Exergy and sustainable building

Article

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Introduction

Different authors have advocated using the exergy concept as a sustainability indicator (Rosen, 2001; Wall, 2001) while others have inspired their building designs on exergy (Kristinsson, 1999; Wall, 1998). In the field of building research, pioneer work is ongoing in Japan (Shukuya, 1994, 1996, 2001) towards applying the exergy concept to the built environment. The International Energy Agency is also supporting an annex on low-energy systems for heating and cooling of buildings. The general objective of Annex 37 is to promote rational use of energy by means of facilitating and accelerating the use of low valued and environmentally sustainable energy sources for heating and cooling of buildings (IEA, 2002).

Strictly speaking, exergy is a fairly complex thermodynamic principle. The aim of this paper is to enhance the understanding of exergy by those in the building profession. To this end, two examples of sustainable-house design are discussed first, followed by a concise introduction to the exergy concept. The exergy concept is then used to indicate how the quality (or ‘value’) of thermal energy relative to the environment, can be evaluated in terms of exergy. Finally an outline is presented of previous research on the exergy of heat and light, to illustrate the concept of exergy consumption.

Exergy and housing design

Architect Jón Kristinsson has made a prize-winning design for an exergy home in The Netherlands. The design comptition Exergy Home, held in 1996, was part of a larger Exergy Pilot Project for the Knooppunt Arnhem-Nijmegen location (KAN) in The Netherlands. The KAN region has been designated for future development as a so-called Vinex[1] location, where ca. fifty thousand new homes are to be built in a period of twenty years. One project target was to investigate to what extent the urban planning process can incorporate an integrated energy infrastructure, based on the exergy approach. Such an approach entails efforts to avoid degrading the quality of energy, for example through the use of waste-heat from industry and electric power plants for district heating. A special workgroup was formed for the exergy study in 1993 (with members from Dutch energy utilities and ministries), with the task of investigating the possibilities and limitations of the exergy approach. (ECN, 1993).

The Exergy Home design competition attracted considerable attention, circa four hundred inquiries for information having been reported. The winning design should be applicable not only to the KAN region, but also to other Vinex locations. Such locations are regarded as highly suitable, because of the lack of a previously existing

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[1] VINEX was the 1990's Dutch government answer to growing demand for housing, an abbreviation for the Fourth Policy Document on Spatial Planing Appendix (VIerde Nota ruimtelijke ordening EXtra). The idea was to "limit suburbanisation" by concentrating housing at the edge of existing cities. A VINEX location is itself a suburb, though.

energy infrastructure. The designs submitted to the competition highlighted several aspects related to energy and occupant comfort: thermal resistance; thermal bridges; relative humidity; shading coefficient and; low-temperature heating, among others.

