Comfortable High-Performance and Low-Exergy Built Environment

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ABSTRACT

This paper outlines the applicability of the “exergy” concept to describe the built environment for a better futuristic view of heating and cooling systems to be developed. We briefly review the fundamental laws of thermodynamics aiming at the derivation of the exergy concept and then discuss some of the findings obtained from the recent exergy research focusing on the built environment. What follows are that 1) any systems from heating to lighting systems, to human-body system work as “exergy-entropy” process; 2) thermal exergy consists of two kinds of exergy: warm and cool exergies; 3) there is the lowest human-body exergy consumption rate in winter season; 4) availability of cool radiant exergy seems very important for a naturally-ventilated room in summer season.

KEYWORDS

Energy, Entropy, Exergy, Built-Environment, Heating, and Cooling

INTRODUCTION

People often claim that energy is consumed; this is not only in everyday conversation but also even in scientific discussion associated with so-called energy and environmental issues. This claim, however, conflicts with the first law of thermodynamics stating that the total amount of energy is conserved even though forms of energy may change from one to another. All macroscopic natural phenomena happening around us involve the dispersion of energy and matter, which in due course change their forms from one to another, but the total amount of energy and matter involved is never consumed but necessarily conserved.

When we use such expressions as “energy consumption”, “energy saving”, and even “energy conservation”, we implicitly refer to “energy” as intense energy available from fossil fuels or from condensed uranium. But, it is confusing to use one of the most well-established scientific terms, energy, to mean “to be conserved” and “to be consumed” simultaneously. This is why we need to use one of the thermodynamic concepts, exergy, intensively and extensively to articulate what is consumed.

Here in this paper, we briefly review the fundamental laws of thermodynamics aiming at the derivation of the exergy concept and then discuss some of the findings obtained from the recent exergy research focusing on the built environment.

EXERGY-ENTROPY PROCESS

Let us first discuss using a simple imaginary heat engine working under a steady-state condition as schematically shown in the left-hand side of **Figure 1**. We first set up its energy balance equation according to the “energy conservation law”. The inflow of energy equals the sum of the outflows of energy. The heat engine works in the dispersing flow of energy, namely “heat”, from the hot source to the cold source and thereby it extracts non-dispersing flow of energy, namely “work”.

Whenever the heat engine produces the useful work, some positive value of entropy is necessarily generated. With this in mind, we can set up the entropy balance equation that is consistent with the energy balance equation. The limit condition of the heat engine that does not generate even a slight amount of entropy is that it is operated with the infinitely-slow motion. The heat engine under such condition is not useful at all Therefore, any useful heat engines generate some amount of entropy. The unigue point in the entropy balance equation is that there exists a term of "entropy generation". The sum of the inflowing entropy to the system and the generated entropy within it equals the outflowing entropy from it. This implies that the generated entropy is discarded out of the system.

The concept of entropy can be regarded to be a measure to quantify in what degree an amount of energy or matter is dispersed or how much the dispersion occurs. "Heat" is one way of energy transfer by dispersion due to conduction, convection or radiation, sometimes together with mass diffusion, namely evaporation. On the other hand, "work" is the other way of energy transfer not by dispersion ; work is, in other words, performed by a directional(parallel) movement of many particles composing of a substance that has a certain shape or form as solid. Energy transfer by heat necessarily accompanies with entropy transfer and entropy generation, while on the other hand, energy transfer by work itself alone accompanies with no entropy transfer.

Generally speaking, energy contained by a body, which has an ability to disperse, is called an energy source. Such an energy source exists within the environmental space, which is filled with dispersed energy. Therefore the cold source shown in Figure 1 can be regarded as the environmental space for the heat source and for the heat engine. Since the concept of entropy is, as mentioned above, a measure to quantify the degree of dispersion and its dimension is J/K (=Onnes) or W/K (=Onnes/s), the dispersed energy level of the heat source surrounded by the environmental space can be expressed as the product of entropy contained by the source and its environmental temperature in Kelvin scale. The product of entropy and environmental temperature is called "anergy", which implies dispersed energy; the dimension of both energy and anergy is J or W.

