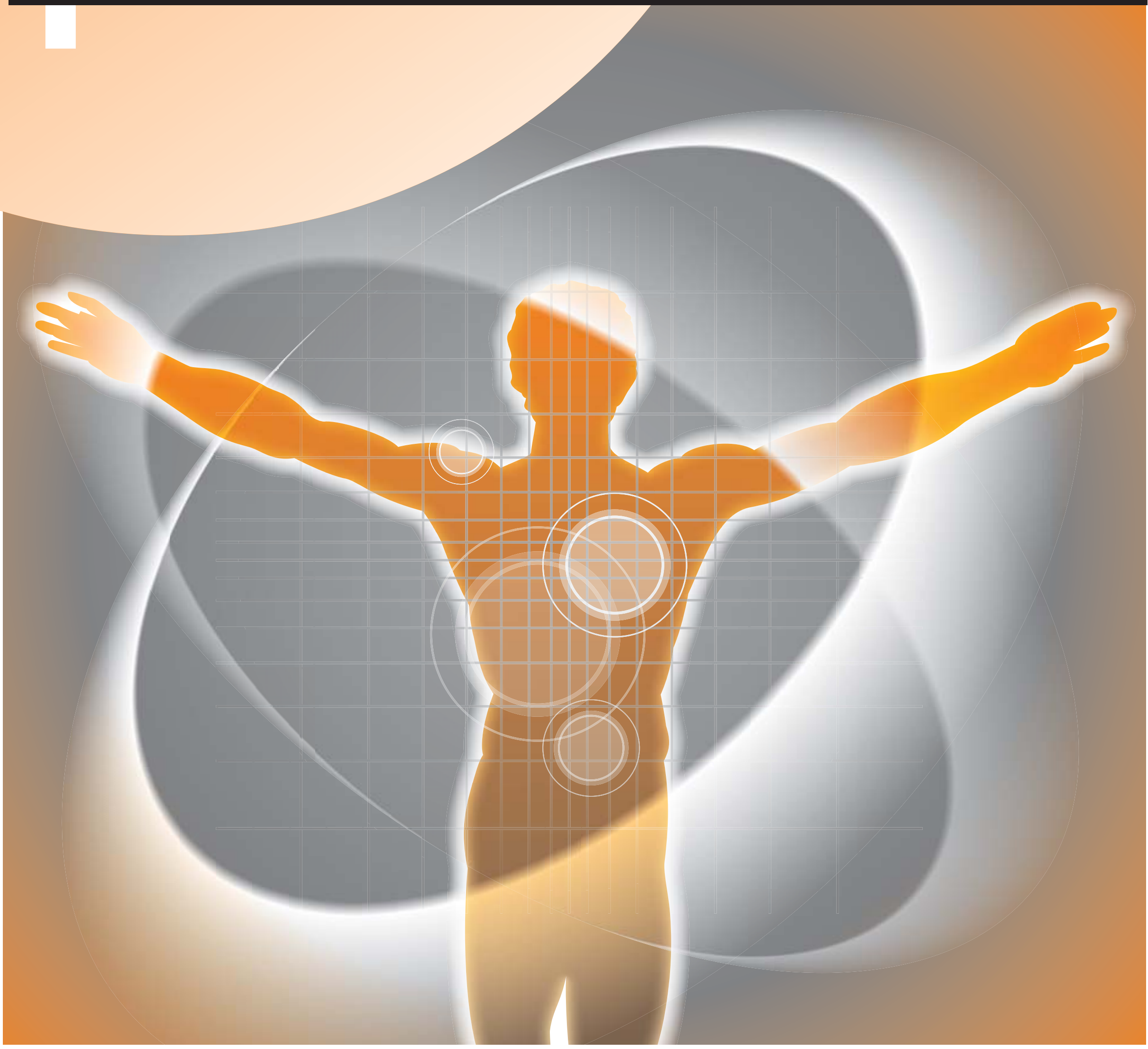
ECBCS Annex 49

report

Low Exergy Systems for High-Performance Buildings and Communities

Working report of IEA ECBCS Annex 49



"Human-Body Exergy Balance and Thermal Comfort"

International Energy Agency
Energy Conservation in
Buildings and Community
Systems Programme

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∗ Much of this text was originally prepared and published in 2004 for a Japanese textbook edited and written by M. Shukuya together with his former Ph.D. students, “Theory of Exergy and Environment” from Hokuto-Shuppan Publisher.

∗ M. Shukuya wrote this report as the principal researcher on the development of human-body exergy calculation model with the help of his former Ph.D. students for the period of 1995 to 2008. He spent three months as an Otto-Mønsted Visiting Professor at the International Center for Indoor Environment and Energy, Technical University of Denmark (ICIEE/DTU) in the period of 2008 to 2009 and, thanks to this visiting professorship proposed and realized by Prof. Dr. Bjarne W. Olesen, he could devote himself much to the preparation of this report.

PREFACE

The first time I encountered with an example of exergy analysis on the built environment dates back to the year of 1994 when Prof. Masanori Shukuya presented his finding at one of the sessions, which I chaired, of Healthy Building conference held in Budapest. It was already common among the scientists and engineers to use the concept of energy, not exergy, for heating and cooling load calculations and also for indoor thermal environment calculations in relation to thermal comfort. Therefore, I asked him whether such an exergy analysis helps us have a better understanding of built environment or open a new way for designing rational heating and cooling systems in buildings, now called low-exergy systems. He replied that he had the same feeling in the very beginning and such an attempt should be worthwhile doing. I agreed that it might be so.

Since then over the last ten years, the application of exergy concept to built environment has become well recognized by the scientists and engineers involved in building thermal science, especially through the international activity of IEA ECBCS Annex 49 and its predecessor Annex 37, which was started in 1999. Exergy analysis helps us understand further the indoor thermal environment and its associated heating and cooling systems in order to meet the requirements of sustainable building design.

The indoor environment is for people residing in buildings. Therefore, such an exergy approach should be extended to the analysis of human-body thermal process. The theoretical development of human-body exergy balance model was initiated by Prof. Masanori Shukuya and his former students about ten years ago and it has grown to the present status described in this report.

I believe that this report is useful for those interested in indoor thermal environmental science and its associated building system design from the viewpoint of exergy to have a basic understanding of human thermal process and also to have a look at what should be challenged in the coming years for sustainable building planning and design for human thermal comfort and well being.

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SUMMARY

This report describes how the human-body exergy balance equation is set up in detail and also discusses some results of its numerical calculation.

Research on the built environment with the exergetic viewpoint has been grown to the present since early 1990s. In due course, the exergy concept itself was developed and sharpened to a large extent, in order to make it possible to apply in particular to the field of building physics and its related areas such as indoor thermal environmental science. Exergy analysis of the built environment equipped with space heating and cooling systems articulates how much and where exergy is consumed in the whole process from its supply and consumption to the resultant entropy generation and disposal. Space heating and cooling systems themselves are physical systems at their own right, but their purpose is to control the built environmental condition within a certain range that allows the occupants to be healthy and comfortable with rational ways of exergy consumption.

Physics with respect to the built environment and its technology must be in harmony with human physiology and psychology. In this sense, it is of vital importance to have a better understanding of the human body as a thermodynamic system at dynamic state from exergetic viewpoint; this is to deepen our understanding of the built environment, especially with respect to heating and cooling and thereby develop rational heating and cooling systems for the built environment in the future.

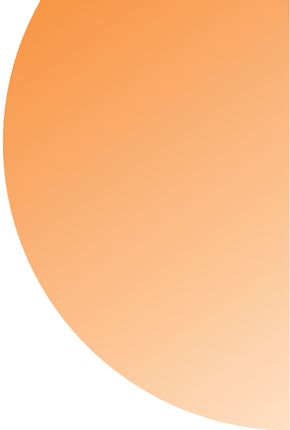
First, this report reviews the fundamentals of the concepts of energy and entropy looking at an imaginary heat engine together with the concept of environmental temperature, then describes the essence of its exergy balance and thereby points out that a working system performs its purpose as “exergy-entropy process” to maintain its state at dynamic equilibrium.

Then, the precise description of respective terms of energy, entropy, and exergy balance equations are given followed by the procedure of numerical calculation. The terms developed for the human-body exergy balance equation are not necessarily self-evident so that some of their characteristics are given and discussed to some extent. They are wet exergy associated with the sweat as liquid water, warm/cool radiant exergies coming into and going out from the human body, and warm/cool exergy flow by convection around the human body. Then, a couple of numerical examples of the whole human-body exergy balance are given for typical winter and summer conditions and their characteristics are discussed.

Finally, the human-body exergy consumption rates for winter and summer conditions are given: the former is shown as a function of mean radiant temperature and air temperature and the latter as a function of mean radiant temperature and air movement. It was found from a series of analyses having done so far that there are the minimum values of human-body exergy consumption rate both in winter and in summer. These findings suggest that the development of so-called low-exergy systems for heating and cooling are on the right track.

