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Original article

A symbolic exergoeconomic study of a retrofitted heating and DHW facility

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ABSTRACT

Thermoeconomic analysis of building energy supply systems are usually performed following the input-output approach, where the supply chain is divided into several subsystems directly related to each other. However, in this paper Symbolic Thermoeconomics has been applied and a dynamic analysis and comparison has been performed between the old and the retrofitted heating and DHW facility of four dwelling blocks located in Bilbao.

Having obtained the heating and DHW demands, the corresponding exergy demands were calculated, both by the simplified and detailed method. Once the productive structure is defined, Symbolic Thermoeconomics is applied. The exergy analysis shows the improvement achieved with retrofitting, going from a 2.55% yearly average exergy efficiency of the old facility to a 4.01% value for the retrofitted.

Then, exergy costs and exergoeconomic costs of the products of each component, particularly the costs of the final products, heating and DHW, are expressed as the amount of external resources required for obtaining them, either in energy or monetary units. As a result, those costs not including the investment costs, are reduced 32.71% for heating and 48.5% for DHW.

Applying a general and rigorous mathematical approach, the thermodynamic nature of costs and their formation process are analysed.

Introduction

Energy analysis in buildings

One of the current main objectives of the European Union is focused on primary energy conservation and the reduction of CO_2 emissions, as a consequence of the enduring climate change the world is undergoing. Buildings are responsible for almost 40% of the final energy use in the EU and for 30% of the CO_2 emissions in the atmosphere [1], while in Spain, the built environment accounts for 28% of the final energy consumption (18% in dwellings and 10% in tertiary sector buildings) [2].

Therefore, the building sector plays an important role in the total energy consumption and many specialists are working for the improvement of buildings energetic efficiency. In recent years, great advances have been made in the application of new materials, new façades and roofs and big improvements have been achieved in the energy supply systems; particularly with the integration of renewable energies in the hybrid installations. Nowadays, the aim is to set up nearly zero energy buildings nZEB, which is the first step towards positive energy buildings. That topic has received increasing attention in recent years, until becoming part of the energy policy in several countries [3].

So far, current analyses of energy systems in the built environment are based on the first law of thermodynamics, i.e. they are performed according to the energy efficiencies and based on the primary energy input and CO_2 emissions, as in [4]; nevertheless, those analyses do not consider the different qualities of the energies and they only assume as losses those flows of energy which are not used, generally heat flows, without considering the irreversibilities related to equipment imperfections as additional loss. The quality of energy is given by a combined analysis of the first and second law of thermodynamics; these combined analyses allow deriving the thermodynamic concept of *exergy*. The exergy aspects of building systems are deeply explained in [5].

Exergy analysis in buildings

Concerning thermal facilities, a significant difference exists between the quality of the energy used for generation, as for example, in a natural gas boiler and the heating and DHW demand, where the aim is to heat a room at about 21 °C or generate domestic hot water at 60 °C. Then, high quality energy is used for producing low temperature thermal energy and, therefore, low quality energy. This situation is clearly exposed when exergy analysis is used [6], because exergy losses clearly pinpoint the locations, causes and sources of deviations from

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ideal circumstances; moreover, the exergy efficiencies measure the approach to the ideal standard. In such a way, the implementation of a low-exergy building system can be performed [7].

Thermoeconomic analysis in buildings

Most analysts agree that exergy is an adequate thermodynamic property which allocates cost because it accounts for energy quality. There are several exergy based-methods [8] and that which follows the goal of improving energy efficiency, reducing the environmental impact and enhances sustainability for the building energy analysis is *Thermoeconomics*. This is the science which connects the physics of buildings with the economy through the second law of thermodynamics [9]. Thermoeconomics suggests that the only rational basis for calculating costs is exergy. Assessing the cost of the flow streams in a plant helps to understand the process of cost formation, from the input resources to the final products.

Even though Thermoeconomics has been widely used on an industrial level [10], it has been less frequently used in the building environment. There are several reasons for this, such as the fact that the energy flows are much lower than those of thermal power plants or those of many industrial processes. In addition, the analysis uses many concepts and definitions that originated in the electrical power and chemical industries, and then, a procedure is required to establish the applicability of those concepts to the built environment. What is more, thermal levels are so low that the choice of environmental conditions can significantly impact the exergy values [11]. However, work based on building systems exergetic performance are rapidly increasing [12–14].