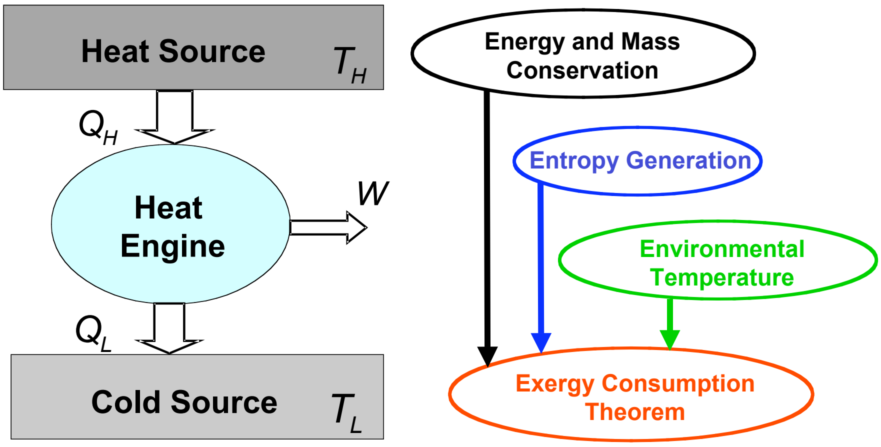

Figure 1. An imaginary heat engine working with the heat source whose temperature is constant at T_H and with the cold source (heat sink) whose temperature is constant at T_L. The engine extracts an amount of work, W, which is not yet dispersed, through the two dispersing flows of thermal energy, Q_H and Q_L, from the heat source to the cold source.

Table 1 Exergy-entropy process

1.	Feed on exergy
2.	Consume exergy
3.	Generate entropy
4.	Dispose of entropy

Disposing of the generated entropy from the system makes new room for feeding on exergy and consuming it again. Thus the process cycles.

A portion of energy to be expressed as the difference between total energy and its dispersed portion, anergy, is the amount of energy, which has an ability to disperse. This is exactly the concept of “exergy”. Exergy balance equation is therefore obtained from the two balance equations in terms of energy and entropy together with the concept of “environmental temperature”. The unigue point of exergy balance equation is that there exists a term of “exergy consumption”; this implies that a portion of exergy supplied from the source flowing into the system is necessarily consumed (destroyed) and thereby an amount of work, which is exergy itself, is extracted.

The heat engine must be operated cyclically to produce the work continuously and thereby becomes useful. To make this cycle realize, it is essential for the engine to keep get rid of the generated entropy so that its state, expressed by temperature and pressure, remains unchanged. The entropy contained by a certain body is a function of the body temperature and pressure; its general characteristics is that the value of entropy increases as the body temperature rises or the body pressure decreases (the volume increases). In order to remain the state of the engine unchanged, it is necesary for the system to dispose of the generated entropy. We call the process described above “exergy-entropy” process. **Table 1** shows the four fundamental steps of exergy-entropy process. Any working systems perform these four steps in series and cyclically. The built-environmental systems such as heating, cooling, or lighting systems and also human-body system are no exceptions (Shukuya, 1994; 2004).

EXERGETIC VIEW OF THE BUILT ENVIRONMENT

Warm and Cool Exergies

The amount of exergy contained by a substance varies with its temperature and also with its environmental temperature. **Figure 2** shows an example of thermal exergy contained by 81 m^3 (= 6m x 5m x 2.7m), a room size, of air as a function of its temperature in the case of an environmental temperature of 288 K (=15 °C). It should be noted that air has a certain amount of exergy both when the air temperature is higher than the environment and when the air temperature is lower than the environment (Shukuya and Hammache, 2002).

The exergy contained by air at a temperature higher than its environment is an ability of thermal energy contained by the air to disperse into the environment. On the other hand, the exergy contained at a temperature lower than its environment is an ability of the air, in which there is a lack of thermal energy compared to the environment, to let the thermal energy in the environment flow into it. We call the former “warm” exergy and the latter “cool” exergy (Shukuya, 1996).