KEYWORDS: Human body, Heating, Cooling, Exergy, Environment, Thermal comfort

CONTENTS



1 INTRODUCTION

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. This is stated clearly by the first law of thermodynamics: i.e., the total amount of energy is conserved even though forms of energy may change from one to another. Nevertheless, such expressions as "energy consumption", "energy saving", and even "energy conservation" are used very much even in scientific discussion these days. In fact, it is confusing to use one of the most well-established scientific terms, energy, to mean "to be conserved", while at the same time "to be consumed". Some may say that it is all right to use these expressions, since it is known that they refer implicitly to "energy" as intense energy available from fossil fuels or from condensed uranium. This may be true in a sense, but it may also be true that we have forgotten to take a careful look at something that we should do, because of having been so accustomed by the use of the word, "energy", with the above-mentioned implicit meaning. It is, I believe, of vital importance to examine our ways of thinking in order to renew them and hence we step forward to be able to have sustainable and better solutions for the future built environment to be developed.

This is why we need to use exergy, one of the thermodynamic concepts, to articulate how a system in question including human body works. In thermodynamic consideration with the exergy concept in its center together with the entropy concept, the following is to be analyzed and to be understood: how much exergy is supplied to a system in question, where and how it is consumed, and then how the generated entropy due to exergy consumption is discarded into the environmental space for the system. Such analysis could lead to a better understanding of lighting, heating, cooling, and ventilating systems, and thereby allow us to come up with better solutions for sustainable built-environment systems for the future. With respect to heating and cooling in particular, it must be interesting and also important for us to take a careful look at human body in relation to thermal comfort from the exergetic viewpoint.

Here in this report, we describe the human-body exergy balance model in details and then its calculation procedure after reviewing briefly the essence of exergy concept in parallel to energy and entropy concepts and finally we discuss some of the important findings obtained from our exergy research done in the period of 2000 to 2008.

2 GENERAL CHARACTERISTICS OF EXERGY CONCEPT

For exergy analysis, it is necessary to set up exergy balance equations for each of the sub-system components in a system in question. Some may consider that it is all right to multiply simply the values of so-called Carnot efficiency and the corresponding energy values to have exergy values, but it could often mislead to a fault answer, or lead only to an insufficient answer that cannot enable us to have a whole image of the "exergy-entropy process" to be described below.

Therefore we need to start with energy balance equation together with its corresponding entropy balance equation and thereby to set up exergy balance equations of respective sub-systems of built-environment system. By doing so, it would become possible to have a rational picture of a series of function, that is, the function from exergy supply to entropy disposal. In other words, such thermodynamic description enables us to have a holistic and rational picture of the built-environment system. The same applies to the human body as a biological system to be described from the viewpoint of thermodynamics.

2.1 Energy and Entropy

Let us take an example of one sub-system as a simple imaginary heat engine working under a steady-state condition as schematically shown on the left-hand side of Figure 2.1. We first set up its energy balance equation according to the "energy conservation law"; i.e., the inflow of energy equals the sum of the outflows of energy. If the sub-system is working under an unsteady-state condition, the change in its energy state must be added to the sum of the outflows of energy.

The heat engine works in the dispersing flow of energy, namely "heat", from the heat 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 to be consistent with the energy balance equation.

The limit condition of the heat engine that does not generate even a scant amount of entropy is when it is operated with the infinitely-slow motion. The heat engine under such condition is not useful at all, since the rate of work extracted is infinitely small. Therefore, any useful heat engines in reality generate some amount of entropy.

The unique feature in the entropy balance equation is that there exists a term of "entropy generation" in comparison with energy balance equation. The sum of the inflowing entropy to the system and the generated entropy within it equals the entropy flowing out from it under the steady-state condition. This implies that all of the generated entropy is discarded out of the sub-system in question. If an unsteady-state condition is assumed, the change in its entropy state must be added to the sum of the outflows of entropy.

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 of water in the built-environmental systems. On the other hand, "work" is the other way of energy transfer not by dispersion; it is, in other words, performed by a directional (parallel) movement of molecules composing of a substance that has a certain shape as solid[1].

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. In reality, there are more or less inevitable causes resulting in a decrease in the amount of work to be transferred, such as friction, electric resistance and so on. All of them turn into "heat". It is very important to keep these facts in mind whenever we set up both energy and entropy balance equations.

So far described is focused on the systems operated under steady-state conditions, but the same description applies to the systems under unsteady-state conditions.

2.2 Environmental Temperature and Exergy

The environmental space for a system in question to be described is filled with dispersed energy. In the case of a system such as a heat engine as shown in Figure 2.1, the cold source 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 unit is J/K (=Onnes[a]) (W/K (=Onnes/s) for the rate), the dispersed energy level of the heat source surrounded by the environmental space can be expressed as the product of entropy contained by the heat source and its environmental temperature in Kelvin scale, the temperature of the cold source. The product of entropy and environmental temperature is called "anergy", which implies dispersed energy; the unit of both energy and anergy is J (W for the rate).

Environmental temperature is sometimes called 'reference temperature'. Historically speaking, the term 'reference temperature' must have originated from the quantification of temperature by measurement with the use of a substance such as water "referring" to particular temperatures, namely freezing and boiling temperatures[2]. With this meaning of "reference" in mind, environmental temperature should not be confused with reference temperature.

Generally speaking, an amount of energy contained by a certain body consists of two portions of energy: one is not-yet dispersed and the other already dispersed; the latter is the energy fully in equilibrium with that in the environmental space whose temperature is exactly the "environmental temperature". In other words, 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 bring about dispersion of energy and matter. 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".

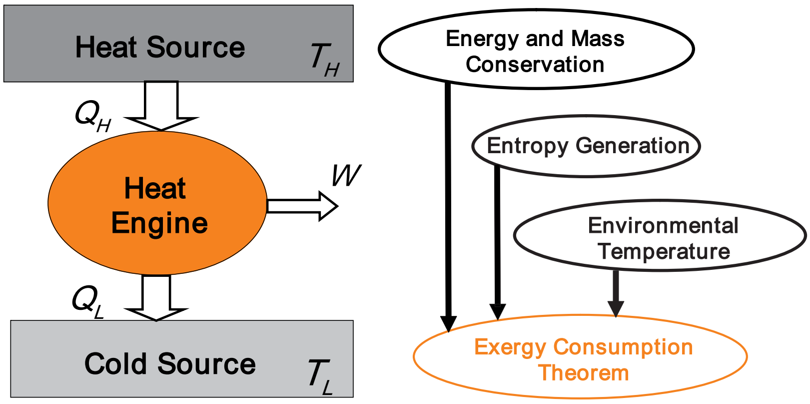


Figure 2.1: An imaginary heat engine representing a portion of the built-environment systems. It works with the heat source whose temperature is constant at T_H and with the cold source (heat sink) whose temperature is constant at T_L. The engine extracts an amount of work, W, which is not yet dispersed, through the two dispersing flows of thermal energy, Q_H and Q_L, together with their corresponding entropy flows, Q_H / T_H and Q_L / T_L, from the heat source to the cold source.

a) *"Onnes" comes from H. Kammerlingh-Onnes, a Dutch scientist, who first succeeded in liquefaction of helium and reaching 4.1 K in due course[14].*

2.3 Exergy-Entropy Process

The unique feature of the exergy balance equation is that there exists a term of "exergy consumption", which implies that a portion of exergy supplied from the heat source flowing into the system is necessarily consumed and thereby an amount of work, which is exergy itself, is extracted.

In order to remain the state of the imaginary engine shown in Figure 2.1 unchanged so as to keep generating an amount of work at a certain rate, it is necessary for the engine to keep disposing of the generated entropy. Even at the limit condition that no entropy is generated within the engine, while at the same time no rate of work is obtained, there needs to be an amount of entropy flowing out of the engine and thrown away into the cold source, which is exactly the same amount to that flowing into the engine.

We call such a series of process, from exergy supply via exergy consumption and then entropy generation to entropy disposal, "exergy-entropy process" [19]. Table 2.1 summarizes the four steps of one cycle of exergy-entropy process. Any working systems in reality work as "exergy-entropy process" so that they can sustain their state at dynamic equilibrium.

Table 2.1: Exergy-Entropy Process: four fundamental steps for a system to continue its work in cyclic operation

1. Exergy supply	To feed on energy or matter which has an ability to disperse;
2. Exergy consumption	To disperse a portion of the supplied energy or matter inside the system to do work;
3. Entropy generation	To generate an amount of entropy proportional to the amount of exergy consumed, which is due to the dispersion of the supplied energy or matter;
4. Entropy disposal	To dispose of the generated entropy into the environmental space from the system to let its temperature, pressure and molar free-energies(chemical potentials), namely the intensive quantities of state, at their desired values so that the process can return to the first step, exergy supply.

"Feeding on negative entropy", which is an expression coined by Schrödinger trying to explain the essence of life[3], some sixty years ago corresponds to "exergy supply" and the whole of exergy-entropy process with respect to human body corresponds to the biochemical process that keeps a "dynamic state of body constituents" clearly shown by Schoenheimer some seventy years ago with clear experimental evidence[4]. Such holistic images together with what is summarized in Table 2.1 applying to a variety of the built-environmental systems including human body is, I think, important for us to look into a better solution to be come up with, though it may sound a little bit philosophical.

