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Exergy costing for energy saving in combined heating and cooling applications

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ABSTRACT

The aim of this study is to provide a price model that motivates energy saving for a combined district heating and cooling system. A novel analysis using two thermoeconomic methods for apportioning the costs to heating and cooling provided simultaneously by an ammonia heat pump is demonstrated. In the first method, referred to as energy costing, a conventional thermoeconomic analysis is used. Here the ammonia heat pump is subject to a thermodynamic analysis with mass and energy balance equations. In the second method referred to as exergy costing, an exergy based economic analysis is used, where exergy balance equations are used in conjunction with mass and energy balance equations. In both costing methods the thermodynamic analysis is followed by an economic analysis which includes investment and operating costs. For both methods the unit costs of heating and cooling are found and compared. The analysis shows that the two methods yield significantly different results. Rather surprisingly, it is demonstrated that the exergy costing method results in about three times higher unit cost for heating than for cooling as opposed to equal unit costs when using the energy method. Further the exergy-based cost for heating changes considerably with the heating temperature while that of cooling is much less affected.

1. Introduction

Energy reduction by means of cogeneration is considered to be an effective way of reducing CO_2 emissions. Simultaneous heating and cooling systems where heat is moved from one client to another client instead of rejecting it to the environment is an example of this. By using district cooling and heating this can be realized on a large scale due to its flexibility. Several studies on simultaneous or combined district cooling and heating have been done [1–4] and many more if cogeneration is considered without district energy [5–9]. The latter studies can as well be generalized to district cooling and heating.

The premise for this study is a scenario where both heating and cooling are supplied by the same company on the same thermal system. The aim is to provide a pricing method that motivate lowest possible energy use and somehow be rational to both the heating and cooling customers. Pricing is assumed to be proportional to the cost in this study, and therefore the words costing and pricing are used interchangeably. When the thermal services (heating and cooling) are produced by the same thermal system to different customers, apportioning the costs objectively to each product individually and thereby pricing them is nontrivial.

In this study two cost apportioning methods referred to as energy costing and exergy costing are presented and compared. The first is an ad hoc energy based method. The second is an exergy based method.

The total cost of a district heating and cooling system consists of the cost of conversion and distribution; where conversion is in this case the owning and operation of the heat pump i.e. the investment and operation cost of the heat pump are included. With focus on comparison of costing methods only the conversion cost is analyzed in this study. The problem is considered as a design problem, and in the design phase the temperatures of the cooling and heating liquid are crucial for the investment cost of their respective system. Often customers demand high temperature for heating and low temperature for cooling in order to reduce their separate

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Nomenclature

c	exergy unit cost [dimension less currency (kJ)
C	fuel or product cost (dimension less currency)
$\dot{C}$	fuel or product cost rate ((dimension less currency)/s)
e	specific exergy (kJ/kg)
$\dot{E}$	exergy rate transfer (kJ/s)
$\dot{E}_D$	exergy destruction rate (kJ/s)
h	specific enthalpy (kJ/kg)
i	effective annual interest rate
$\dot{m}$	mass flow rate (kg/s)
n	number of year of payment
OH	annual operation time (h)
P	power consumption (kW) or pressure (bar)
PC	purchase cost (dimension less currency)
s	specific entropy (kJ/(kg K))
T	temperature (°C)
$\dot{W}$	power (kW)
uC	unit cost ((dimension less currency)/kW h)
$\dot{Q}$	heat rate transfer (kW)
Z	non fuel cost or capital investment (dimension less currency)

Greek letters

η	efficiency
η_{is}	isentropic efficiency

Subscripts and superscripts

c	compressor
$cold$	cooling
C, r	cooling return line
C, s	cooling supply line
co	condenser
D	destruction
el	electricity
ev	evaporator
en	energy costing method
ex	exergy costing method
F	fuel
$heat$	heating
H, r	heating return line
H, s	heating supply line
$H2O$	water
is	isentropic
j	component number
k	state
mo	electric motor
$NH3$	ammonia
P	product
tot	total
va	expansion valve
1,2,3...	state point numbers (subscripts)
0	dead state

investment cost, but this will in general increase the energy consumption in the conversion process. Therefore to promote efficient use of energy, the cost methods should be applied already in the design phase.

Several studies have been performed on apportioning the cost in multiple products thermal systems. In [10] a non-exergy based method is used for apportioning cost to electricity and heating in a monopoly company. In [11] an exergy cost accounting method with a non-exergy method is used for a co-generation of power and desalted water. In [12] it is suggested that the heating cost should also be reflected by the temperature and exergy loss and not only by the amount of heat transfer in a district heating transmission line.

The cost apportioning methods can be divided in two categories: non-exergy and exergy based. Common for the non-exergy based methods is the lack of coherency and clear structure and can therefore be called ad hoc methods. Some works recommended that cost accounting based on exergy instead of energy is the most rational way of distributing the costs to various streams of a thermal system, since exergy is the true thermo dynamic value of a stream [13–15]. This will be demonstrated in this study on a thermal system providing simultaneous heating and cooling.

The thermal system used in this study is a vapour compression heat pump using ammonia as refrigerants and water as external fluids. In practice cost accounting should be based on an economical optimized system with physical/technical constraints. Optimization has been omitted in this study to keep the focus on the accounting methods. Instead we mention the application example of a vapour compression heat pump where economic optimization based on an exergy analysis has been carried out in [16,17]. Furthermore, the concept of economic cost accounting based on exergy instead of energy can also be used for resource accounting [18].

The exergy economic methods have been developed for more than five decades in the quest for optimizing complex thermal systems. Exergy economic is often called thermoeconomic and its name was coined by professor M.Tribus in the sixties, where some of the earliest application of thermoeconomic was on seawater desalination and power generation processes [19,20]. Several branches of exergy economic have emerged and with [21–24] as some of the first structured studies. Some of these provide methods for allocating the cost to each stream of a system and can thus also be used for apportioning the product costs. One of these is known today as the SPECO method [25] which will be used in this study.

Even though cost allocation methods have been demonstrated to various complex systems with success, they have not been adopted by the utility companies for pricing their products. In addition, the comparison of an exergy cost allocation method has not been done on a thermal system providing simultaneous heating and cooling. This study will demonstrate the two costing methods on an ammonia heat pump providing simultaneous heating and cooling. The unit costs of heating and cooling with respect to the associated temperatures are to be found. As a case study the cooling capacity is fixed while the heating capacity will vary according to temperatures of the heating and cooling sides of the heat pump.

2. Model and methods

The schematic diagram of the heating and cooling ammonia heat pump system is shown in Fig. 1. The heat pump consists of four components: evaporator, compressor, condenser and valve. The evaporator and the condenser are both water coupled intended