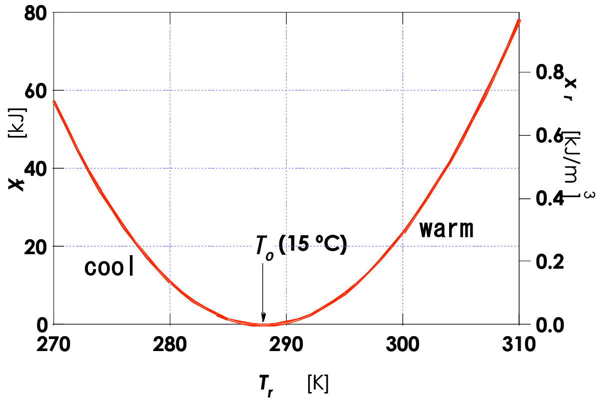

Figure 2 Thermal exergy contained by air, X_r, as a function of temperature, T_r. The unit of thermal exergy, X_r, is kJ. Air volume is assumed to be 81m^3 (= 6m x 5m x 2.7m). Environmental temperature, T_o, is 288 K (=15 °C).

Either "warm" exergy or "cool" exergy described above is a quantity of state contained by a substance relative to its environment. When a room space is heated, we have room temperature higher than the outdoor environment. In such a case room air has "warm" exergy as a quantity of state. On the other hand, when the room space is cooled, we have room temperature lower than the outdoor environment. In this case, room air has "cool" exergy as a quantity of state.

The role of heating systems is to supply and consume exergy for keeping "warm" exergy contained by room space in a certain desired level. Cooling systems, on the other hand, are the systems that supply and consume exergy for keeping "cool" exergy contained by room space at a certain desired level. The exergy supply is to transfer exergy either by flows of conduction, convection, or radiation.

Human-body Exergy Consumption Rate and Thermal Comfort in Winter

Biological systems including human body also works as a kind of heat engine. So-called metabolism is another expression of exergy-entropy process. Whether one can feel thermally comfortable or uncomfortable in a room space is related to how much of warm exergy is consumed within the human body. **Figure 3** shows an example of such relationship in winter condition obtained from human thermo-regulatory system analysis from the exergetic viewpoint (Isawa et al., 2002; 2003).

The horizontal axis represents air temperature and the vertical axis mean radiant temperature surrounding a human body. Mean radiant temperature is the average of internal surface temperatures of building windows, walls, floor, and ceiling. Fine lines with numbers are equi-exergy-consumption-rate lines within a human body. The bold line drawn from upper-left down to lower-right corresponds to the state of human body whose metabolic energy emission rate equals the energy outflow due to radiation, convection, evaporation, and conduction.

According to the previous knowledge of human thermal physiology, such a condition in which overall energy outflow from the human-body surface equals the metabolic energy emission rate provides the human body with thermal comfort. In other words, any sets of room air temperature and mean radiant temperature on the bold line in Figure 3 must give a comfortable indoor thermal condition. Nevertheless, according to experienced architects and engineers concerned about designing comfortable built environment, a set of relatively high mean radiant temperature and relatively low air temperature brings about a better indoor thermal quality in winter season. This is just consistent with such an indoor condition that brings about the lowest exergy consumption rate within the human body as shown in Figure 3.

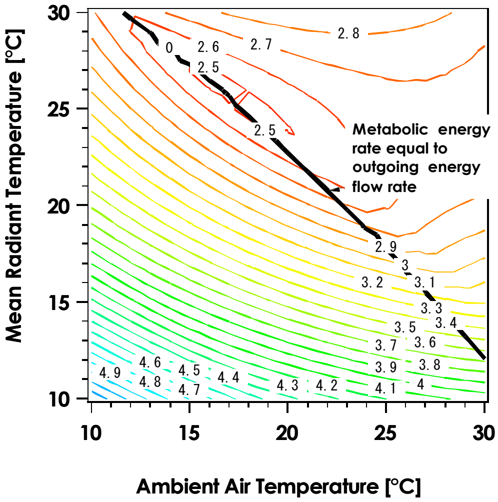

Figure 3 Relationships between human-body exergy consumption rate, whose unit is W/m^2 (body surface) and his/her environmental temperature under a winter condition (0°C; 40%rh). There is a set of room air temperature (18 to 20 °C) and mean radiant temperature (23 to 25 °C) which provides him/her with the lowest exergy consumption rate.