3 SETTING UP THE HUMAN-BODY MODEL

Animals including human being live by feeding on organic matters containing a lot of exergy in chemical forms. They move muscles by consuming it not only to get their food but also not to be caught as food by other animals. All of such activity realized by their body structure and function is made possible by chemical-exergy consumption.

The chemical-exergy consumption brings about quite a large amount of "warm" exergy. In fact, this is the exergy consumed effectively by those animals called homeotherms including human being to keep their body-core temperature almost constant, at which various bio-chemical reactions necessary for life proceed smoothly at a controlled rate. This temperature level, as we know by our own experience through usually unconsciousness, is generally higher than the environmental temperature.

There are two kinds of animals from the viewpoint of thermoregulation of their body temperature: homeotherms (endotherms) as described just above and poikilotherms (ectotherms). To the former belong those animals maintaining their body temperature at an approximately constant level regardless of their environmental temperature variations and to the latter those animals whose body temperature fluctuates in accordance with their environmental temperature variations.

Either homeotherms or poikilotherms generate a certain amount of entropy in proportion to the exergy consumption inside their bodies in due course of life and they must excrete the generated entropy into their environmental space, as summarized in Table 2.1, by long-wavelength(LW) radiation, convection, conduction, and evaporation.

It is vitally important for the homeotherms to be able to get rid of the generated entropy immediately and smoothly to be alive because of their relatively large rate of exergy consumption. We humans are no exception.

In what follows, we discuss the exergy balance of human body as a system of homeotherms and then its relation to thermal comfort in the built environment.

3.1 Water Balance

We drink water several times a day and also excrete water with waste, namely urinate, several times a day. The urination is the primary way of discharging the water from our body, but there are two other ways:

one is by breathing and the other by secreting sweat. The former is originated from the secretion and evaporation of water inside the internal space of the lung and the latter takes place at our skin surface.

The primary purpose for us to drink water is to maintain the concentration of various cations, anions and organic compounds necessary for all of roughly 60 trillion living cells within our body, while at the same time to dispose of the used blocks of amino-acids and others by dispersing them into the water and excrete as urination, and the second purpose, equally important as the primary one, is to maintain the body-core temperature at an almost constant level regardless of the fluctuations of surrounding temperature.

In order for keeping the dynamic equilibrium[4] of human body, the disposal of generated entropy due to chemical-exergy consumption is of vital importance. The thermal-exergy consumption within the human body is, in other words, for such inevitable entropy disposal.

Table 3.1 summarizes the approximate amounts of water taken in and given off by an average person for one day[5]. The water supplied to the body by drinking and by eating food amounts to 86% and the rest is generated by biochemical reactions inside the body.

The chemical compounds contained by most of the foodstuffs are composed of carbon and hydrogen atoms in addition to nitrogen in proteins so that their decomposition under the condition at body temperature with a help of various enzymes and with the existence of much oxygen molecules brought by breathing results in the production of carbon-dioxide and water molecules as by-products of the primary production of building blocks and a variety of proteins made of amino-acids as building blocks for our body cells and ATP, adenosine tri-phosphate, as fuel.

In short, the hydrogen atoms contained by various organic matters such as glucose, proteins, and fatty acids react with the oxygen atoms supplied by breathing and thereby the water molecules are generated. This implies that the "wet" exergy of water is produced by the consumption of chemical exergy originally contained by food.

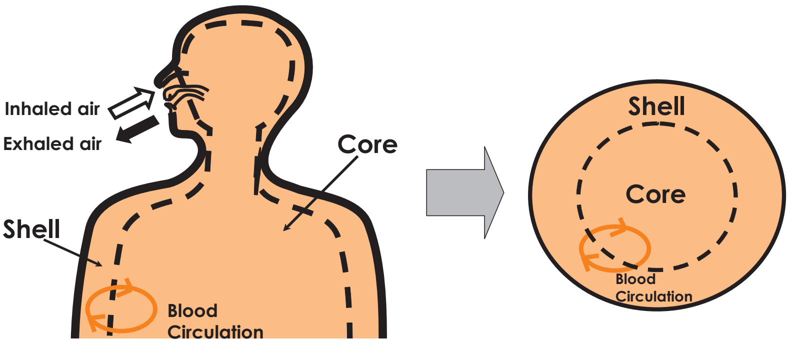


Figure 3.1: Modeling of a human body consisting of two subsystems: the core and the shell. The core is the central portion of the body whose temperature is kept almost constant at 37°C independent of the variations of surrounding temperature and humidity. The shell is the peripheral portion, whose temperature is dependent much on the variations of surrounding temperature and humidity and on the level of metabolism.

The output of water amounts to 2500 ml/day, which is the same as the input. The 60% of water output is due to urination and a half of the rest, 20%, is due to breathing and the other half is due to sweat secretion by 80%, namely 16% of the total output, and the excretion with waste matter by 20%, namely 4% of the total.

Both drinking and urinating are the intermittent behaviors so that our body weight changes from time to time, but if we take a look at our average body weight at one-day intervals, there is no change due to water inflow and outflow. Therefore we can set up a water-balance equation for the human body at a steady-state condition. The water input equals the water output.

An interesting estimation with respect to the water balance of human body is such that all of water contained by the body is replaced within twenty days or so assuming that the 70% of the body weight of a 70 kg person is comprised of water.

Table 3.1 Water balance of a human body for one day

Input			Output		
	2500 ml	(100)*		2500 ml	(100)
Drinking	1000	(40)	Urination	1500	(60)
Eating food	1150	(46)	Breathing	500	(20)
Metabolism	350	(14)	Sweat secretion	400	(16)
			Excretion with waste matter	100	(4)

* The figures in the brackets are relative amounts to the input or the output in percentage

As described in the beginning of this section, human being is one kind of homeotherms, but the temperature of the peripheral part of the body such as hands and foots in particular varies with the surrounding-temperature variations. Therefore, let us assume that the human body consists of two subsystems for thermodynamic modeling: the core and the shell as shown in Figure 3.1.

The core is one subsystem whose temperature is maintained nearly constant at 37°C almost independently from the variations of surrounding temperature and humidity variations; while on the other hand, the shell is the subsystem whose temperature is rather dependent much on their variations. Between these two systems, there is a circulation of blood, whose rate is variable dependent on external and internal conditions of the body.

The steady-state mass balances of these two subsystems with respect to humid air and liquid water can be described in the form of input being equal to output as follows. At the "core" subsystem,

[The inhaled humid air] +
[The liquid water generated by metabolism in the core] +
[The blood flowing into the core from the shell]
= [The exhaled humid air] +
[The blood flowing out of the core to the shell]. (3.1)

At the "shell" subsystem,

[The liquid water generated by metabolism in the shell] +
[The blood flowing into the shell from the core]
= [The liquid water secreted as sweat at the skin surface] +
[The blood flowing out of the shell to the core]. (3.2)

In these equations, all terms of the left-hand side of the equal sign are input and those of the right-hand side are output. The generated liquid water, which appears in each of the above two equations, includes an amount of water absorbed in the course of drinking water and eating food in addition to that generated in the course of metabolism.

Combining the two equations yields the water balance equation for the whole human body.

[The inhaled humid air]
+ [The liquid water generated by metabolism in the core]
+ [The liquid water generated by metabolism in the shell]
= [The exhaled humid air]
+ [The liquid water secreted as sweat at the skin surface].
(3.3)

The exhaled humid air is more humid than the inhaled humid air, since it contains the water vapor originating from the liquid water generated in the core. The liquid water to be secreted as sweat at the skin surface is assumed to originate from the liquid water generated in the shell that is expressed at the left hand side of eg. (3.3).

3.2 Energy and Entropy Balances

According to our daily experience, chemical exergy contained within the foodstuffs may seem to be consumed mostly for the production of work, but we must not forget that it is also consumed for maintaining a variety of body structure and function in order[4]. From the thermodynamic viewpoint, the human body is a typical dissipative structure, which self-organizes its form by running the "exergy-entropy" process, the chain of exergy supply, its consumption and the resultant entropy generation, and the entropy disposal. The production of work is never realized without chemical-exergy consumption for the body structure and its associated function.

If the liquid water contained by foodstuffs is squeezed, then they would burn very well. Although it is only with an imagination, the same would be true for the human body. As described in 3.1, there is always the water inflow and outflow through the human body. The 65 to 70 % of our body weight is always filled with liquid water so that a sudden rise of body temperature is not likely to happen; if it happened, it could cause an irreversible fatal damage of a complex body structure and function. We can say that the structure and the function of our body are formed by a moderate rate of burning foodstuffs in a special manner with the abundance of water. In due course, a large amount of thermal energy and entropy is produced necessarily.

The thermal energy has to be dumped into the environmental space, because it is accompanied with a lot of entropy generated within the human body for the complex bio-chemical reactions. Otherwise the human body could malfunction as described above.

