EXERGY EFFICIENT BUILDING DESIGN

Proefschrift

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Contents

1. Introduction

The research work is original in the sense of applying the exergy concept to building and building services design. The applicability of existing exergy-related definitions is systematically investigated in built-environment conditions (e.g. smaller temperature differences between a system and environment), incorporated to existing exergy calculation models.

This chapter begins with the context of the dissertation to describe a relation of the research to previous research. The problem definitions, the research objectives and the research questions, are subsequently presented. After that, the research approach and methodology are described, starting with a brief overview of the exergy concept and relevance of the exergy concept to building and building services design. At the end of this chapter, the dissertation outline is given.

1.1. Context of this dissertation

This dissertation is a compilation of five peer-reviewed papers presenting the results of the first doctoral research done in the Netherlands on exergy analysis applied to buildings and building services. This topic is relatively new worldwide. In addition to publication in peer-reviewed journals, the results of this work have been presented in numerous international conferences, as listed in the publication list.

Prior to the research, there has been pioneering work done by Prof. Shukuya (1994, 1996), an architectural engineer by background, who has been studying different aspects including fenestration, building services and more recently the human body.

The exergy concept has been applied to the built environment (Shukuya, 1994; Boelman, 2002; Asada and Boelman, 2004; Sakulpipatsin et. al., 2005, 2006; Schmidt and Shukuya, 2003). Some researchers (Wall, 1986, 1990; Rosen and Dincer, 2001) have also used the exergy concept in a context of sustainable development. In the last few years, a working group of the International Energy Agency has been formed within the Energy Conservation in Buildings and Community Systems programme: "Low Exergy Systems for Heating and Cooling of Buildings" (Ala-Juusela M. (ed.), 2004; Annex37, 2002). The overall objective of the IEA Annex 37[1] was to promote the rational use of energy by means of low-valued and environmentally sustainable energy sources. This annex is being followed up by the international LowExNet group, which works towards providing knowledge on and tools for exergy analyses to be applied in the built environment (LowExNet, 2004). In addition, some of the researchers have been active in current international research projects: IEA Annex 49 and COST Action 24.

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[1] The International Energy Agency has supported an annex on low-exergy systems for heating and cooling of buildings.

1.2. Problem definitions

This item discusses necessities of exergy application for building and building services design, and gives some examples of exergy efficiencies of some HVAC[2] systems. Some impediments of using the exergy concept for building and building services design are given at the end of the item.

Buildings account for ca. 40% of final energy use in the European Union (EuroACE[3], 2005), and heating and cooling amount more than 50% of the yearly energy demand of buildings in the operational phase (EC[4], 2001). The need for energy efficiency improvement in the building sector has been addressed in the European Directive on the Energy Performance of Buildings. Buildings rely primarily on high-exergy fossil fuels for HVAC functions. Their exergy efficiency is usually less than 10% (Kilkis, 2006; Rosen and Dincer, 1997). Fossil fuels are in general employed to produce low-temperature heat. Since the fossil fuels burn at very high flame temperatures up to 2000K (Dincer and Cengel, 2001), the available work obtained by the fossil fuels is largely wasted when the fossil fuels are utilised for hot water heating, space heating, or even industrial steam production. Indoor space heating boilers have an estimated exergy efficiency of 6% and heat pumps when combined with conventional HVAC systems is not much better: 9% (Kilkis, 2006). It is unfortunate that this problem, known for a relatively long time, has not yet been addressed: the building sector with a dominant share in the annual energy use has a very low exergy efficiency of energy utilisation and thereby is polluting the atmosphere in an unnecessary way. An effective way to address this is to make use of low-exergy waste and alternative energy resources directly in temperatures compatible with new HVAC systems yet to be developed. The building sector in general has a high potential for improving the quality match between energy supply and energy demand, partly because high exergy sources are used for meeting low temperature and thereby low exergy needs.