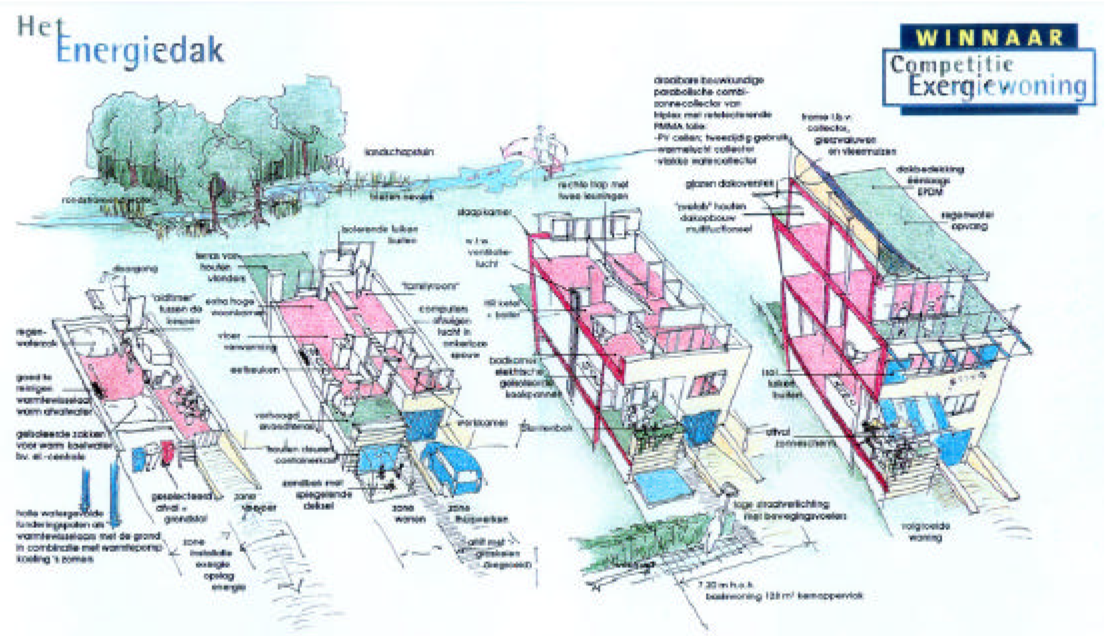

Fig. 1 The exergy home (Kristinsson, 1999)

Jón Kristinsson's design incorporated several energy-saving features to his design, as shown in Fig. 1. The exergy homes feature hollow piles in which ground water can be pumped up, with a yearly average temperature of 10 °C. In winter a heat pump is used to raise the water temperature, while in summer the relatively cold water can be used as a cold source. The house also incorporates a parabolic solar heat collector on the roof for warm tap water, and seasonal heat storage around the water-filled piles in the ground. Solar cells are used for electricity supply, while roof lights, sun bay windows and sun reflectors are incorporated to make use of passive solar energy. Shutters are placed in front of the windows for additional insulation of the façade.

Another award-winning house, the Ouroboros Project (Fig. 2), began as a design project under the supervision of an architecture professor at the university of Minnesota (Holloway, 2001). 160 students contributed designs and labor toward what has been described as an evolving laboratory for energy conservation and self-sufficiency. Already in 1973, the house incorporated a sod roof, active solar hot water heaters for space heat, a wind powered electric generator, a composting toilet, and an enclosed sewage system for recycling water and wastes. In 1976 Professor Holloway was awarded the Environmental Quality Award in Science and Technology from the United States Environmental Protection Agency for his pioneering work on Project Ouroboros. The project also resulted in his career becoming a subject of record in Marquis Who's Who in Frontier Science and Technology (First Edition 1984-85).

Fig. 2 The Ouroboros house (Holloway, 2001)

The project targeted self-reliance, and was inspired by the ancient Greek mythical serpent, *Ouroboros*, that survived by eating its own tail. Almost three decades later, Exergy researcher Marc Rosen took an interesting look at the *Ouroboros* tale from the viewpoint of thermodynamics and exergy. While praising the Ouroboros house an as example of sustainable design, Rosen (2001) argued that the mythical Greek serpent could not have survived without having an impact on the environment. The serpent's existence would not have violated the first law of thermodynamics (which states that energy is conserved), but would have violated the second law (which states that exergy is reduced for all real processes). Assuming that the serpent *Ouroboros* was an isolated system (i.e., it received no energy from the sun or the environment, and emitted no energy during any process), its existence would have violated the second law of thermodynamics. This is because *Ouroboros* would have had to obtain exergy externally to regenerate the tail it ate into an equally ordered part of its body (unless it was a reversible creature, it would otherwise ultimately have dissipated itself to an unordered lump of mass).

This reasoning can be extrapolated to the Ouroboros house: although environmentally benign and relatively self-sufficient, its very existence implies inputs of energy (e.g. sunlight) and materials. These inputs are eventually degraded (e.g., sunlight into heat, materials into waste) and disposed into the external environment. Like the serpent's tail, these flows of degraded energy and materials cannot be regenerated into their original state (e.g. low-temperature heat will not be spontaneously restored into sunlight). The second law of thermodynamics provides means for dealing with the phenomenon of irreversibility, and the exergy concept is instrumental in expressing and quantifying the notion of energy resource degradation and consumption.