Let us assume that a human-body system as shown in Figure 3.2 resides in a room space. The temperatures of the human-body, room air, and outdoor air are assumed to be higher in this order. Thermal energy outgoing across the body surface first enters the room space and then flows out into the outdoor environmental space. The liquid water secreted from the sweat glands forms a thin water film over the skin surface and then it evaporates into the room space unless the moisture contained by the room air is saturated. A portion of the room air having the water vapor originating from the human body has to be ventilated so that the room air can always allow the moisture discharged from the human body to disperse.

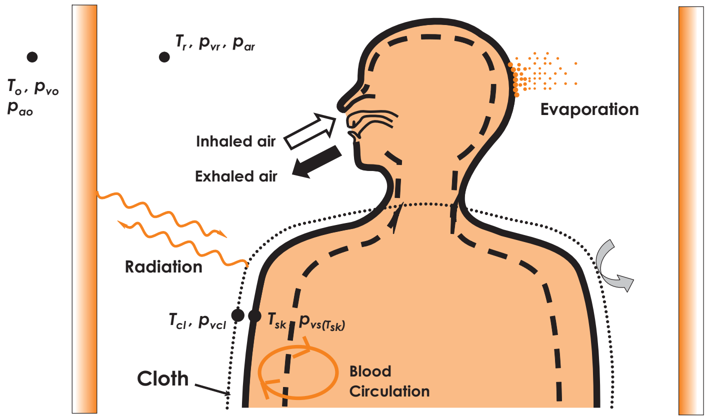


Figure 3.2: Modeling of a human body consisting of two subsystems: the core and the shell. The core is the central portion of the body whose temperature is kept almost constant at 37°C independently from the variations of surrounding temperature and humidity. The shell is the peripheral portion, whose temperature is dependent much on the variations of surrounding temperature and humidity and on the level of metabolism.

Most portions of the outside surface of the body-shell are covered by cloth, but the rest is naked; the head, the face, and the hands are exposed usually to the environmental space. The whole shape of human body is complex because of the head, the arms, and the legs hanging on the body center. Theoretically speaking, it should be possible to set up energy, entropy, and exergy balance equations taking such complexity and non-uniformity into consideration, but the more complicated the equations are, the more unknown variables we have to assume for actual calculation. This could result in little improvement of the accuracy, especially when looking into the exergy balance, and could even bring about such results that are hard to understand. Therefore, we had better make a moderate model with reasonably accurate exergy calculation by compromising two rather opposite requirements, the precision and the simplicity.

Here we start with a two-node energy-balance model of the human body, since it has been used quite extensively by building-science researchers and engineers in the field of heating and cooling in buildings[6)~9)]. This model was given as the energy balance equation, in which the metabolic energy emission rate as input equals the sum of thermal energy stored within the body and the net thermal energy transfer into the surrounding space by respiration, evaporation, convection and radiation. There is also conduction in reality, but it is neglected and implicitly considered in a portion of convection.

This model has a form convenient for the calculation of body-core, body-shell, and clothing temperatures, but not for that of warm/cool exergy and wet/dry exergy. Therefore, it is necessary to make a little bit of modification of the model.

One modification is to change the net thermal energy transfer due to the humid-air transport by breathing and the evaporation of sweat into five explicit forms of the enthalpy values: those of inhaled and exhaled humid air, those of liquid water produced by metabolism in the body-core and in the body-shell, and that of water vapor discharged from the skin surface by evaporation.

One other modification is to make the net radiant energy transfer between the human body and his/her surrounding into the explicit forms of radiant energy: one absorbed by the whole of skin and clothing surfaces and the other emitted from the whole of skin and clothing surface.

The modified energy-balance model, the form of which is consistent with the water balance equation (3.3), is expressed as follows.

[Thermal energy emerged by metabolism]
+ [Enthalpy of the inhaled humid air]
+ [Enthalpy of the liquid water generated in the core by metabolism]
+ [Enthalpy of the liquid water generated in the shell by metabolism]
+ [Radiant energy absorbed by the whole of skin and clothing surface]
= [Thermal energy stored in the core and the shell]
+ [Enthalpy of the exhaled humid air]
+ [Enthalpy of the water vapor originated from the sweat secreted]
+ [Radiant energy emitted by the whole of skin and clothing surfaces]
+ [Thermal energy transferred by convection from the whole of skin and clothing surfaces into the surrounding air].
(3.4)

Metabolic thermal-energy generation as input on the left-hand side and thermal energy stored within the human-body on the right-hand side are the characteristic difference in the energy balance equation from the water balance equation (3.3). This energy balance equation is set up with an assumption of unsteady-state condition, while on the other hand, the water balance equation with steady-state condition.

This energy balance equation assumes that the thermal conduction from the foot to the floor or from the back to the chair is implicitly included in the portion of convective energy transfer. It is also assumed that the output of work is neglected; in other words, this energy balance equation can be applied to the human body at the posture of standing or seating with up to light office work.

All of five terms of the enthalpy values in equation (3.4) must be expressed as the enthalpy differences from the humid air outdoors. This is in order for the actual numerical calculation of exergy balance. This mathematical operation is done by adding the same enthalpy values of outdoor humid air, whose amounts are consistent with water balance equation, if converted into their corresponding mass values, to both sides of the energy balance equation.

It is also necessary to make the two terms of radiant energy be those of radiant energy difference measured from the radiant energy emitted by an imaginary surface at the outdoor air temperature; this is done by adding the same radiant-energy values, which could be emitted from the imaginary surface at outdoor air temperature, to both sides of the energy balance equation.

Such operations applied to the terms of enthalpy and radiant energy are not necessary for other three terms: thermal energy emerged by metabolism, thermal energy stored in the body-core and the body-shell, and thermal energy transfer by convection.

The sum of the enthalpies of inhaled humid air and the liquid water generated by metabolism in the body-core, which appear on the second and third terms on the left-hand side of equation (3.4) relates to the enthalpy of the exhaled humid air on the right-hand side of the equation. Their difference is the thermal energy discharged by respiration.

The enthalpy value of the liquid water generated in the body-shell by metabolism, which appears on the fourth term of the left-hand side of the energy balance equation relates to the enthalpy of the water vapor originated from the sweat secreted and dispersing into the surrounding space, which appears on the third term of the right-hand side of the energy-balance equation. Their difference is the thermal energy dissipated by evaporation at the skin temperature.

The entropy balance equation, which is consistent with equation (3.4) can be written as follows10)~13).

[Thermal entropy given to the body by metabolism]
+ [Entropy of the inhaled humid air]
+ [Entropy of the liquid water generated in the core by metabolism]
+ [Entropy of the liquid water generated in the shell by metabolism]
+ [Radiant entropy absorbed by the whole of skin and clothing surfaces]
+ [Entropy generation]
= [Thermal entropy stored in the core and the shell]
+ [Entropy of the exhaled humid air]
+ [Entropy of the water vapor originated from the sweat secreted and dispersing into the surrounding space]
+ [Radiant entropy discharged from the whole of skin and clothing surfaces]
+ [Thermal entropy given off by convection from the whole of skin and clothing surfaces].
(3.5)

The first term in the left-hand side of this equation, the entropy given to the body by metabolism, is the entropy generated by all of bio-chemical reactions in order to keep the body structure and function.

The term of "entropy generation" appeared in the end of the left-hand side of the above equation, which is unique in entropy balance equation being distinct from the energy balance equation, is due not only to thermal energy dispersion caused by temperature difference between the body-core and the body-shell, but also due to the dispersion of water molecules into the surrounding moist air. The pressure difference in water vapor between the wet skin surface and the surrounding space of the body plays a key role in the latter case.

Mathematical operations similar to the energy balance equation are also necessary for the entropy balance equation to be applied to develop the exergy balance equation. There are three such operations in the case of entropy balance equation.

The first two of them are exactly the same as those applied to the energy balance equation. One of them is to make the five terms of entropy associated with the inhaled and exhaled humid air, the liquid water generated by metabolism in the body-core and in the body-shell, and the water vapor discharged from the skin by evaporation, into the respective five terms of entropy differences measured from the enthalpy value of the humid air outdoors. The other is to make the two terms of radiant entropy be those of radiant entropy measured from the radiant entropy emitted from an imaginary surface at the outdoor air temperature.

The third of the mathematical operations required is unique in entropy balance equation. Let us look at the third term of the right-hand side of the entropy balance equation (3.5). The dispersion of water vapor takes place in the surrounding space, where there is room air. In other words, the water vapor does not disperse into a space of vacuum. Therefore, we need to assume a corresponding amount of dry air, which is to disperse mutually with water vapor to become a portion of room air with a certain value of humidity. Its entropy value is added to both sides of equation (3.5) to be applied for developing the exergy equation. The idea of this operation is again exactly the same as that to be done for entropy values relating to mass transport by respiration and sweat secretion and also for radiant entropy values.