Symbolic thermoeconomic analysis in buildings

Symbolic Thermoeconomics (ST) is a methodology for the analysis of the *productive structure* and the natural resources consumption in energy systems. Based on the Exergy Cost Theory (ECT), it allows obtaining general equations, which relate the overall efficiency of an energy system and other thermoeconomic variables such as fuel, exergy cost, etc., with the efficiency of each component which forms it. By bringing together ECT and Symbolic Computation (using symbolic computation packages, like *Mathematica* or *Matlab*) it is possible to obtain general formulae of any energy system. Examples of ST application can be found as in the case of the control strategies study of an airport HVAC system in [15] or the analysis of co-generation with gas expansion system [16].

Building dynamic case study

The research in dynamic exergy or exergoeconomic analyses is limited. This paper deals with the energetic, exergetic and thermoeconomic comparison of an old facility and the new retrofitted one of four residential blocks in Bilbao (north of Spain) over a typical meteorological year. Instead of using the usual input-output approach which is suitable for sequential systems, in this paper we make use of ST which allows taking into account the different fictitious junction and branching points that can appear in any functional diagram of facilities.

The paper is organized in six different sections as follows. Section "Energy, exergy and thermoeconomics in buildings" briefly reviews the heating and DHW demands in buildings, goes over the associated exergy demands and refers to ST applied in buildings. Section "Case Study" presents the characteristics of four dwelling building blocks to be simulated by the dynamic simulation software Trnsys v17. This Section "Case Study" also portrays the characteristic of the heating and DHW installation, the old and the retrofitted one, as well as their control systems. In Section "Results and discussion", the conventional energy results obtained through simulation are shown and the exergy results are also displayed and compared with the energy values. In Section "Symbolic thermoeconomic study" the economic costs of the flows are obtained and the exergy costs of the irreversibilities are evaluated and discussed. Finally, the main contributions and discussion of the paper are summarized in Section "Conclusions & discussion".

Energy, exergy and thermoeconomics in buildings

Heating and DHW demands

The *heating energy demand* is calculated in this work following the ISO 13,790 (2008). According to this, the demand is based on the building characteristics, the local climate and the users' patterns. In this way, the heating demand results from the imbalance between energy losses (transmission, ventilation and infiltration) and energy gains (solar gains and internal gains) as follows:

$$\dot{Q}_{heat} = \dot{Q}_{losses} - \dot{Q}_{gains} \tag{1}$$

This balance is accomplished in every building zone and gathered afterwards for the whole building demand calculation. The balance of those thermal zones includes flows of heat and matter, such as ventilation and infiltration, but neither humidification nor dehumidification is regarded.

The energy demand for DHW supply is evaluated as a function of the required set-point temperature for DHW use and the demanded mass flow.

For an efficient use of energy in buildings, the energetic needs may be covered by using the least amount of primary energy as possible. For that, the various existing energy quality levels must be taken into account in order to use them appropriately, such as high-quality energy as electricity for lighting and electrical appliances or low-quality energy as waste heat for space heating and cooling. High-valuated energy sources may be used to cover high-valued energy demands and vice versa. This is pointed out through the *exergetic analysis* of buildings.

Heating and DHW exergy demands

Although the exergetic analysis is less common than the energetic one, authors who apply the exergetic point of view in the building sector are increasingly growing. A thorough literature review on exergy analysis in buildings is found in [17].

Several studies using air source ground source heat pumps can be found [18,19] as well as publications referring to solar thermal collectors [20]. Likewise, work analysing the exergetic performance and implementing it in simulation methodologies have been published, as in the case of a hospital trigeneration system in [21].

The *exergy demand for heating* is calculated on the basis of the heating energy demand and can be defined as the exergy content of this energy, i.e. the minimum amount of work needed to provide the energy demand for heating. In similar terms we define the exergy demand for DHW.

There are two methods for calculating the heating exergy demand: the simplified method, which is mostly used, as in [17], and the detailed exergy demand calculation method. Both of them are extensively described in Annex 49 [22]. Likewise, in the case of energy, the exergy demand for DHW is evaluated as a function of the required set point temperature and the demanded mass flow, when using the appropriate equation.

One of the aims of this paper is to show the improvement in the energy and exergy performance of the whole energy supply chain in a