Exergy: the quality of energy

Energy is a familiar notion; we know that energy can be stored within systems (e.g. heat storage), transformed from one form to another (e.g. electricity into heat) and transferred between systems (e.g heat transfer through a building envelope). The first law of thermodynamics states that the total amount of energy is conserved in all transformations and transfers (Moran and Shapiro, 1998). For example (see Fig. 3), in order to keep the indoor temperature T_{in} constant, the heat loss Q_{out} through the building envelope has to be compensated by an equal quantity of thermal energy supply indoors (SQ_{in}). The idea that energy can neither be produced nor consumed is contrary to the familiar notion of energy resource depletion, however: if energy quantities are always in balance, how can there be an energy crisis?

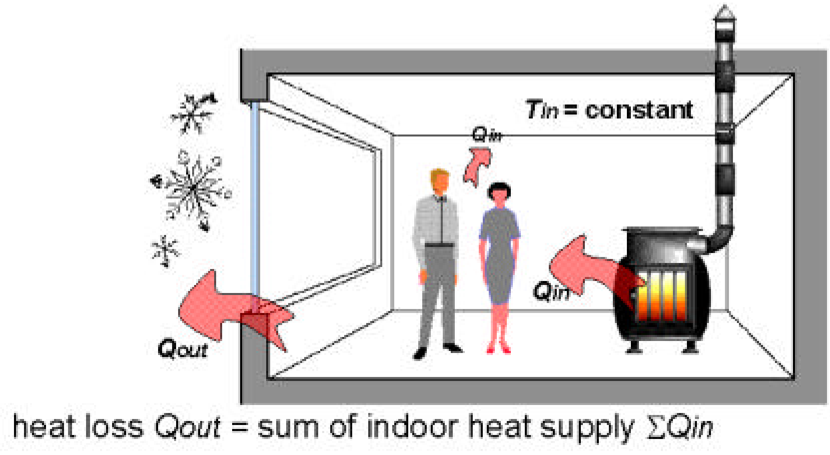

Fig. 3 Energy conservation

Strictly speaking, the familiar expressions "energy consumption", "energy saving" and "energy conservation" are not accurate, since they imply violating the first law of thermodynamics. Intuitively, we understand that something is being consumed when we burn (fossil) fuels to obtain electricity or heat, even though the amount of energy is conserved throughout the process. Shukuya (2001) contends that the thermodynamic concept exergy is needed to articulate what is actually being consumed. This concept is derived from the second law of thermodynamics.

The second law of thermodynamics provides guiding principles to deduce whether certain processes can occur spontaneously, and also in which direction they are likely to take place. For example, we know that falling from a higher to a lower height is a spontaneous process (e.g. a waterfall), but that rising from a lower to a higher height requires an input of work (e.g. water pump).

When left to themselves, systems tend to undergo spontaneous changes until a condition of equilibrium is achieved, both internally and with their surroundings. For example, we know that an ice cube left outside a freezer will gradually melt (if the surrounding temperature is above 0°C), and eventually evaporate (if the surrounding air is not saturated with water vapor). We also know that water from a waterfall will stop falling once it attains a lower plateau, and that it may also slow down substantially if it falls into a very large lake. All these processes are driven by an imbalance with the surroundings (e.g. by a difference in temperature, partial vapor pressure or height), and will cease once equilibrium is attained with the surroundings.

By exploiting spontaneous processes it is possible, in principle, for work to be developed as equilibrium is attained. For example, the kinetic energy from a flow of water may be used to drive a turbine for obtaining electricity (Fig. 4).

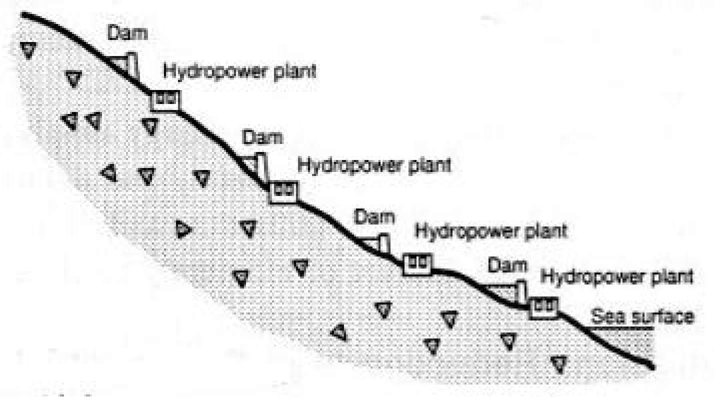

Fig. 4 The force of falling water over different heights (Hirata, 1997)