3.3 Thermal Exergy Balance[12][13]

Thermal exergy balance of human body can be derived by combining the energy balance equation and the entropy balance equation, both of which are the resultant equations of the mathematical operations described above, together with the environmental temperature for exergy calculation, which is outdoor air temperature.

One may wonder if the environmental temperature is room air temperature or operative temperature, but it is neither of them, except a case that the human body is assumed to be outdoors, for which the surrounding air temperature of the human body turns again to be exactly the outdoor air (or operative) temperature. If an overall investigation of the human-body exergy balance is made together with space-heating or –cooling system's exergy balance, the environmental temperature to be taken must be the same for both human body and space heating or cooling system.

[Warm exergy generated by metabolism]
+ [Warm/cool and wet/dry exergies of the inhaled humid air]
+ [Warm and wet exergies of the liquid water generated in the core by metabolism]
+ [Warm/cool and wet/dry exergies of the sum of liquid water generated in the shell by metabolism and dry air to let the liquid water disperse]
+ [Warm/cool radiant exergy absorbed by the whole of skin and clothing surfaces]
- [Exergy consumption]
= [Warm exergy stored in the core and the shell]
+ [Warm and wet exergies of the exhaled humid air]
+ [Warm/cool exergy of the water vapor originating from the sweat and wet/dry exergy of the humid air containing the evaporated water from the sweat]
+ [Warm/cool radiant exergy discharged from the whole of skin and clothing surfaces]
+ [Warm/cool exergy transferred by convection from the whole of skin and clothing surfaces into the surrounding air].
(3.6)

The first term of eq.(3.6) is the warm exergy produced as the result of chemical exergy consumption for a variety of cellar activities, mainly for the contraction of muscle tissues, the composition of proteins, and the sustenance of the relative concentrations of various minerals in the body cells. The metabolic exergy balance can be expressed as follows:

[Chemical exergy supply]
– [Exergy consumption]
= [Exergy supply for body function]
+ [Warm exergy generated]
(3.7)

The chemical exergy supplied to the human body by eating food is the exergy trapped by the special compositions of carbon, hydrogen, oxygen, nitrogen and other miscellaneous atoms, which originates from the short-wavelength radiant exergy provided by solar radiation. The hydrogen atoms in the liquid water generated by metabolism originate from the hydrogen atoms contained within the liquid water molecules absorbed by the roots of plants for photosynthesis. All of the warm and wet exergies generated within the human body come from the matters brought by other living creatures. This is the important fact that we should keep in mind. The second term of the right-hand side of eq.(3.7) is exactly the warm exergy appeared in the first term of eq.(3.6).

The exergy-consumption appeared in the last term of the left-hand side of eq.(3.6) is due to two kinds of dispersion: one is thermal dispersion caused by the temperature difference between the body core, whose temperature is almost constant at 37°C, and the body shell, namely the skin, whose temperature range from 30 to 35°C, and the clothing surface, whose temperature range from 20 to 35°C; the other is dispersion of liquid water into water vapor, in other words, free expansion of water molecules into their surrounding space.

The chemical exergy consumption appeared in eq.(3.7) usually amounts to more than 95% of chemical exergy supply. It implies that the amount of entropy generated in due course is very large, since the amount of entropy generation is exactly proportional to that of exergy consumption.

All terms in the right-hand side of eq.(3.6) except the first term, exergy storage, play important roles respectively in disposing of the generated entropy due to chemical exergy consumption within the human body, while at the same time disposing of the generated entropy due to thermal exergy consumption appeared in eq.(3.6). These processes of outgoing exergy flow together with exergy consumption influence very much on human well-being: health and comfort.

Tables 3.2-a), b) and c) summarize the details of all terms of eq.(3.6) to make numerical calculation. Those interested in the derivation of mathematical formulae in Table 3.2-a) are welcome to go through Appendices from A.1 to A.3.

The procedure of calculation is as follows:

1) Assume six variables: metabolic energy generation rate; amount of clothing in clo unit; surrounding air temperature; surrounding air relative humidity; mean radiant temperature; air current.
2) Calculate the body-core temperature, the body-shell (skin) temperature, the clothing-surface temperature, and the skin-wettedness. These values can be determined by following the procedure given by Gagge et al.[6)~8)].
3) Calculate the sweat-secretion rate using the skin wettedness.
4) Substitute the results of three calculated temperatures and the sweat-secretion rate into the terms given in Table 3.2-a) and calculate their values except the term of exergy consumption.
5) Substitute the values of exergy obtained from the above calculation into eq.(3.6) and then calculate the value of exergy consumption.

The infinitesimal time interval, dt, given in Table 3.2-a) is replaced to be the finite increment of time, Δt, e.g. 300 seconds, for actual numerical calculation. The same applies to the values of dT_{cr} and dT_{sk}. For example, The infinitesimal temperature change, dT_{cr}, is replaced to be a finite difference in temperature between time n and time $n-1$, so that the skin temperature at time n is calculated from that at time $n-1$.

If the average rate of exergy input, consumption, storage and output are to be calculated, then the values obtained from the calculation above are divided by the assumed finite increment of time, Δt.

Table 3.2-a): The mathematical formulae of the respective terms in eq.(3.6)

Warm exergy generated by metabolism	$M(1-\frac{T_o}{T_{cr}})dt$
Warm/cool and wet/dry exergies of the inhaled humid air	$V_{in}\left[\begin{array}{l}\left\{c_{pa}(\frac{\mathfrak{M}_{\mathfrak{a}}}{RT_{ra}})(P-p_{vr})+c_{pv}(\frac{\mathfrak{M}_{\mathfrak{w}}}{RT_{ra}})p_{vr}\right\}\left\{(T_{ra}-T_o)-T_o\ln\frac{T_{ra}}{T_o}\right\} \\ +\frac{T_o}{T_{ra}}\left\{(P-p_{vr})\ln\frac{P-p_{vr}}{P-p_{vo}}+p_{vr}\ln\frac{p_{vr}}{p_{vo}}\right\}\end{array}\right]dt$
Warm and wet exergies of the liquid water generated in the core by metabolism	$V_{w-core}\rho_w\left[\begin{array}{l}c_{pw}\left\{(T_{cr}-T_o)-T_o\ln\frac{T_{cr}}{T_o}\right\} \\ +\frac{R}{\mathfrak{M}_{\mathfrak{w}}}T_o\ln\frac{p_{vs}(T_o)}{p_{vo}}\end{array}\right]dt$
Warm/cool and wet/dry exergies of the sum of liquid water generated in the shell by metabolism and dry air to let the liquid water disperse	$V_{w-shell}\rho_w\left[\begin{array}{l}c_{pw}\left\{(T_{sk}-T_o)-T_o\ln\frac{T_{sk}}{T_o}\right\} \\ +\frac{R}{\mathfrak{M}_{\mathfrak{w}}}T_o\left\{\ln\frac{p_{vs}(T_o)}{p_{vo}}+\frac{P-p_{vr}}{p_{vr}}\ln\frac{P-p_{vr}}{P-p_{vo}}\right\}\end{array}\right]dt$
Warm/cool radiant exergy absorbed by the whole of skin and clothing surfaces	$f_{eff}f_{cl}\sum_{j=1}^{N}a_{pj}\varepsilon_{cl}h_{rb}\frac{(T_j-T_o)^2}{(T_j+T_o)}dt$
Exergy consumption rate, which is only for thermoregulation	$\delta S_g T_o$
Warm exergy stored in the core and the shell	$Q_{core}(1-\frac{T_o}{T_{cr}})dT_{cr}+Q_{shell}(1-\frac{T_o}{T_{sk}})dT_{sk}$
Warm and wet exergies of the exhaled humid air	$V_{out}\left[\begin{array}{l}\left\{c_{pa}(\frac{\mathfrak{M}_{\mathfrak{a}}}{RT_{cr}})(P-p_{vs}(T_{cr}))+c_{pv}(\frac{\mathfrak{M}_{\mathfrak{w}}}{RT_{cr}})p_{vs}(T_{cr})\right\}\left\{(T_{cr}-T_o)-T_o\ln\frac{T_{cr}}{T_o}\right\} \\ +\frac{T_o}{T_{cr}}\left\{(P-p_{vs}(T_{cr}))\ln\frac{P-p_{vs}(T_{cr})}{P-p_{vo}}+p_{vs}(T_{cr})\ln\frac{p_{vs}(T_{cr})}{p_{vo}}\right\}\end{array}\right]dt$
Warm/cool exergy of the water vapor originating from the sweat and wet/dry exergy of the humid air containing the evaporated sweat	$V_{w-shell}\rho_w\left[\begin{array}{l}c_{pv}\left\{(T_{cl}-T_o)-T_o\ln\frac{T_{cl}}{T_o}\right\} \\ +\frac{R}{\mathfrak{M}_{\mathfrak{w}}}T_o\left\{\ln\frac{p_{vr}}{p_{vo}}+\frac{P-p_{vr}}{p_{vr}}\ln\frac{P-p_{vr}}{P-p_{vo}}\right\}\end{array}\right]dt$
Warm/cool radiant exergy discharged from the whole of skin and clothing surfaces	$f_{eff}f_{cl}\varepsilon_{cl}h_{rb}\frac{(T_{cl}-T_o)^2}{(T_{cl}+T_o)}dt$
Warm/cool exergy transferred by convection from the whole of skin and clothing surfaces into the surrounding air	$f_{cl}h_{ccl}(T_{cl}-T_{ra})(1-\frac{T_o}{T_{cl}})dt$

Table 3.2-b): The mathematical symbols used in Table 3.2-a)

Every term in Table 3.2-a) is expressed for the infinitesimal period of time, and for one squared-meter of human-body surface. The symbols used in the formulae from the top to the bottom denote as follows.