HVAC systems can be exergy efficient if their operation temperatures are directly compatible with temperatures of low-exergy energy resources and temperatures of indoor air. At present, a radiant panel system is an alternative, which can operate at very moderate supply temperatures. But the system is limited in its ability to handle latent loads (TIAX, 2002). This limitation requires additional convective HVAC for humidity control. The hybrid HVAC System is an optimum solution as it uses different radiant and convective equipment in the same indoor space. Although the hybrid HVAC system seems to be an option for the better utilisation of low-exergy renewable and waste energy resources, they cannot eliminate equipment over-sizing and temperature conditioning. For example, the use of 45°C waste water in such a hybrid HVAC system requires 60% equipment over-sizing and a boiler to peak the resource temperature from 45°C to 55°C (Kilkis, 2006). For cooling applications, there have been efforts in Japan to develop radiant panel systems that allow surface condensation (Hirayama, 2004; Hirotani et. al., 2005).

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[2] HVAC stands for Heating Ventilation Air Conditioning.

[3] EuroACE is the European Alliance of Companies for Energy Efficiency in Building.

[4] EC stands for European Commission.

Nowadays, energy systems in buildings are designed based solely on the energy conservation principle. Nevertheless, this principle alone does not provide a full understanding of important aspects of energy use in buildings (Schmidt, 2004; Boelman and Asada, 2002, 2003; Sakulpipatsin et. al., 2006, 2007a; Itard, 2005). From this viewpoint, exergy analysis (Kotas, 1985; Szargut et. al., 1988; Ahern, 1980) can quantify the potential for improving this match, and the contribution of this match to better energy resource utilisation.

1.2.1. Why an exergy approach to building design?

Many researchers and practicing engineers refer to exergy methods as powerful tools for analysing, assessing, designing, improving and optimizing systems and processes. Benefits of exergy analysis are numerous, especially compared to energy analysis. For example, exergy methods can assist for evaluation of the thermodynamic values of the energy products. Exergy losses clearly pinpoint the locations, causes and sources of deviations from ideal circumstances in a system. Exergy efficiencies are measures of the approach to ideal. Nevertheless, exergy analysis is used only by a small group of those people. Rosen (2002) collected some reasons why it is not widely accepted by industry at present. Exergy methods might seem cumbersome or complex (e.g. choosing a suitable reference environment) to some people, and the results might seem difficult to interpret and understand.

Moreover, the analysis (Alefeld, 1988; Moran, 1989; Wall, 1990; Krakow, 1991; Bejan 1997) uses many concepts and definitions (e.g. efficiency, reference conditions) that originated in the electric power and chemical industries. Systematic analysis is required to establish the applicability of these concepts to the built environment. Also, exergy is often perceived as a highly complex concept. Furthermore, some practicing engineers have simply disbelieved exergy methods to lead to tangible, direct results.

Consequently, concrete examples of exergy analyses and calculation frameworks specifically developed for the built environment are needed to make the concept more familiar and usable to the building profession.

1.3. Research objectives and research questions

This research aims at developing knowledge into the applicable domains and potential added values of exergy analysis in the built environment, by studying under what conditions exergy could function as a useful concept for the built environment.

Research question Q1, as the main research question, is concerned with the potential added values of developing exergy analysis for buildings and building services, in particular HVAC systems. Research questions Q2 to Q4, as the specific research questions, are in line with the research approach and methodology (described in item 1.4), and address the development of specific knowledge and insight into potentially applicable domains. These research questions are answered in chapter 7, based on the results of the work described in chapters 2 to 6.

Q1. Under what conditions could exergy function as a useful concept for the built environment?

  a. What is the potential relevance of the exergy concept for integrating building and HVAC system design?

  b. What are possible advantages and disadvantages of incorporating exergy analysis into energy building system designs and indoor climate conditions?

  c. What can building designers learn from an exergy analysis that they could not learn from an energy analysis?

Q2. Which metrics can be used to quantify and express exergy values in buildings and HVAC systems?