From a thermodynamic viewpoint, exergy can be defined as the maximum amount of work that can be produced by a system (or by a flow of matter or energy) as it comes to equilibrium with the reference environment (Çengel et al., 2002). Exergy recognizes that the energy that is carried by substances can only be used 'down' to the level that is given by the environment; exergy hence gives an upper limit to the work that is extractable from any process (Wall and Gong, 2001). The exergy of an energy form or substance is a measure of its usefulness, quality or potential to cause change, as a result of not being completely in stable equilibrium with the reference environment. Unlike energy, exergy is not subject to a conservation law, except for ideal processes; rather, it is consumed or destroyed in any real process. (Rosen and Dincer, 2001).

If exergy is defined as the maximum work potential of a material or a form of energy in relation to its environment, then the environment must be specified. Usually, average values of the earth are selected, i.e. a reference temperature T_0 of 298.15 K (25°C) and a reference pressure of 1 atm. However, the earth is not in equilibrium; temperatures vary from place to place and also in time. For systems near environmental temperature (e.g. space heating or cooling), one should use local temperatures (Wall and Gong, 2001) for the season or even the time of the day being considered.

Thermal exergy

Exergy often appears as heat and cold; thermal exergy can be described by temperature differences from the environment. Exergy reflects better than energy that heat or cold becomes more valuable at temperature levels further from the environment. Fig. 5 shows that high-temperature heat can be converted into electric power; the figure also illustrates how close hot water supply and space heating temperatures are to environmental temperature. This is shown in more detail in Fig. 5 and Fig. 6.

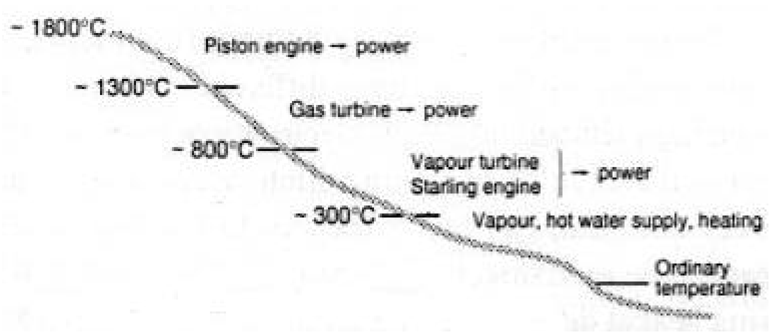

Fig. 5 The usefulness of heat at different temperatures (Hirata, 1997)

A general relationship between thermal exergy and temperature is illustrated in Fig. 6 (Wall, 1990 and 2001). The vertical axis of Fig. 6 displays the exergy factor E/Q, which indicates the fraction of the total heat content (Q) with a potential to be useful as thermal exergy (E). This usefulness depends on the temperatures involved. The horizontal axis relates the temperature T_{in} inside a given system (e.g. oven, chemical reactor, furnace) to the outdoor temperature T_{out}, by means of the ratio T_{in}/T_{out}. Note that these temperatures are in degrees Kelvin (0°C = 273°K).

The use of such dimensionless ratios has the advantage of enabling the exergy factor for different temperature combinations (T_{in} and T_{out}) to be expressed in one single curve. Fig. 6 shows that the exergy factor E/Q is higher the further the temperature of a system is from the environment temperature.

Since Kelvin temperatures are used (0 °C=273 K), the built environment falls within the relatively narrow range of T_{in}/T_{out} between 0.9 and 1.3. For example, on a winter day the outdoor temperature T_{out} may be -10°C (263 K); for an indoor temperature T_{in} of 293 K (20°C), the ratio T_{in}/T_{out} is 1.1. By way of comparison, in a furnace (e.g. for baking bricks), temperatures may reach 1473 K (1200 °C), whereby the ratio T_{in}/T_{out} becomes 5.0.