M	metabolic energy generation rate [W/m^2]
T_o	outdoor air temperature as environmental temperature for exergy calculation [K]
T_{cr}	body-core temperature [K]
t	time [s] and dt is its infinitesimal increment
V_{in}	volumetric rate of inhaled air [(m^3/s)/ m^2]
c_{pa}	specific heat capacity of dry air [J/(kg K)] (=1005)
$\mathfrak{M}_{\mathfrak{a}}$	molar mass of dry air [g/mol] (=28.97)
R	gas constant [J/(mol K)] (=8.314)
T_{ra}	room air temperature [K]
P	atmospheric air pressure [Pa] (=101325)
p_{vr}	water-vapor pressure in the room space [Pa]
c_{pv}	specific heat capacity of water vapor [J/kg K] (=1846)
$\mathfrak{M}_{\mathfrak{w}}$	molar mass of water molecules [g/mol] (=18.05)
p_{vo}	water-vapor pressure of the outdoor air [Pa]
V_{w-core}	volumetric rate of liquid water generated in the body core, which turns into water vapor and is exhaled through the nose and the mouth [(m^3/s)/ m^2]
ρ_w	density of liquid water [kg/m^3] (=1000)
c_{pw}	specific heat capacity of liquid water [J/(kg K)] (=4186)
$p_{vs}(T_o)$	saturated water-vapor pressure at outdoor air temperature [Pa]
$V_{w-shell}$	the volumetric rate of liquid water generated in the body shell as sweat [(m^3/s)/ m^2]
T_{sk}	skin temperature [K]
f_{eff}	the ratio of the effective area of human body for radiant-heat exchange to the surface area of the human body with clothing (=0.696~0.725)
f_{cl}	the ratio of human body area with clothing to the naked human body area (=1.05~1.5)
a_{pj}	absorption coefficient between the human body surface and a surrounding surface denoted by j [dimensionless] (it can be assumed to be equal to configuration factor, the ratio of incoming diffuse radiation to the human body to the diffuse radiation emitted from surface j in most cases);
ε_{cl}	emittance of clothing surface [dimensionless](its value is usually higher than 0.9)
h_{rb}	radiative heat-transfer coefficient of a black surface [W/(m^{2}K)] (=5.7~6.3)
T_j	temperature of surface j [K]
δS_g	amount of entropy generation during the infinitesimal period of time [(Onnes/s)/m^2] ("Onnes" is the unit of entropy, exactly equal to J/K. "Onnes" comes from H. Kammerlingh-Onnes, a Dutch scientist , who first succeeded in liquefaction of helium and reaching 4.1 K in due course[14].)
Q_{core}	heat capacity of body core [J/(m^{2}K)]
dT_{cr}	infinitesimal increment of body-core temperature [K]
Q_{shell}	heat capacity of body shell [J/(m^{2}K)]
dT_{sk}	infinitesimal increment of skin temperature [K]
V_{out}	volumetric rate of exhaled air [(m^3/s)/ m^2]
$p_{vs}(T_{cr})$	saturated water-vapor pressure at body-core temperature [K]
T_{cl}	clothing surface temperature [K]
h_{ccl}	average convective heat-transfer coefficient over clothed body-surface [W/(m^{2}K)]

Table 3.2-c): Footnotes for Table 3.2-b)

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*1 The value of V_{in} can be determined from the empirical formula given for human-body energy balance calculation[7] as a function of metabolic generation rate. $V_{in} \approx 1.2\text{x}10^{-6} M$.

*2 The value of V_{w-core} can be determined from the empirical formula as a function of metabolic energy generation rate and water-vapor pressure in the room space.

$$V_{w-core} \approx 1.2\text{x}10^{-6} M \cdot (0.029 - 0.049\text{x}10^{-4} p_{vr})$$

*3 The value of $V_{w-shell}\rho_w$ is given as the product of the skin wettedness, w [dimensionless], and the maximum evaporative potential from the skin surface to the surrounding room space, E_{max} [W/m²], divided by the latent-heat value of evaporation of liquid water at 30 °C (=2450 J/g). $V_{w-shell}\rho_w \approx w \cdot E_{max} / 2450$.

The value of w is determined by the calculation procedure given for effective temperature based on human-body energy balance by Gagge et al. [6~8]. The value of E_{max} can be determined as the product of evaporative heat-transfer coefficient, which is proportional to convective heat-transfer coefficient via a Lewis-relation constant, and the difference in water-vapor pressure between liquid water at skin-surface temperature and room air.

*4 The values of Q_{core} and Q_{shell} are given by the following formulae[9].
$Q_{core} = (1 - \alpha_{sk})(m_{body} / A_{body}) \cdot c_{body}$ and $Q_{shell} = \alpha_{sk}(m_{body} / A_{body}) \cdot c_{body}$, where α_{sk} is the fractional skin mass depending on the blood flow rate to the body shell (skin); m_{body} / A_{body} is the ratio of body mass to body-surface area [kg/m²]; and c_{body} is specific heat capacity of human body that is 3490 J/(kg K).

*5 The value of V_{out} is assumed to be equal to that of V_{in}.

*6 We assume that the boundary-surface temperature of human-body system is represented by the average clothing temperature. Therefore, thermal exergy outflow by radiation and convection from the human body includes the clothing temperature(see the last two columns of Table 3.2-a).) The water vapor pressure for the calculation of wet/dry exergy of humid air coming out from the human-body system should also, strictly speaking, be based on the value at the clothing surface. But, in reality, much dispersion of water vapor takes places directly at the skin surface such as forehead, neck, arms and so on. For this reason together with the avoidance of unnecessarily complicated calculation, we use water vapor pressure in the room space for the calculation of wet/dry exergy of the humid air containing the evaporated sweat (see the third row from the bottom of Table 3.2-a).).

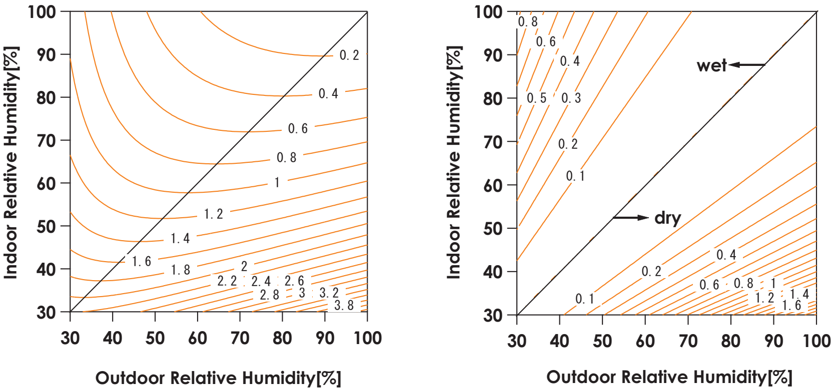
*7 The value of h_{ccl} can be determined by one of the empirical formulae of convective heat-transfer coefficient of the human body as a whole, which is given for human-body energy balance calculation[8].

4 SOME NUMERICAL EXAMPLES AND THEIR DISCUSSION

Here in this section, we first show some numerical examples of wet exergy given by sweat, warm/cool exergy in relation to radiation and convection, a whole exergy balance under typical outdoor/indoor conditions in winter and in summer, and thereby discuss their essential characteristics. Finally some results of the sensitivity analysis of exergy consumption rates with respect to mean radiant temperature and room air temperature in winter conditions and those with respect to mean radiant temperature and air movement in summer conditions are given and discussed.

4.1 Wet Exergy Consumption by Evaporation of Water as Sweat

Wet exergy contained by liquid water as sweat originating from the skin surface is consumed more or less until it reaches the surrounding humid air. This relates much to the effectiveness of human-body entropy disposal.



a) Wet exergy contained by the sum of sweat and its associated dry air

b) Wet/dry exergy of the humid air after the evaporation of sweat

Figure 4.1: Rates of wet exergy contained by the sum of sweat and its associated dry air, a), and wet/dry exergy of the humid air after the evaporation of sweat, b). All of the lines in these graphs represent the equi-exergy flow rate in the unit of W/m².

