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Exergy analysis of network temperature levels in Swedish and Danish district heating systems

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ABSTRACT

Exergy concept is applied on district heating systems with different network temperature levels in their distribution networks. These district heating systems use a combination of renewables and heat recovery from other primary processes. The aim is to show simplicity and value of using exergy concept when comparing current and future temperature levels. Both the traditional exergy factor and the novel exergy utilisation rate are used in these analyses. Exergy utilisation rate expresses the ratio between the exergy delivered to customer heating systems and the exergy content in heat supply input to the distribution network. The analyses are performed on four different generations of district heating technologies, two national groups of district heating systems in Denmark and Sweden for revealing variations among systems, and two municipal systems for revealing variations within systems. The main conclusions are simplifications can be introduced in order to analyse the network temperature levels, current exergy factors reveal that current temperature levels can be reduced, and that almost two thirds of the exergy content in heat supply input are lost in the heat distribution chain. These conclusion will be vital input in developing the future fourth generation of district heating systems using both renewables and heat recovery.

1. Introduction

Space heating and hot water services based on district heating, heat distribution networks for whole cities and regions, are common in many cold urban areas in the world. In Scandinavia, district heating systems cover 70–90% of the central city areas. The main purpose with district heating systems is to reduce primary energy demands with higher energy efficiency. This purpose is fulfilled by a high degree of large scale heat recovery.

The fundamental idea of district heating is then to use local energy sources that would otherwise be wasted. Due to resource depletion and climate change, renewable energies, such as geothermal heat, solar heat, and biomass, have also become more common as energy sources for district heating systems. Both heat recoveries and renewables become more efficient used, if low network temperatures are applied. Examples of such established efficient renewable processes are flue gas condensation from combustion of biomass with high degrees of moisture in Sweden, higher conversion efficiencies from solar collectors in the emerging Danish solar district heating systems, and higher utilisation of current low temperature sources of geothermal heat in Europe. Heat storages in atmospheric water tanks become also more efficient with lower temperature levels in distribution networks.

When traditional fossil fuels as natural gas and fuel oils were used for heating, less focus was directed to temperature levels in district heating systems, since high temperature levels was easy to generate from fossil fuels. Hereby, old traditions in this respect should be replaced with new ideas and knowledge. Future efficient district heating systems using heat recovery and renewables should avoid direct use of high quality energy sources in order to deliver relative low quality heat supply for low quality space heating and domestic hot water demands. District heating systems should therefore either utilise renewables with low exergy content or recover heat from primary processes that first shave off the exergy content.

Network temperature levels in current district heating systems are often too high to correspond to the actual low temperature levels of final heat demands. A proper analysis method is required to quantify and assess temperature levels in district heating systems. Traditional energy analyses usually do not give proper

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answers to energy quality lost in heat distribution networks.

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 thermodynamics. 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 exploring the goal of more efficient energy-resource use, since it enables the locations, types, and true magnitudes of wastes and losses to be determined. The applications of exergy based methods are applied in a wide number of fields. It covers energy and material balances for societies [2–5], industries [3,6], as well as biological processes [7] and ecosystems [8,9].

Earlier studies on district heating systems have rarely used exergy analyses. However, some studies of Turkish district heating system based on geothermal heat have applied exergy analyses [10–16]. The primary goal of these studies were mostly to evaluate exergy losses of main parts and compare distribution systems through exergy method in order to find the potential for possible improvements; to know the most severe exergy losses which were identified as a) natural direct discharge of the return pipe flows, b) heat exchangers, and c) pumps. Another goal was to provide comprehensive information about the design and operation of the district heating systems. These studies were focused on exergetic and exergoeconomic analyses.

Recently, some additional publications on district heating and exergy analysis have been published, e.g. Ref. [17]. In this paper, the aim was to compare energy and exergy efficiencies and to identify exergy losses for some major district heating system components. The analysis showed that large performance margins can be reduced through further reducing the exergy destruction for district hot water and space heating preparation. Further performance improvements rely on the quality match between district heating supply and customer heat demands, indicating exergy losses in heat distribution. Another conclusion was that low temperature systems can reduce the distribution heat losses.

However, most of these exergy analyses papers were using complicated exergy analyses to evaluate district heating systems, and do not consider the exergy content in the actual customer heat demands. Examples of these complications are inclusion of minor pressure drops, chemical exchanges, and temperature losses in distributions pipes.

The main purposes with this paper are to simplify the exergy losses and document the current exergy levels in some Swedish and Danish district heating systems. These purposes will be fulfilled by providing the answers to the following three research questions:

- How can exergy analyses of district heating networks be simplified without losing most important information?
- Which are the exergy contents in current heat supplied into various district heating networks?
- Which are the proportions of the exergy demands in customer heating systems related to the exergy contents in current heat supplies?

The following simplifications have been introduced: pressure drops in distribution pipes are neglected, exergy destruction due to mixing hot water with cold water by customer is out of scope, and annual or daily averages have used to describe variations among systems and within systems, respectively.

2. Exergy

Exergy is sometimes defined as work which is not correct. Work is a specific form of energy. Exergy should instead be defined as motion or the ability to produce motion [3,18]. This is certainly a less specific, but a more correct definition. Energy is also conserved in all processes, which imply the use of energy balances.

Carnot published a relation between heat and work in 1824, which Kelvin later made explicit and finally resulted in formulation of the second law of thermodynamics [19]. Gibbs expressed the general relation for work as early as 1873 [20]. But not until 1956 did Rant [21] suggest the name exergy and a general definition was given by Baehr [22] in 1965. These works became some of the important steps in the definition of exergy. Exergy is the maximum amount of work that can be extracted from a system [7]. 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 reference environment must be specified.

2.1. Reference temperature

It is important that the reference state is specified completely for an exergy analysis. This includes the temperature, pressure and chemical composition of the reference environment. In this study, no chemical compositions change and no phase change is involved except when steam heating systems are analysed. The reference temperature is set after the actual local environment, i.e. the outdoor temperature; and the reference pressure is 100 kPa.

2.2. Exergy factor

Traditionally, the exergy factor (ε) is defined as the relation between exergy and energy. Temperatures in this paper are always absolute temperatures in Kelvin degrees in all equations. The exergy factor of heat transferred at a constant temperature T in a reference temperature T_0 then becomes [18].

$$\varepsilon = 1 - \frac{T_0}{T} \tag{1}$$

Since the heat carrier temperature along the distribution pipe is decreasing, the exergy factor of a one-pipe system becomes [18].

$$\varepsilon = 1 - \frac{T_0}{T_s - T_0}\ln\frac{T_s}{T_0} \tag{2}$$

where T_s is the water temperature of the supplied heat. This supply temperature in distribution systems varies from 55 °C to 200 °C in different heat distribution systems [23]. Only a part of the supplied heat in a two-pipe district heating system is used by the consumer, since the water is returned at a temperature above the reference temperature. The exergy factor of the heat supplied from the heat supply units to the distribution networks becomes then [24].

$$\varepsilon = 1 - \frac{T_0}{T_s - T_r}\ln\frac{T_s}{T_r} \tag{3}$$

where T_r is the water temperature in the return pipe.

Fig. 1 shows an example of supply and return temperatures with corresponding exergy factors for a two-pipe district heating system