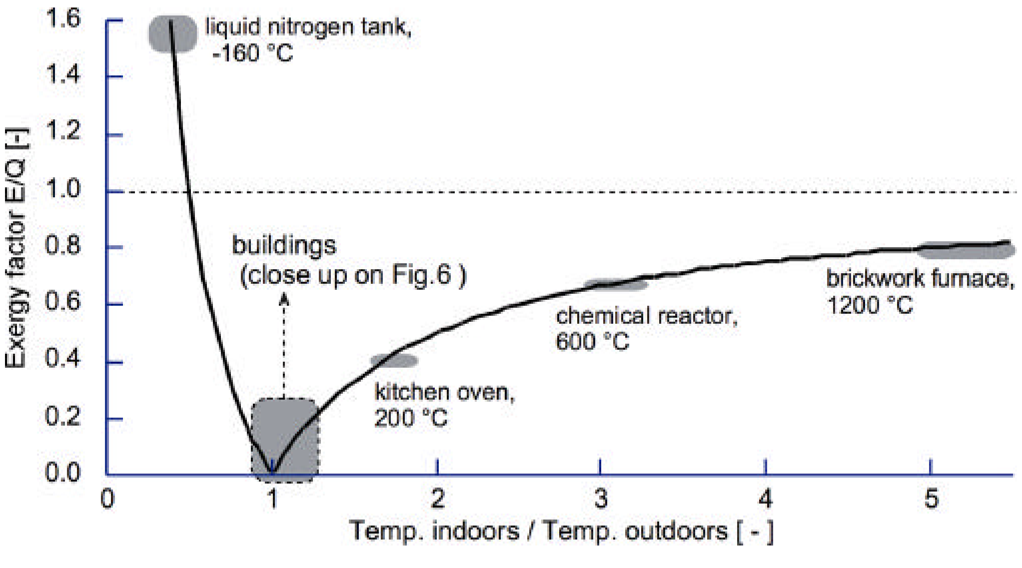

Fig. 6 Thermal exergy and temperature (adapted from Wall, 1990, 2001)

Fig. 7 is a close-up view of Fig. 6, focusing on the range of near-environmental temperatures commonly found in the built environment. It represents a winter situation T_{out} = 263 K (-10°C). From this figure we see, for example, that the exergy factor is 0.2 for a heat storage tank at 60°C when the outdoor temperature is -10°C. This relatively low exergy factor indicates that heat of 60°C is of relatively low grade. Because the demand for heat in buildings is in the low-exergy range, low-grade heat sources are thermodynamically adequate to supply heat for buildings.