Q3. To what extent do existing exergy knowledge and definitions require adaptation in order to be meaningfully applied in buildings and HVAC systems?

Q4. Which are the relevant parameters, precision and aggregation levels required by a calculation framework comprising energy and exergy analyses for integrated building and HVAC system design?

1.3.1. Energy, exergy, and built environment

The growing concern of environmental problems has amplified both the significance of all kinds of energy saving measures, and the inevitability for an increased efficiency in all forms of energy utilisation. Despite plenty of efforts made to improve energy efficiency in buildings, the issue of gaining an overall assessment and comparing different energy sources still exists. At present, analysis and optimisation methods do not differentiate between different qualities of energy flows in building-related applications (Schmidt, 2004).

The exergy analysis method is well known for optimisation of energy conversion in large industrial and power plants (Zhang et. al., 2006; Zvolinschi et. al., 2006). Exergy analysis can help building designers meet functionality and comfort requirements while keeping the associated energy resource depletion to a minimum (Alpuche et. al., 2005; Prek, 2006). Exergy provides a common basis for comparing the energy performance of systems associated to buildings and to building services (Schmidt, 2004; Annex 37, 2002; Action C24, 2006). For example, exergy analysis allows a designer to compare on the same basis between heat supplied by a fuel (e.g. through a boiler) and by solar heat (e.g. through a window). It also allows comparison between e.g. the electricity required by a mechanical ventilation system and the thermal energy savings resulting from the use of a heat recovery unit (Sakulpipatsin et. al., 2007a). This information can assist designers in integrating building and building services design, so as to meet user requirements with a minimum depletion of energy resources.

In the theory of thermodynamics, the concept of exergy is stated as the maximum work that can be obtained from an energy flow or produced by a system. The exergy content expresses the quality of an energy source or flow. This concept can be used to combine and compare all flows of energy according to their quantity and quality. Unlike energy, exergy is always destroyed because of the irreversible nature of energy conversion process. The exergy concept enables us to articulate what is consumed by all working systems (e.g. man-made systems like thermo-chemical engines and heat pumps, or biological systems including the human body) when energy and/or materials are transformed for human use.

Exergy analysis can give insight into the extent to which the quality levels of energy supply (e.g. high-temperature combustion) and energy demand (e.g. low-temperature heat) are matched. High-valued energy such as electricity and mechanical work consists of pure exergy. Energy which has a very limited convertibility potential, such as heat close to room air temperature, is low-valued energy. Low exergy heating and cooling systems allow the use of low-valued energy, which can be delivered by sustainable energy sources (e.g. Kilkis, 2006; Xiaowu and Ben, 2005; Torres et. al., 1998). Most of the energy needed for heating and cooling is used to maintain room air temperatures around 20°C. In this sense, because of the low temperature level, the exergy demand for applications in room conditioning is naturally low. In most cases, however, this demand is met with high quality sources, such as fossil fuels or using electricity. Exergy analysis provides us with additional information on where and when the losses occur. It helps us to see in which part of the energy chain the biggest savings can be achieved (Schmidt, 2004).

This also explains partly the resistance which is felt by engineers and consultants to use exergy as a tool. It clearly shows the sometimes extreme low exergy efficiencies of common systems like burning gas to heat at near environmental temperatures. In these cases exergy analysis is however at its strongest. It leads to the inevitable conclusion that certain processes or systems, however widely accepted and applied, are fundamentally wrong and should be replaced by more exergy efficient ways. This however contradicts the interests of huge industries and gas companies.

1.4. Research approach and methodology

This item gives an overview of the exergy concept and presents some definitions of exergy from literature, followed by an approach adopted in this research. The approach rests on three main pillars. These pillars are integrated into two levels of HVAC and building systems. Details of the research approach are given in the second part of this item.

