Summary

The concept of exergy is stated as the maximum work that can be obtained from an energy flow or produced by a system. The fraction of 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 during conversions because of the irreversible nature of energy conversion process. The exergy concept enables people 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 convertible potential, such as heat close to room air temperature, is low-valued energy. Low exergy heating and cooling systems therefore allow the use of low-valued energy, which can be delivered by sustainable energy sources, as well. However, in most cases, the low-valued energy demand is met with high quality sources, such as fossil fuels or using electricity.

Many researchers and practicing engineers refer to exergy methods as powerful tools for developing and optimizing systems and processes. 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 only used by a small group of people, because the analysis method 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.

In building profession, the exergy concept has been applied to the built environment. Some researchers 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; IEA Annex 37”. The overall objective of the IEA Annex 37 was to promote the rational use of energy by means of low-valued and environmentally sustainable energy sources. This PhD research has been carried out in close collaboration with the international LowExNet network of exergy researchers, which is a follow-up of the annex. During the course of the PhD research, the COSTeXergy project (COST Action 24) and the EOS-LT project (entirely financed by SenterNovem) were initiated and have been running. In addition, research outputs of the PhD research have served as inputs to the formulation of the annex on low exergy systems for high-performance buildings and communities (IEA Annex 49).

The objective of this PhD research is to develop 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. The research is carried out in the levels of HVAC components and systems and of building systems, and provides metrics that can be used to quantify and express exergy values in buildings and HVAC systems.

Firstly, the influence of possible definitions of the standard state of environmental air are critically analysed in order to determine the exergy of air in buildings. The exergy value of air entails three contributions, a thermal one related to the air temperature, a mechanical one related to the air pressure, and a chemical one related to the humidity ratio of the air. The possibility to calculate the exergy of air in buildings, based on only one or two of these contributions, for example expressed by a characteristic air temperature and/or air as dry air, is explored for three different locations on earth. These values are compared to those calculated using hourly statistical climate data during one year. The results show that it is acceptable in some climates to consider a static reference environment only, instead of a dynamic reference environment, for calculating the exergy value of air in buildings for a year. In a cold climate, the exergy value of the air strongly depends on its thermal contribution. Accordingly, the outdoor air temperature might be sufficient as a reference environment for the exergy calculation. This is not acceptable for the exergy calculation in a hot and humid (or temperate sea) climate, where the chemical contribution to exergy due to moisture can be substantial.

Secondly, exergy analysis is carried out for HVAC components and systems.

In the level of HVAC components, critical analyses of exergy efficiency definitions are carried out for air-to-air sensible heat exchangers and vapour compression heat pumps. The exergy efficiency definitions that were studied in the work are: the universal ones in which gross exergy inputs and outputs are considered, and the functional ones in which net exergy flows are considered respectively. A dimensionless temperature is defined and used to illustrate the analysis results. The dimensionless temperature expresses a distance between the hot (or cold) inlet air temperature and the environmental air temperature, relative to the inlet air temperature difference. These analyses resulted in a better understanding of exergy values and of the sensitivity of exergy efficiency definitions applied to these equipments operating at near environmental temperatures.

The functional exergy efficiency in combination with the dimensionless temperature can be used as a guide for selecting temperatures to operate heat exchangers near environmental temperature in an exergy efficient way. The functional exergy efficiency shows that not only heat exchanger performance (expressed in terms of exchanger heat exchanger effectiveness), but also the relationship between temperatures (in the heat exchanger and of the environment) is important to operate the heat exchanger efficiently. The analysis for the air-to-air sensible heat exchangers can be useful when designing a heat exchange system, for example when deciding between using a heat exchanger of higher exchanger heat transfer effectiveness and pre-heating the outside air (e.g. by using a sunspace or the underground).

The functional exergy efficiency is also recommended to be used as a performance criterion for the heat pump for space cooling application, especially when the temperature of the environmental air is between the inlet temperatures of the hot and cold air streams and also close to the inlet temperature of the hot air stream.

In the level of HVAC systems, energy and exergy analyses for dwelling ventilation with and without air-to-air heat recovery, in winter conditions in the Netherlands, are presented. The analyses are carried out on an instantaneous and a daily basis. The analysis results show that, from the viewpoint of total exergy consumption (which is the summation of thermal exergy by a ventilation airflow and electricity exergy by a ventilation unit) at room level, it could make sense to use heat recovery only when the environmental air temperature is low enough to compensate the additional need for electricity, when the temperature of the environmental air is not too low let ventilation air bypass the heat recovery unit, or if possible by operating the heat recovery unit at low ventilation airflow rate. Nevertheless, the ventilation airflow rate must be qualified to guarantee the indoor occupancy conditions.

Lastly, a method for energy and exergy analysis of a building and building services is proposed. The analysis is based on a build-up model from the energy demand of the building side to the energy supply side. This method is intended to enable building designers (and building engineers) to compare, in terms of exergy, the impact of improvements in the building envelope and in building services. In addition, some examples of the energy and exergy analysis of the building and its building services with some changes of their parametric values are studied by using the building simulation tool TRNSYS. The analysis results show that, in terms of exergy, solar exergy gains in a cold day create the main exergy losses when cooling is needed. These solar exergy gains should be minimized, or better captured to be useful somewhere else e.g. for domestic hot water production or electricity generation. Exergy losses in the building services depend on a temperature level of the thermal energy supply and (electric) auxiliary energy required by the building services, and this is applicable for both heating and cooling cases.

This research provides knowledge that is essential to future development of design instruments and guidelines for exergy efficient building and building services design. Yet, the exergy analyses for the HVAC components and systems and for the building systems are carried out only with outdoor conditions of a cold climate. The exergy analyses for other climates are excluded from this study, since the standard states of environmental air in different climates for the analyses are not similar and should be carefully defined in a proper way. In addition, buildings in different climates are mostly designed in different ways. Exergy in buildings and building services, where they have other different and more complex types, is an interesting topic to study in the near future, and at the same time the knowledge obtained from the research should be disseminated to students and practitioners in a field related to building and HVAC system design.

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