This suggests that human body as a biological system has evolved over the long years since the birth of life on the globe so that we humans can feel the most comfortable with the lowest exergy consumption rate, at least in winter conditions.

Cool and Warm Radiant Exergies and Thermal Comfort in Summer

We can make a similar chart to Figure 3 as we change the outdoor environmental condition for summer season. The values obtained are different, but such a relationship that a combination of higher mean radiant temperature and lower air temperature gives the lowest exergy consumption rate becomes almost the same. This seems consistent with what has been so far aimed at in case of conventional convective cooling.

A good combination of nocturnal natural ventilation together both with external solar shading and with an appropriate amount of internal thermal mass provides us with such indoor condition of a little lower mean radiant temperature and higher air temperature during daytime, which is comfortable enough especially in residential buildings. **Figure 4** shows an experimental example of the relationship between the percentage of comfort votes and warm/cool radiant exergies available in a naturally ventilated room where the subjects perceived no air current because of little outdoor wind, though the windows for cross ventilation were open. This result was obtained from an in-situ experiment made in two small wooden buildings with natural ventilation in summer(Shukuya et al., 2006).

The closed circles "●" denote the cases that cool radiant exergy is available and the open circles "○" denote warm radiant exergy. As the warm radiant exergy rate grows, the percentage of subjects voting for comfort decreases. The warm radiant exergy flow rate reaching 20 mW/m^2 results in the condition that no subjects vote for comfort. On the other hand, the same rate of "cool" radiant exergy results in totally opposite condition in which most of the subjects vote for comfort. Cool radiant exergy of 20 mW/m^2 is available provided that the mean radiant temperature is lowered slightly compared to the outdoor air temperature.

This result confirms that the use of external solar shading is the first priority in order to make a comfortable built environmental condition in summer with natural ventilation. The use of external solar shading devices together with nocturnal ventilation and the use of moderate thermal mass of floors and walls realise the production of cool radiant exergy during the daytime in summer. There are a lot of existing buildings having no external but internal solar shading. The built environment in those buildings in summer is equivalent to being heated by internal solar shading devices as radiant heating panels. This in turn requires lower air temperature for cooling.

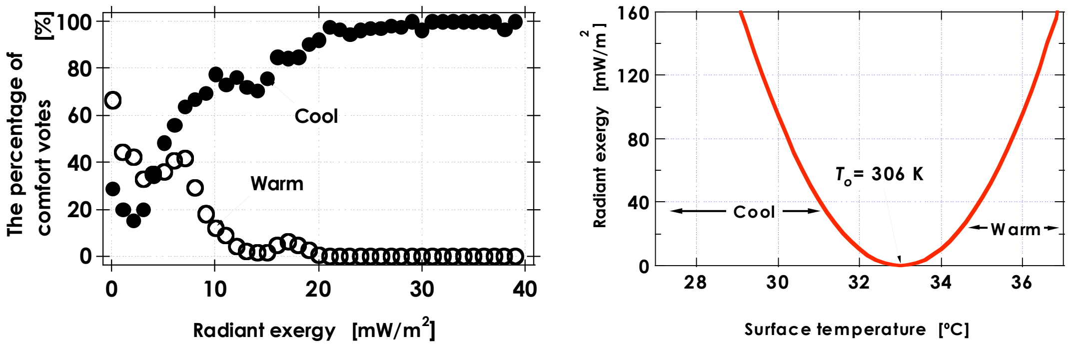

Figure 4 The percentage of the comfort votes under the condition of no perceived air current as a function of radiant exergy emitted from interior wall surfaces(see the chart on your left). Warm and cool radiant exergies are both in the range of 0 to 100 mW/m^2 (see the chart on your right)

CONCLUDING REMARKS

As described above, exergy consumption is always accompanied with entropy generation, thus the generated entropy must be discarded constantly from the room space to the outdoor environment to keep “warm” or “cool” exergy within a desired level. A challenge is to seek a design solution of a system that works with as small amount of exergy supply as possible, while at the same time producing the required exergy from our immediate outdoor environment and making its smart use to get a certain level of well-being in the built-environmental space.

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