1.4.1. Thermodynamics, exergy and buildings

The basis of thermodynamics is stated in the first and second laws. The first law is concerned with the conservation of energy, whereas the second law is concerned with the dissipation of energy (Bruges, 1959). The first law of thermodynamics states that energy is conserved, and makes no distinction between different energy forms (e.g. heat and work). The second law, on the other hand, allows energy quality levels to be quantitatively valued (Kyle, 1999) and rank-ordered. It also asserts that accessible work potential is always lost in any real process, and provides a measure of the loss in all real energy transformation processes (Connely and Koshland, 2001).

Exergy is not subject to a conservation law, but can be lost when or where the quality of energy is degraded, due to irreversibility in any process. Exergy analysis is a method that applies the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the design and analysis of energy systems. The exergy analysis is used to estimate the theoretically ideal operating conditions of a system, and the extent to which a real system deviates from the corresponding ideal performance (Bejan, 1997). The exergy method can be suitable for furthering the goal of more efficient energy resource use, for it enables the locations, type and true magnitudes of wastes and losses to be determined (Connely and Koshland, 2001).

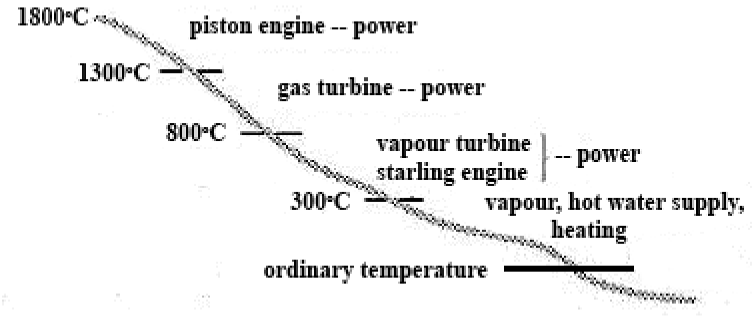
Generally speaking, exergy is essentially related to work potential and quality changes of energy and matter in relation to a pre-defined environment. Nevertheless, many various authors choose to emphasize specific aspects in their definitions, depending on the objective and scope of their analysis.

> "Exergy is the maximum theoretical work that can be extracted from a combined system consisting of the system under study and the environment as the system passes from a given state to equilibrium with the environment - that is, passes to the dead state at which the combined system possesses energy but no exergy.'' (Moran, 1989)
>
> "Exergy is the minimum theoretical useful work required to form a quantity of matter from substance present in the environment and to bring the matter to a specified state. Exergy is a measure of the departure of the state of the system from that of the environment, and is therefore an attribute of the system and environment together." (Bejan, 1997)
>
> "The property exergy defines the maximum amount of work that may theoretically be performed by bringing a resource into equilibrium with its surroundings through a reversible process." (Connely and Koshland, 2001)
>
> "Exergy is the concept, which quantifies the potential of energy and matter to disperse in the course of their diffusion into their environment, to articulate what is consumed within a system." (Ala-Juusela M. (ed.), 2004)

The classical exergy concept enables us to pinpoint the location, to understand the cause, and to establish the true magnitude of waste and loss upon energy conversion. Exergy analysis approach is therefore a vital tool for system designs since it provides designers with answers to two important questions of where and why system losses occur. The designers can then proceed forward and work on how to improve the system.

Exergy often appears as heat and cold; thermal exergy can be in general described by temperature differences from the environment in some outdoor climate conditions (Sakulpipatsin et. al., 2007b). Exergy reflects better than energy that heat or cold becomes more valuable at temperature levels further from the environment. Figure 1.1 shows that high-temperature heat can be converted into electric power, and also illustrates how close hot water supply and space heating temperatures are to environmental temperature.

