower grey curve in Fig. 2. The exergy factor is varying stepwise between about 0.10 and 0.22 when the temperature decreases from +20 to -30 ˚C.

But, since only a part of the supplied 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

$$\frac{E}{Q} = 1 - \frac{T_0}{T_s - T_r} \ln \frac{T_s}{T_r} \quad (8)$$

where T_r is the temperature of the returned water. When this is assumed as 55 °C (T_r = 328.15 K), we instead get the upper black curve in Fig. 2, which is, of course, above that of the delivered heat. As we expected the exergy factor becomes higher, since the heat now is taken out at a higher average temperature. It now varies stepwise between about 0.15 and 0.32.

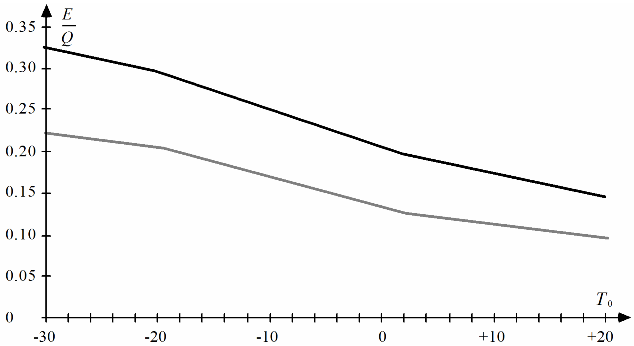


Fig. 2 Exergy factor (E/Q) of district heat.

EXERGY IN DISTRIBUTION SYSTEM

District system in Helsingborg and Marstal

As case study we will examine two district heating system: Helsingborg and Marstal district heating system.

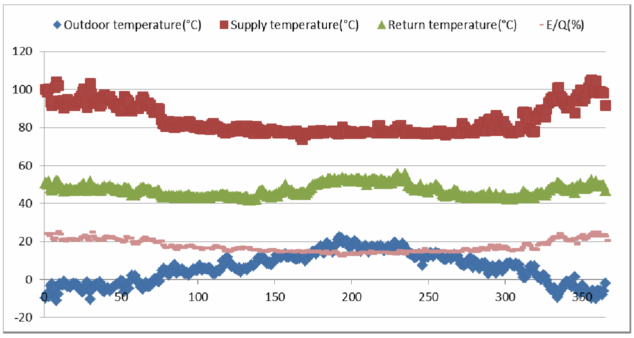
Helsingborg had a population of 129000, of which 96% lived in urban areas. During 2010, the district heating system had a heat supply of 4207 TJ to the network. The corresponding quantity of heat sold to customers was 3715 TJ, which gave a relative annual distribution heat loss of 11.7%. This heat loss share is somewhat higher than the typical average system, since 38% of all one-family buildings are connected to district heating in Helsingborg [19].

Helsingborg district heating system (shortly called Helsingborg later) mostly come from Öresunds power plant, and it had an annual average supply temperature of 84 ºC and an annual average return temperature of 47 ºC with an annual average outdoor temperature of 5.8 ºC during the analysed year.

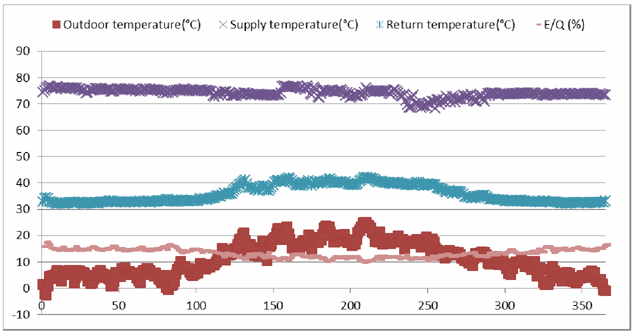
Marstal district heating system (shortly called Marstal later) is the biggest solar district heating energy system in the World; it is in operation found in Denmark at the small town Marstal. It comprises arrays of solar collectors with a total active area of 18000 m^2 are placed on the ground. Seasonal storage is performed in a large insulated pond. Marstal had an annual average supply temperature of 74 ºC and an annual average return temperature of 36 ºC with an annual average outdoor temperature of 10.9 ºC during the analysed year.

The Marstal management has hereby proven that it is possible to operate a whole district heating system very near to the theoretical supply and return temperatures. Most Swedish district heating systems obtain substantially higher return temperatures than what should be obtained from an error free substation with respect to available technology and system solutions [18].

The average supply and return temperatures of Helsingborg district heating system are 10 ºC more than Marstal district heating system. The temperature in Marstal is about 5.1 ºC warmer than in Helsingborg.