Figure 4.1-a) shows the wet exergy contained by the sum of liquid water generated in the body shell as sweat and dry air to let this liquid water disperse, while on the other hand -b) shows the wet/dry exergy of humid air containing the water vapor originated from the sweat. Each line of respective graphs represents equi-exergy flow rate of wet exergy or dry exergy for 1 m^2 of body surface area with the outdoor air humidity on the horizontal axis and with the indoor air humidity on the vertical axis. In these graphs, the outdoor air temperature is assumed to be 30°C and equal to the indoor air temperature and mean radiant temperature. The sweat secretion rate is assumed to be 0.013 g/(s m^2), which is given by the calculation of skin wettedness[6~8]. For example, wet-exergy flow rate of 0.13 W/m^2 corresponds to the liquid water containing 10 J/g (=0.13/0.013) of wet exergy coming out from the skin surface each second.

The wet exergy values indicated just on the diagonal line in the left-hand side graph are those for the condition of outdoor air humidity being equal to indoor air humidity, which are the smallest for a variety of outdoor air humidity values.

As can be seen in the right-hand side graph, there is “wet” exergy in the cases of indoor air humidity higher than outdoors and “dry” exergy in the opposite cases. “Dry” exergy contained by a certain amount of resultant humid air even after sweat evaporation implies that this volume of humid air still holds a capacity to let disperse the water vapor contained by outdoor air. Their values are, whether they are wet exergy or dry exergy, much smaller than the wet exergy values to be found in the left-hand side graph, the sum of sweat and dry air. Their difference is the exergy consumption due to sweat evaporation.

For example, in the case of indoor air humidity of 70% at the condition of outdoor air humidity of 60%, the sum of liquid water as sweat and its associated dry air flows out at the rate of 0.65 W/m^2 of wet exergy, while on the other hand, the corresponding humid air after evaporation flows at the rate of 0.05W/m^2 into the surrounding humid air. Their difference, 0.6 W/m^2 is the exergy consumption rate due to the evaporation of sweat.

4.2 Warm/Cool Radiant Exergies Coming in and Going Out

Thermal radiative exergy exchange between the human body and his/her surrounding surfaces influences very much on thermal comfort so that it is important not only to understand its qualitative aspect, but also to grasp the orders of thermal exergy values available indoors.

Figure 4.2-a) and -b) show the radiant exergy incident upon human body and that emitted from the human body, respectively. These two graphs are drawn with an assumption of mean radiant temperature equal to room air temperature. The horizontal axis represents outdoor air temperature as environmental temperature for exergy calculation and the vertical axis the mean radiant temperature.

Radiant exergy incident upon the human-body surface becomes null if the outdoor air temperature equals the mean radiant temperature. The diagonal line in Figure 4.2-a) represents such a case. The left-hand side of this diagonal line represents the cases that "warm" radiant exergy is incident upon the whole of human body and the right-hand side the cases that "cool" radiant exergy is incident upon the human-body surface.

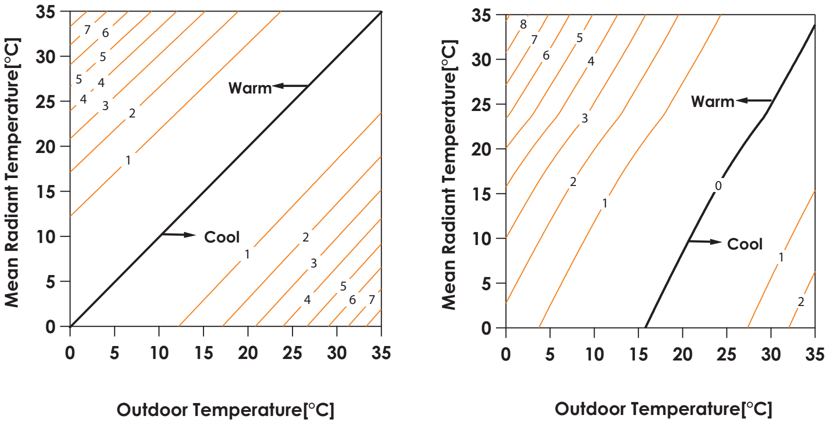
In Figure 4.2-b), the line with neither warm nor cool exergy emission, namely 0 W/m², corresponds to the condition that the clothing temperature is just equal to the outdoor air temperature. The left-hand side of this line is the cases that warm radiant exergy is emitted from the whole of human-body because of the clothing temperature higher than the outdoor air temperature. The right-hand side of this line is the cases that "cool" radiant exergy is emitted because of the clothing temperature lower than the outdoor air temperature.

For example, under a winter condition of outdoor air temperature of 5°C, if the mean radiant temperature is controlled at 20°C, "warm" radiant exergy of 1.5 W/m² is available at the body surface. On the other hand, emitted by the human body is warm radiant exergy of 3.6W/m². Under such winter condition, net warm radiant exergy transfer from the human body to the surrounding surfaces turns out to be 2.1 (=3.6-1.5) W/m².

If the mean radiant temperature is lower than 20°C, say 15°C, the warm radiant exergy received reduces to 0.8 W/m² from 1.5 W/m², while on the other hand, the warm radiant exergy emitted reduces to 2.4 W/m² from 3.6 W/m². Radiant exergy values in the case of 15°C of mean radiant temperature are smaller than those in the case of 20°C and the net warm radiant exergy transfer turns out to be 1.6 (=2.4-0.8) W/m², which is also smaller than that in the case of 20°C of mean radiant temperature.

Radiant-exergy exchange between the human-body surface and the surrounding surfaces at a higher temperature level must relate much to the thermal comfort in winter with less cognition of draught. Such a condition is usually more comfortable than conventional forced convective heating that has been used much in the room spaces with low mean radiant temperature due to poor thermal insulation for building envelopes.

An appropriate use of heat capacity of the walls together with the external insulation and of thermally-well insulating glass windows and sashes enable us to have higher interior surface temperatures, which fluctuate less for the whole period of one day. Such an indoor condition lets the warm radiant exergy available in the room space be at a favorably high level and thereby let the cognition of warmth emerge[15)16)]. Actual examples of this kind of condition are the well-designed passive solar houses or those buildings with thermally activated floors or walls together with appropriate thermal insulation for the windows and the walls.



a) Warm/cool radiant exergy rate incident on one squared-meter of body surface

b) Warm/cool radiant exergy rate emitted from one squared-meter of body surface

Figure 4.2: Warm/cool radiant exergy rates incident upon and emitted from the human-body surface area of 1 m². The former is shown on your left and the latter right. In either of these graphs, there is the line indicating the case of exergy rate at null, which split warm exergy side in its left and cool exergy in its right.

Let us discuss a summer case with a similar viewpoint to the winter case described above. Under a summer condition of outdoor air temperature of 30°C, if the mean radiant temperature is 25°C, "cool" radiant exergy of about 0.3 to 0.4 W/m² (=300 to 400 mW/m²) is available. If the mean radiant temperature rises to 28°C, there is still a small rate of cool radiant exergy available from the surrounding surfaces, around 0.02 to 0.06 W/m² (=20 to 60 mW/m²) . Such amounts of rather small radiant exergy rate seems to play a key role in providing the occupants with adaptive thermal comfort with natural ventilation[17)18)].

"Cool" radiant exergy available from the sky on a horizontal surface ranges from 0.5 to 1 W/m², namely from 500 to 1000 mW/m² [19)20)]. A radiant cooling system, which makes the ceiling or wall surface temperature a little lower than outdoor air temperature, let those surfaces emit about 0.02 W/m² (20 mW/m²) of cool radiant exergy quite easily. This is even possible by nocturnal ventilation, if the room space is equipped with an appropriate level of heat capacity together with external shading and insulation as well as the internal heat generation is minimized[18)]. The fact that the rate of radiant exergy to be available indoors necessary for having coolness is very small, say 20 mW/m² or so, and it is only one-fiftieth of cool radiant exergy rate from the sky, is worthwhile keeping in mind. This kind of exergetic consideration let us recognize the importance of natural exergy to be found in our immediate outdoor environment[1)].

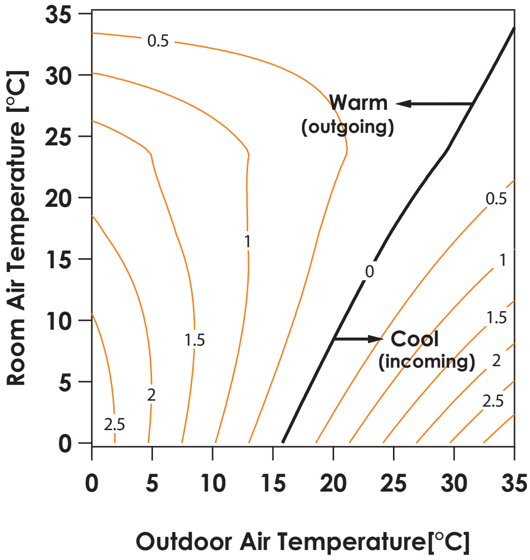


Figure 4.3: Warm/cool exergy flow rate by convection between the human body and the surrounding air. The exergy values are indicated with the unit of W/m². The left-hand side of the line indicating the warm/cool exergy flow rate of zero represents the cases that warm exergy is going out from the human body, and the right-hand side the cases that cool exergy is coming into the human-body.