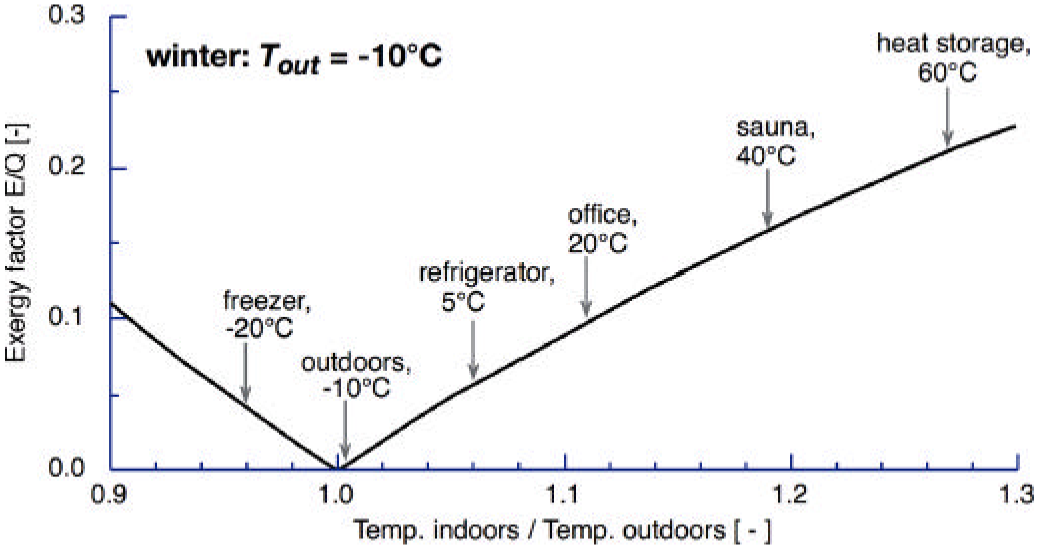

Fig. 7 Thermal exergy and temperature in the built environment

Exergy shows not only the quality of energy but also how energy is degraded ('what is consumed' in which locations within a system). It also provides a common basis for comparing between different energy carriers, and for indicating how much energy is degraded (consumed) in which locations within a system. Contrary to energy, exergy is not conserved. This is illustrated in an example below.

Exergy consumption in a lighting system

In this example of previous research (Asada and Shukuya, 1999), we first show the exergy supply and consumption process for a fluorescent tube. Then, we show how the exergy of visible radiation emitted by the fluorescent tube is consumed within a room. This enables us to show an energy input-output flow through the system (e.g., fluorescent tube, room) as a series of exergy supply, consumption, and output.

Fig. 8schematically shows the energy flow of a 40 W fluorescent tube. Electricity (40 W) is supplied to the tube and converted into thermal energy (31 W) and visible radiation (9 W), which flow out from the tube surface. The total energy flows (input and output) are conserved according to the first law of thermodynamics. As far as the numbers in Fig. 8 are concerned, the fluorescent tube should be regarded as a heater rather than a lighter, since the thermal energy flow is more than three times greater than the visible radiation. This does not fit our sense, though. The energy concept by itself cannot show explicitly the difference in quality between electricity, visible radiation and thermal energy; it also cannot show what is consumed within the fluorescent tube.

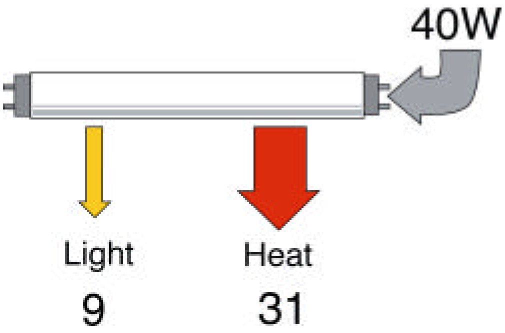

Fig. 8 Energy input and output of a fluorescent tube

Fig. 9 schematically shows the input, output, and consumption flows of a 40 W fluorescent tube in terms of exergy. The input exergy is electricity (40 W). About 70 % of this supplied exergy (29 W) is consumed in the tube, as a result of multiple energy conversion steps[2]. The exergy output from the tube surface as visible radiation is 7 W, and the remaining 4 W (=40-29-7) are released as thermal exergy.

Exergy analysis clearly shows that something is consumed in the process of converting electricity into light. By taking into account the temperature levels, it also shows that the heat emitted by the tube is of very little usefulness (low exergy value). The exergy of visible radiation, on the other hand, is about 1.8 times larger than that of heat. From an exergy viewpoint, thus, the fluorescent tube is a lighter rather than a heater.

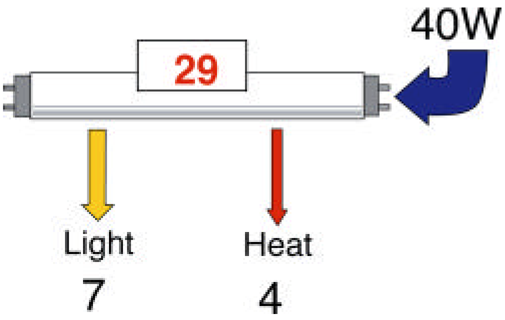

Fig. 9 Exergy input, consumption, and output of a fluorescent tube

The exergy concept can also show how the light emitted by the fluorescent tube eventually degrades into heat. The visible radiation emitted by the fluorescent tube shown in Fig. 8 illuminates the room interior and is absorbed by the wall and floor surfaces. Through this absorption, all of the visible radiation is converted to thermal energy. During this energy conversion process, the quantity of energy is conserved