(a)



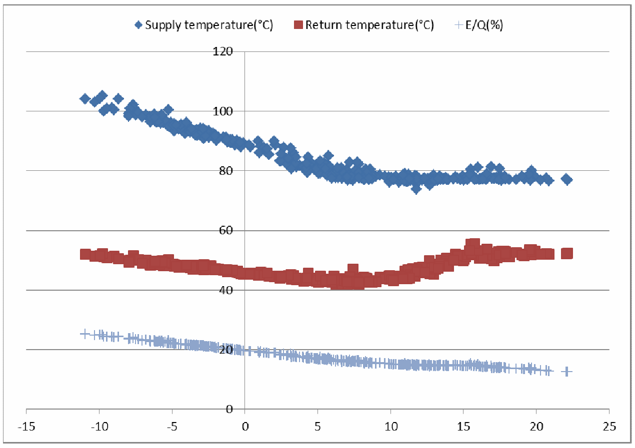
(b)

Fig. 3 Average outdoor temperature, average supply and return temperature and exergy factor (E/Q) vs. days (from 1st January to 31st of December) during one year in (a) Helsingborg district heating system, Sweden (b) Marstal district heating system, Denmark.

Figure 3 shows the average outdoor temperature, average supply and return temperature and exergy factor (E/Q) from 1st of January to 31st of the December for the two systems. The average E/Q is 0.174 for Helsingborg, and 0.133 for Marstal since the Helsingborg has higher supply and return temperature than Marstal, they use higher quality energy. The higher temperature is used, the more exergy is destroyed. From this point view, Marstal is better than Helsingborg.

Exergy factor is related to supply and return temperature and outdoor temperature as shown in Figure 4. When the outside is cold weather, the supply temperature is higher in Helsingborg as well as higher exergy factor. Let look at both systems when the outdoor temperature is around 0 ºC, the supply/return temperature is 88/45 ºC and 76/34 ºC and the exergy factor is 0.19 and 0.16 for Helsingborg and Marstal respectively. During summer season space heating is not need, the supply and return temperature is closer, the lower exergy factor, i.e. less exergy losses.

Figure 5 shows the variations take place seasonally for the daily energy and exergy loads. The energy load is more than the exergy load during to exergy is a part of energy which can be utilized. The variation of energy load is greater than the variation of exergy load. Both energy and exergy loads are minimal during summer season since only hot water need for the domestic use. However, the energy load is dropped much more than the exergy load during the low quality of energy.



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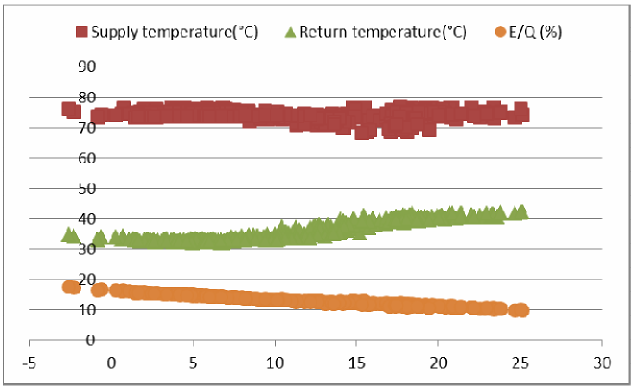


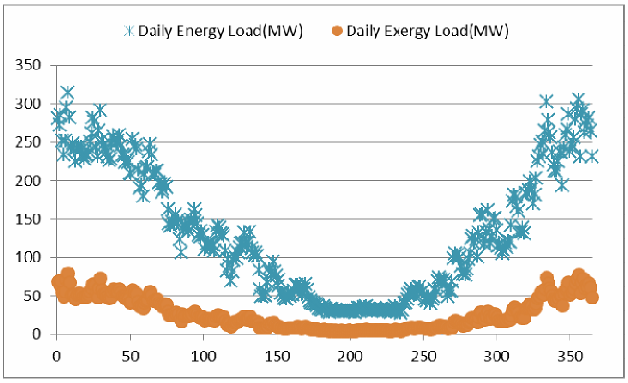
(b)

Fig. 4 Average supply and return temperature and exergy factor (E/Q) vs. outdoor temperature during one year in (a) Helsingborg, Sweden (b) Marstal district heating system, Denmark.

142 district systems in Sweden

Figure 6 shows exergy factor (E/Q) of 142 district systems in Sweden. The annual supply temperature varies from 66.7 ºC (case 41) to 115.1 ºC (case 117), and the annual return temperature varies from 37.5 ºC (case 1) to 72.2 ºC (case 142) where the outdoor temperature varies from -0.1 ºC (case 132) to 10.3 ºC (case 128) as listed in Table 1.

Among the 142 district systems the maximum exergy factor is 0.225 in case 139 which has the annual average supply/return and outdoor temperature is 110/64 ºC and 6 ºC respectively. The minimum exergy factor is 0.142 in case 4 which has the annual average supply/return and outdoor temperature is 70/40 ºC and 8 ºC respectively. The average exergy factor is 0.174.



