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Thermoeconomic analysis of a building heating system

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ABSTRACT

An analysis of a high-temperature circuit of a building energy system is applied with respect to the thermodynamic- and thermoeconomic point of view. The building energy system is supplied by a micro CHP unit and two boilers in parallel. Following the second law of thermodynamics, in the thermodynamic analysis parameters can be found, which affect the magnitude of thermodynamic inefficiencies. The thermoeconomic analysis combines thermodynamic analysis with economic aspects to identify factors involved in the generation of energy costs. The used economic model is based on the Total Revenue Requirement method. As input for the analysis, data from a model of the energy system is used. To capture dynamic effects of the energy system, the system is modelled and simulated with the help of the object-oriented modelling language Modelica. The results of the simulation are afterwards analysed with the help of an evaluation tool implemented in MatLab. Highest inefficiencies and costs are related to the processes in which natural gas is burned, hence in the CHP unit and boilers. Furthermore, the charging and discharging cycles of the heat storage tank and the heat consumption units cause high inefficiencies and costs. The presented analysis can be extended to other energy systems.

1. Introduction

In the last decades, there has been a rapidly growing energy consumption due to globalization, the unbroken industrial and population growth and the increasing demand of building services. As a consequence, the concern over energy supply difficulties, the depletion of conventional fossil fuels and the environmental impact has been increasing.

The global contribution from buildings, both residential and commercial, represents between 20% and 40% of the overall energy consumption in developed countries and emerging economies. That is a consequence of the rise in the time spent inside the buildings, the development of communication networks and enhancement of comfort levels which lead to an improvement of living conditions. Among building services, the percentage of energy used in heating, ventilation and air conditioning systems (HVAC) is particularly significant (it reaches 20% of the total consumption in the USA) [14].

Furthermore, the trend for the following years shows a continuous increase in world population, CO_2 emissions and primary energy consumption. For that reason, in the building environment, the design of efficient systems has become a primary objective for energy policies in most countries and one of the most important engineering challenges.

The trend towards the reduction of production costs and boost of efficiency in energy transformation processes has promoted the introduction of more and more developed analysis- and control techniques, improvements and investment strategies which allows the installation of more efficient technologies.

Thermodynamic analysis studies the energy transformation processes which allow, according to the first law of thermodynamics, to qualify the amount of resources consumed in a determined process, and according to the second law of thermodynamics, to quantify the irreversibilities of the process. As a result, the costs of the process in consumed resources terms can be assessed and the parameters involved in the formation of thermodynamic inefficiencies are found.

However, a thermodynamic analysis itself is not enough to estimate the magnitudes of all the inefficiencies of a system, which should be studied considering fuel costs amortization, operation and maintenance costs.

Thermoeconomic analysis combines economy and thermodynamics aspects of the energy system obtaining a balance between capital costs (depreciation, return on investment, maintenance and fuels) and exergy costs (losses due to irreversibilities). Allocation of an economic cost to all the exergy flows (matter or energy) involved

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Nomenclature

c_p	levelized cost of exergy (Euro/MWh)
C	levelized cost rate (Euro/sec)
ξ	exergy efficiency
h	enthalpy flow (J/sec)
e	specific exergy (J/kg)
E	exergy rate (kW)
f	exergonomic factor
m	mass flow (kg/sec)
N	economic life of the plant (years)
p	pressure (Pa)
Q	heat flow (W)
s	entropy flow (W/K)
T	temperature (K)
t	time (sec)
v	specific volume (m^3/kg)
W	power (W)
ξ	exergy efficiency
Z	cost rate associated with an equipment (Euro/hour)

Subscripts

0	environment
av	average
CH	chemical
cond	conduction
conv	convection
D	destruction
F	fuel
In	input
iter	iteration
iss	issentropic conditions
j	jth stream
k	kth component
L	loss
LEV	levelized
m	in reference to a mass flow
Out	output
PH	physical
P	product
Q	in reference to a heat flow
sat	saturation
W	in reference to a work flow

Abbreviations

AdjV	adjustable valve
AFUDC	allowance for funds used during construction
B	boiler
CC	carrying charges
CG	consumer group
CHP	combined heat and power
NS	number of streams
Eq	equipment
FC	fuel cost
FCI	fixed capital investment
HE	heat exchanger
HS	hydraulic shunt
HV	hydraulic shunt valve
HVAC	heat, ventilation and air conditioning
OM	operation and maintenance
Mix	mixer
P	pump
PEC	purchased equipment cost
S	stream
SepV	separation valve
SR	static radiator
ST	storage Ttank
SUC	start-up costs
TCI	total capital investment
TCR	total capital recovery
TRR	total revenue requirement
TV	tank valve
ROI	return on investment
WC	working capital

in an installation allows a proper cost distribution in a multiproduct plant. Hence, economic factors involved in the generation of energy can be determined and the production cost of the system may be minimized.

The latest methodologies in engineering thermodynamics, heat transfer and engineering economics required to analyse an energy system from a thermodynamic-, economic- and thermoeconomic point of view are well established by Ref. [4]. The thermodynamic analysis is based on concepts introduced by the Second Law of Thermodynamics and the economic model is performed according to the Total Revenue Requirement method.

A lot of research has been conducted on the general application of the thermoeconomic concept in energy system analysis. Kim proposed a new methodology for cost allocation, cost optimization, and cost analysis [12]. Cardona et al. presented a simplified exergoeconomic methodology based on aggregate consumption data and on a case-oriented procedure for analysis simplification [6]. Ansari et al. performed a thermoeconomic optimization of a hybrid pressurized water reactor power plant coupled to a multi effect distillation desalination system with thermo-vapour compressor [1]. Despite the fact these studies cover a wide range of applications, there is still a need to illustrate the thermoeconomic analysis process in the building-scale, as not much research has been performed on this field. Campos-Celador et al. performed a thermoeconomic analysis to determine the location and quantification of costs in a residential micro-CHP plant [5]. Baldvinsson et al. conducted an exergy and exergoeconomic evaluation of a heat supply system paradigm of Japan and a district heating system from a single user perspective, providing cost-based information on the systems inefficiencies and improvement potential [3]. Gibson et al. undertook a comprehensive study surrounding the impact of the introduction of Australia's carbon pricing mechanism within the context of a steam turbine CHP system [10]. Bagdanavicius et al. carried out energy, exergy and exergoeconomic analysis of four Community Energy Supply systems [2]. Yücer et al. performed an exergoeconomic and enviroeconomic analyses of a building heating system using the specific exergy costing method with a low-exergy analysis [7,8].

This paper presents a systematic approach to perform a thermoeconomic analysis of building energy systems. In the course of this study, a Matlab-based tool has been developed, which is capable of performing exergy and exergeoeconomic analysis. The tool can import the simulation results produced by a building simulator; calculate the required thermodynamic properties of each stream, and realize the inputs and outputs required for exergy or exegoeconomic calculations based on the category of the