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[2] The electricity supplied to the tube provides a stream of electrons flowing between the electrodes at both ends of the fluorescent tube. These electrons collide with mercury vapour atoms floating inside the bulb. This changes the energy level of the mercury atoms, and they eventually release ultraviolet radiation. This ultraviolet radiation collides with the phosphor coating the inside of the tube, and the phosphor fluoresces to produce visible light.

but the quality is changed. This quality change (degradation) is expressed in terms of exergy consumption.

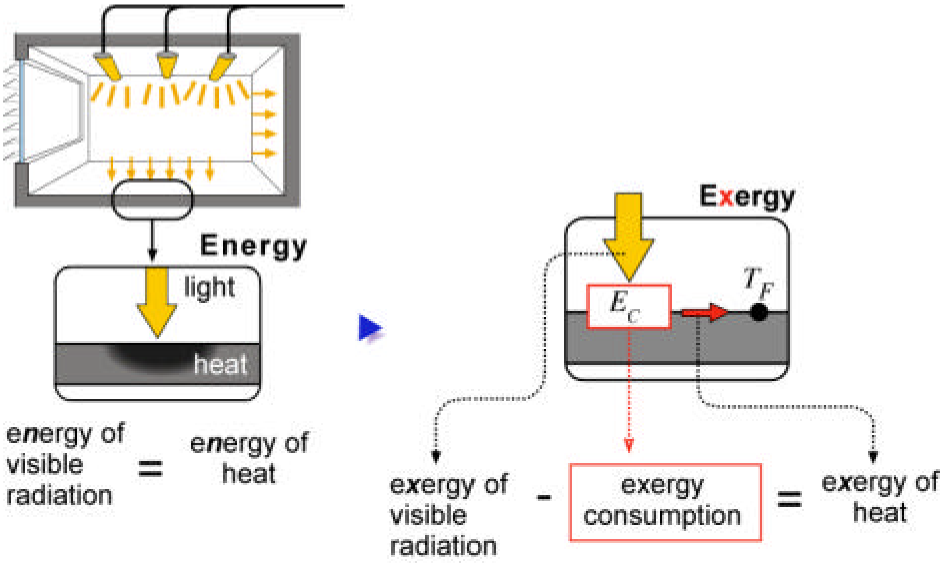

Fig. 10 Exergy consumption of visible radiation by absorption on interior surface

Conclusions

An important strength of the exergy concept is the possibility it offers to articulate and quantify intuitive notions such energy resource consumption and degradation. Unlike energy, which is always conserved, exergy is consumed in real processes such as heat transfer (e.g. heat losses through a wall) and energy conversion (e.g. electricity or light into heat). Also noteworthy is the ability of exergy to express differences in value between different energy sources (e.g. electricity, light and heat). In strict engineering terms, exergy is a rather complex thermodynamic concept, which is more deeply rooted in energy-intensive sectors (e.g. electric power generation, chemical industry) than in the built environment.

This paper aimed at enhancing the understanding of exergy by those in the building profession. In Japan, research has been ongoing since the early 1990’s towards defining a conceptual framework for applying exergy analyses in the built environment (Shukuya, 1996, 2001). The International Energy Agency also supports an annex on low exergy systems for heating and cooling of buildings (IEA, 2002). In the Netherlands, research into integrating environmental control systems and building design has been started at the building services chair, faculty of architecture, Delft University of Technology (Asada, 2002; Boelman, 2002).

In this paper, the exergy concept was explained and applied to articulate the notions of energy ‘value’ and consumption. The exergy requirements of systems near environmental temperature were shown to be very low; this implies that low-grade heat sources would be thermodynamically better suited for use in buildings, since their temperatures better match the temperature levels often required in buildings. The conversion of electricity into light and heat in a fluorescent tube was also investigated; the analysis showed an exergy consumption path, first in the initial conversion from electricity into light and heat, and then when the resulting light was converted into heat. From an energy-analysis viewpoint, the fluorescent tube produces more heat than light. In exergy terms, however, the fluorescent tube provides us with more light than heat. This intuitive notion can be confirmed because an exergy analysis implies assigning a higher value to light than to heat.