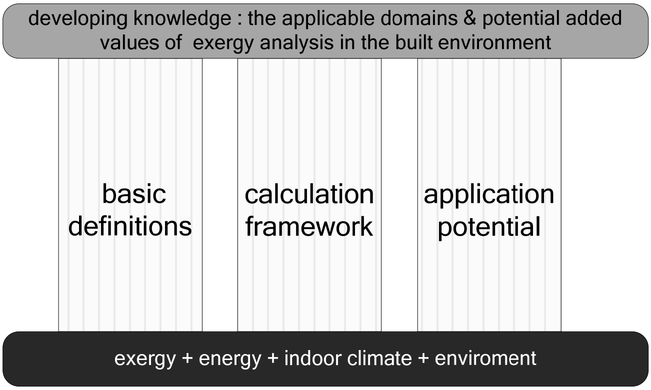
Figure 1.1 The usefulness of heat at different temperatures (Hirata, 1997)



1.4.2. *Approach adopted in this research*

The research rests on three main pillars, as shown in Figure 1.2.

Figure 1.2 The research scheme



1. <u>Basic definitions</u>: many exergy-related definitions (e.g. exergy efficiency and reference environment) have been developed for use in the electric power and chemical industries. Their applicability to built-environment conditions (e.g. smaller temperature differences between a system and environment) is investigated in pillar 1.
2. <u>Calculation framework</u>: existing exergy calculation models tend to allow detailed investigation of parameters related to either the building or the HVAC systems, but not to both. An energy and exergy calculation framework is developed in pillar 2 for use with a number of integrations between building design concepts and HVAC systems (e.g. a heat recovery unit in balanced ventilation systems, low-temperature heating and high-temperature cooling systems in a number of building design concepts).
3. <u>Application potential</u>: in a small but important pillar, the calculation models are applied to integrated systems in buildings (e.g. heat recovery of dwelling ventilation systems, district heating systems and cooling machines) and HVAC components (e.g. heat exchangers and heat pumps). This provides concrete

examples of insights that can be gained from exergy analysis, and shows how these insights differ from what can be learned from energy analysis.

These three pillars are integrated into two levels: namely “HVAC components and systems” and “building systems”. A brief overview of the main tasks is given below; in relation to the research questions (item 1.3).

HVAC components and systems:

This part entails the set-up of a conceptual analysis framework and application of the exergy concept to HVAC component and system design. It collaborates with some outputs from the IEA Annex 37. This part focuses on research questions Q1 to Q3.

Critical analysis of basic exergy definitions and their applicability to HVAC systems in built environment conditions is systematically carried out at component level (e.g. heat exchanger and heat pump) and at system level (e.g. mechanical exhaust ventilation with natural air supply and balanced ventilation with heat recovery). Results of the analysis are discussed, by using defined metrics, to potential relevance and application possibility of the definitions to the built environments.

Building systems:

This part integrates the conceptual analysis framework, developed in the previous part, with a conceptual analysis framework of exergy in buildings. This part targets research questions Q1 to Q4.

An analysis framework to study the influence of possible definitions of a reference environment is introduced to determine the exergy of air in buildings. Then calculation models of exergy uses in buildings and building services are developed and make use of an extended built-up model in which the energy balance is considered from the demand side to the supply side, developed by Sakulpipatsin et. al. (2006) and Bezuijen (2006). The calculation models are applied for sensitivity analysis of thermal exergy demands in a building to changes of building envelope properties, and sensitivity analysis of exergy losses in building services to changes of system operations like temperature levels, in the climate of the Netherlands. At the end, some analysis results of energy and exergy of the building and building services are given in order to summarise the uses of the exergy concept in buildings and the built environment.

1.5. Dissertation outline

For the purposes of this dissertation, the exergy concept can be understood as a potential of matter to cause change, as a result of not being entirely stable relative to a reference environment. Its operational definition for this thesis is defined in chapter 2, item 2.

The quantity of exergy depends on the state of the system and on the condition of the environment. The state of the reference environment must be given for exergy analysis. This is regularly done by specifying the temperature, pressure and chemical composition of the reference environment. Past research (Wepfer et. al., 1979; Liley, 2002) lacks a clear and accessible framework for quantifying exergy of humid air allowing for changes in environmental air temperature. In chapter 2, an analysis framework to study the influence of possible definitions of a reference environment is introduced to determine the exergy of air in buildings. Chapter 2 analyses the influence of possible definitions of the standard state of air, to determine the exergy of air in buildings, taking into account thermal, chemical and mechanical contributions. It discusses the importance of these contributions and the possibilities to determine the conditions at which it is allowable to assume that air contains no water vapour. In addition, the exergy calculations of dry air are compared with exergy values based on the assumption of using annual statistical values of the indoor and outdoor air temperatures. This chapter is related to research questions 3 to 4. This analysis framework has been accepted to be published in the international journal of exergy.