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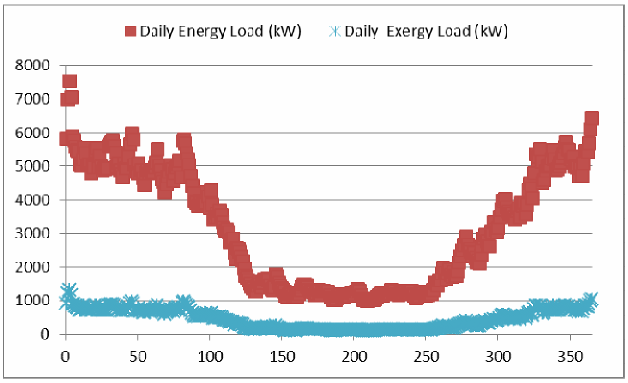

(b)

Fig. 5 Average daily energy and exergy loads vs. days (from 1st January to 31st of December) during one year in (a) Helsingborg, Sweden (b) Marstal district heating system, Denmark.

Table 1 List of cases with maximum/minimum and average of supply/return and outdoor temperature and exergy factor in 142 district system.

Case	T_s (ºC)	T_r (ºC)	T_0 (ºC)	E/Q
41	66.7	45.6	7.6	0.147
117	115.1	51.1	9.1	0.206
1	82.4	37.5	7.0	0.158
142	94.6	72.2	6.8	0.215
132	85.6	53.8	-0.1	0.203
128	80.6	53.1	10.3	0.166
4	69.6	40.0	8.0	0.142
139	110.4	64.1	6	0.225
Avg. of 142	84.2	48.1	6.8	0.174

Comparing these two systems they have similarly outdoor temperature, however, larger difference in supply/return temperature, it causes the different exergy factor. Case 139 has the highest exergy loss among 142 district systems.

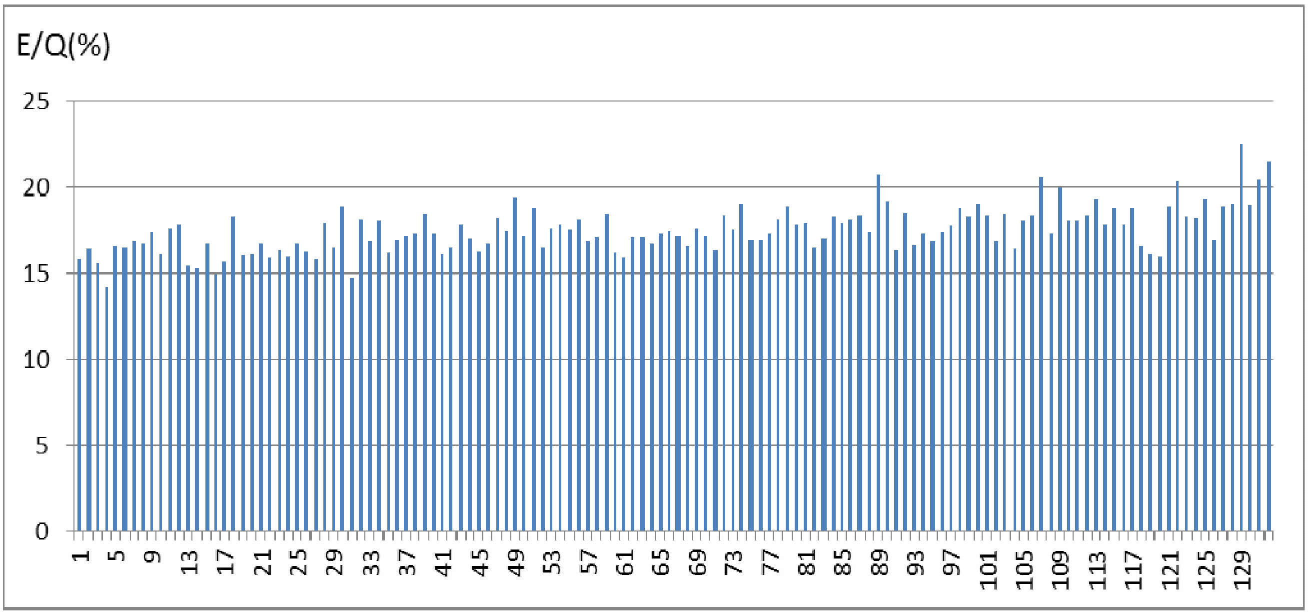

Fig. 6 Exergy factor (E/Q) for 142 district systems in Sweden.

CONCLUSION

In this paper 142 district systems in Sweden and Marstal district heating system in Denmark were examined with the exergy factor. E/Q varies from 14.2% to 22.5% for Swedish district heating systems, which the average E/Q for Marstal is 13.3%. The lower the exergy factor, the better district system is from the point of meeting the exergy need by the user, i.e., a space heating system. The exergy factor varies from system to system, and it is more related to supply and return system.

In this study the exergy loss is neglected which should be considered in future studies. Exergy analysis of the whole distribution system needs to be furthered studied in order to find out the more inefficient process.

FURTHER INFORMATION

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