Acknowledgements

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References

ASADA, HIDEO AND SHUKUYA, MASANORI (1999) *"Numerical analysis of annual exergy consumption for daylighting, electric-lighting, and space heating/cooling system", Conference proceedings of the 6th International IBIPSA Conference*. Kyoto, Japan, September 1999, p. 121-127.

ASADA, HIDEO AND TAKEDA, HITOSHI (2002) *"Thermal environment and exergy analysis of a ceiling radiant cooling system", Conference proceedings of the Sustainable Buildings 2002 Conference*. Oslo, Norway, September 2002, in press.

BOELMAN, ELISA (2002) *"Exergy needs for winter ventilation in buildings", Conference proceedings of the Sustainable Buildings 2002 Conference*. Oslo, Norway, September 2002, in press.

ÇENGEL, YUNUS A., WOOD, BYARD AND DINCER, IBRAHIM (2002) *"Is bigger thermodynamically better?"* Exergy, an International Journal, Vol.2, No.2, p. 62-68.

ECN, ENERGY RESEARCH CENTRE OF THE NETHERLANDS (1993) *"Exergy pilot project"*, http://www.energie.nl/index2.html?evn/1993/evn93e012.html

HIRATA, MASARU (1997) *"Quality of the environment in Japan"*, www.env.go.jp/en/org/qe/1997/ch1-2.html

HOLLOWAY (2001) *"Project Ouroboros, Univeristy of Minnesota, School of Architecture and Landscape Architecture,1973-1976"*, http://www.taosnet.com/architectVRe/html/Ouroboros1.html

IEA, INTERNATIONAL ENERGY AGENCY (2002) *"Annex 37 – Low exergy systems for heating and cooling of buildings"*, http://www.vtt.fi/rte/projects/annex37/

KRISTINSSON, JON (1999) “*Exergy projects*” TVVL Magazine, Vol.28, No.10, p. 92-96, in Dutch.

MORAN, MICHAEL J. AND SHAPIRO, HOWARD N. (1998) *Fundamentals of Engineering Thermodynamics: SI version*. Wiley, Chichester.

ROSEN, MARC A. AND DINCER, IBRAHIM (2001) *“Exergy as the confluence of energy, environment and sustainable development”* Exergy, an International Journal, Vol.1, No.1, p. 3-13.

SHUKUYA, MASANORI. (1994) “*Energy, entropy, exergy and space heating systems*”, *Conference proceedings of the 3rd International Conference: Healthy Buildings ’94*, Budapest, Hungary, August 22-25, 1994, Vol.1, pp.369-374.

SHUKUYA, MASANORI AND KOMURO, DAISUKE. (1996) “*Exergy-entropy process of passive solar heating and global environmental systems*”, Solar Energy, Vol.58, No.1-3, pp.25-32.

SHUKUYA, MASANORI. (1996) “*Thermodynamic consideration for sustainable architecture*”, *Conference proceedings of the 13th International Passive and Low Energy Architecture Conference*, Louvain-la-Neuve, July 16-18, 1996, pp.319-324.

SHUKUYA, MASANORI. (2001) *“Introduction to the concept of exergy – for a better understanding of low temperature heating and high temperature cooling systems*”. IEA Annex 37.

WALL, GÖRAN (1990) *“Exergy needs to maintain real systems near ambient conditions”*. In: A Future for Energy, (S.S.Stecco, M.J.Moran, editors). p. 261-270. Pergamon.

WALL, GÖRAN (1998) http://www.exergy.se/goran/home.html

WALL, GÖRAN AND GONG, MEI (2001) *“On exergy and sustainable development – Part 1: Conditions and concepts*” Exergy, an International Journal, Vol.1, No.3, p. 128-145.

Fig. 11 The Ouroboros house (Holloway, 2001)