Exergy efficiencies are often defined considering the intended application of a given system under specific conditions, and therefore the definitions frequently lack uniformity. Several authors have provided definitions for exergy efficiencies (Semenyuk, 1990; Sorin and Brodyansky, 1992; Tsatsaronis, 1993; Kotas, 2001) on the large scale of energy supply systems. Woudstra (2002) distinguishes two different kinds of exergy definitions: the universal ones in which gross exergy inputs and outputs are considered, and the functional ones in which net exergy flows are considered respectively. To the best of current knowledge, there is a deficiency of systematic approach to be able to apply exergy efficiency definitions for buildings and building services, and there is a very limited knowledge on the efficiency behaviour for buildings and building services at near environmental conditions. Chapter 3 and chapter 4 critically analyse the exergy efficiency definitions for all-air HVAC system components operating at near environmental and indoor conditions. Chapter 3 deals with investigation of which relevant information the functional exergy efficiency definition provides for selection and operation of sensible heat exchangers for indoor climate control in space heating applications. It focuses on the exergy analysis of a simplified sensible heat exchange process for heating applications, by varying temperatures and heat transfer rates, considered simply in terms of exchanger heat transfer effectiveness. Chapter 4 critically analyses the universal and functional exergy efficiency definitions for a simple vapour-compression heat pump cycle for space cooling applications, by varying temperatures and internal irreversibility, considered simply in terms of the second-law efficiency. A dimensionless temperature is used to illustrate the analysis results, and to discuss the sensitivity of the exergy efficiency definitions to temperature variations for the HVAC system components. These chapters are related to research questions 1 to 4. The analysis results of the exergy efficiency definitions for the air-to-air heat exchangers have been accepted to be published in the international journal of exergy.

In cold and moderate climates, improvements in building shell insulation and air-tightness imply a shift in heating loads from transmission and infiltration towards ventilation. Heat recovery from ventilation airflow plays an increasingly important role in minimising energy needs. Such heat recovery systems rely on the input of electric power (to drive fans, heat pumps, etc.) in order to recover thermal energy. Since electricity input is relatively small compared to the amounts of thermal energy recovered, such systems are efficient from an energy viewpoint. One important yet often overlooked aspect, however, is the difference in ‘quality’ between the high-grade electricity input and the lower grade thermal energy recovered. Chapter 5 presents steady-state energy and exergy analyses for dwelling ventilation with and without air-to-air heat recovery, and discusses the relative influence of heat and electricity on the exergy demand by ventilation airflows. Energy and exergy analysis results for De Bilt, the Netherlands, are presented in terms of heat and electricity, on an instantaneous and a daily basis. Chapter 5 is related to research question 1. The steady-state energy and exergy analyses for dwelling ventilation have been published in the international journal of ventilation.

Chapter 6 introduces an integrated and dynamic method for energy and exergy analysis of buildings and building services, since at present there is no ready-to-use dynamic model for exergy calculation over the entire energy demand and supply chain in the built environment. The method is intended to enable building designers (and building engineers) to compare between the impact of improvements in the building envelope and in building services. The method is demonstrated with a building in a cold climate and used for investigation of thermal exergy and thermal energy demands of the building and thermal energy and thermal exergy losses in the building services when some parameter values of the building and the building services are changed. This study is an initial attempt of the sensitivity analysis of the exergy values in a building and building services. This chapter is related to research question 1.

Chapter 7 finally recapitulates the findings from the previous chapters and concludes with recommendations for further research.

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