4.3 Warm/Cool Exergy Transfer by Convection

Convection due to air movement affects very much on thermal comfort levels as well as radiation. This is the well-known fact by our own daily experience. Discussed here are some pieces of findings from human-body exergy analyses focusing on thermal-exergy transfer by convection.

Figure 4.3 shows the relationship between room air temperature and "warm/cool" exergy transferred by convection between the whole of human body and the room air. Air movement is assumed to be 0.1 m/s for the whole of Figure 4.3. The horizontal axis represents outdoor air temperature and the vertical axis room air temperature, which is assumed to equal the mean radiant temperature. Under a condition that the clothing temperature is equal to outdoor air temperature, there is neither warm nor cool exergy transferred by convection. This is indicated by the bold line going upward from around the middle of horizontal axis to the upper right corner of the graph. The left-hand side of this line corresponds to the cases that warm exergy is flowing out from the human-body surface into the room air and the right-hand side of this line the cases that cool exergy is flowing onto the human-body surface from the room air by convection.

Under a winter condition of outdoor air temperature of 5°C, if the room air temperature is controlled at 20°C, about 1.7 W/m² of "warm" exergy flows out by convection from the human body. Even if the room air temperature is raised up to 30°C, there is still 0.9 W/m² of warm exergy flowing out by convection. This confirms that the purpose of space heating is not to provide a human body with a certain amount of "warm" exergy, but to let him/her dissipate warm exergy at an appropriate rate by convection[b].

Under a summer condition of outdoor air temperature of 30°C, if the room space is naturally ventilated with a sufficient number of air change and thereby the room air temperature is about the same as outdoor air temperature, 0.1 to 0.2 W/m² of "warm" exergy flows out from the human body by convection. On the other hand, if the room air temperature is controlled at 24°C or lower, the human body does necessarily receive about 0.1 W/m² of "cool" exergy by convection. Symptoms of so-called space-cooling syndrome, *"reibo-byo"* in Japanese, which is one of the combination of dullness, fatigue, and/or stiffness felt around shoulders and legs, and/or dried eyes usually emerge in such a room condition of low air temperature and humidity. "Cool" exergy, probably together with "dry" exergy, given by convection could be its primary cause[21)22)]. If this is so, the purpose of space cooling is not to provide a human body with "cool" exergy by convection.

According to the above discussion so far, the purpose of space heating and cooling seems to be neither to provide the human body with "warm" exergy nor "cool" exergy, but to make the human body discharge "warm" exergy at an appropriate rate, that is exactly for entropy disposal.

4.4 Exergy Balance under Typical Conditions

Following the discussion from 4.1 to 4.3 on the characteristics of the respective terms appeared in the human-body exergy balance equation, let us move onto the discussion on the whole exergy balance of a human body under some typical summer and winter conditions.

The general form of exergy balance equation for a system is expressed as follows.

$$\text{[Exergy input]} - \text{[Exergy consumption]} = \text{[Exergy stored]} + \text{[Exergy output]} \quad (4.1)$$

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b) *If convective exergy flow rate calculated from the term given in Table 3.2-a) turns out to be positive, it implies "outgoing warm exergy". If the calculated result is negative, it implies "incoming cool exergy"[18)]. More about convective thermal exergy calculation is described in Appendix A.5.*

What we described in 3.3 was to give all terms of the above equation in detail, specific to the human body residing in a room space. Equation (4.1) may be rewritten as follows.

[Exergy input] = [Exergy consumption] + [Exergy stored] + [Exergy output]
(4.2)

All of the twin-bar graphs shown in Figures 4.4.1 to be discussed below are consistent with the expression given in equation (4.2). Let us explain this further taking a look at Figure 4.4.1, which shows three numerical examples of the whole human-body exergy balance in a winter condition, outdoor air temperature and relative humidity of 0°C and 40%, respectively. The indoor operative temperature in these three examples is assumed to be 22°C equal to each other, but the combination of mean radiant temperature and surrounding air temperature are different from each other: they are, from the top to the bottom, 22°C; 22°C, 19°C; 25°C, and 25°C; 19°C.

The left-hand-side bars shows the exergy input and the right-hand-side bars the sum of exergy consumption, exergy stored, and exergy outputs. The exergy input consists of five components:

1) metabolic thermal exergy, which is given by chemical-exergy consumption within all of the human-body cells;
2) the sum of the exergy contained by the inhaled humid air;
3) the exergy contained by liquid water generated in the body core;
4) the exergy contained by the sum of liquid water as sweat together with dry air for mutual dispersion; and
5) warm radiant exergy.

In Figure 4.4.1, three components associated with the inhaled humid air and liquid water emerged in the body-core and in the body–shell are not so large as other two components so that they are shown all together as one to be "Humid air + Water". Since the exergy stored is very small compared to the exergy consumption and other terms of exergy output, it is not apparent in the bars shown in Figure 4.4.1.

The exergy output consists of four components:

1) the exergy contained by the exhaled humid air;
2) the exergy contained by the resultant humid air containing the evaporated sweat;
3) warm radiant exergy discharged from the whole of skin and clothing surfaces; and
4) warm exergy transferred by convection from the whole of skin and clothing surfaces into the surrounding air.

If the convective exergy transfer to be calculated as one of the outputs turns out to be negative, it implies that there is cool-exergy inflow by convection; this results in the number of input components being six, while on the other hand, that of output three, although such a case is not likely to occur in ordinary winter conditions.

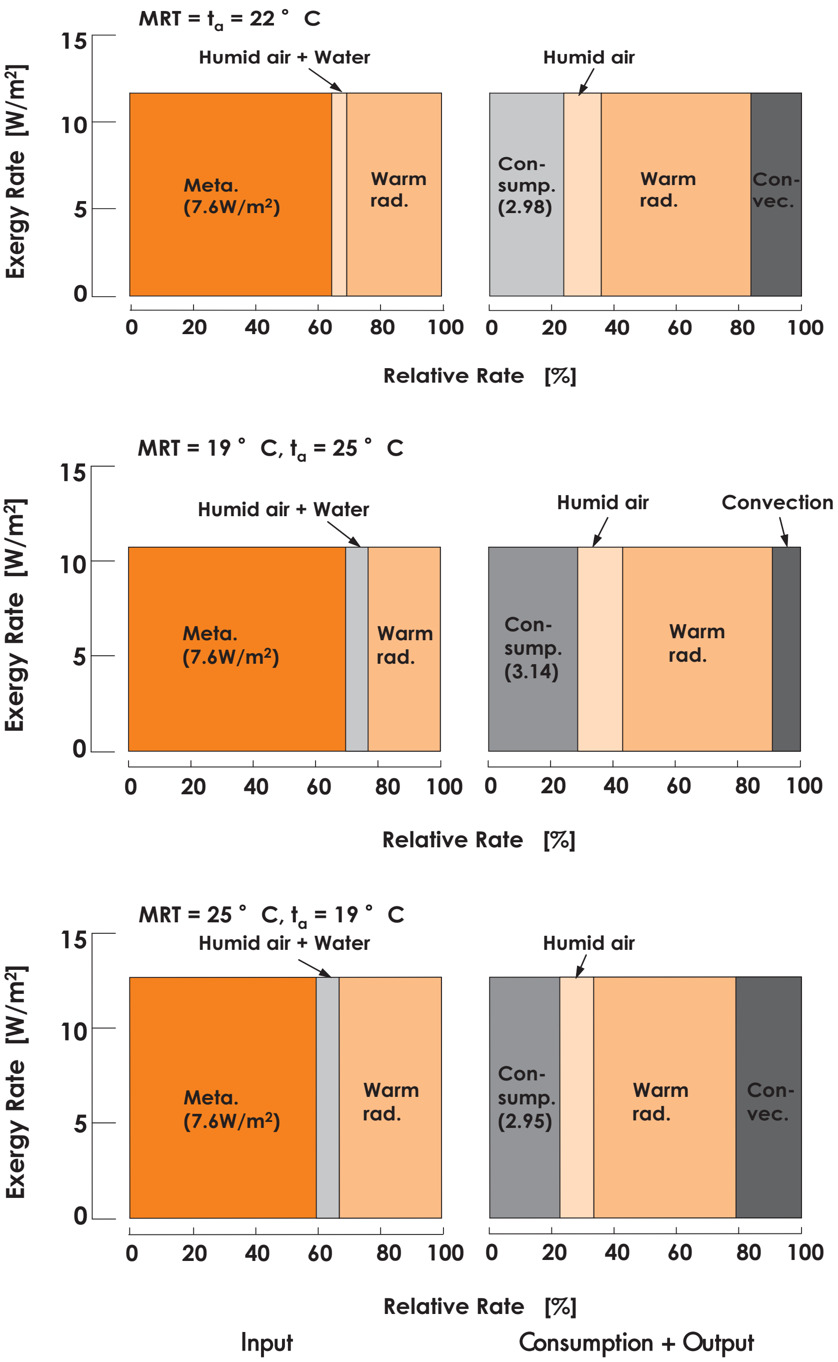


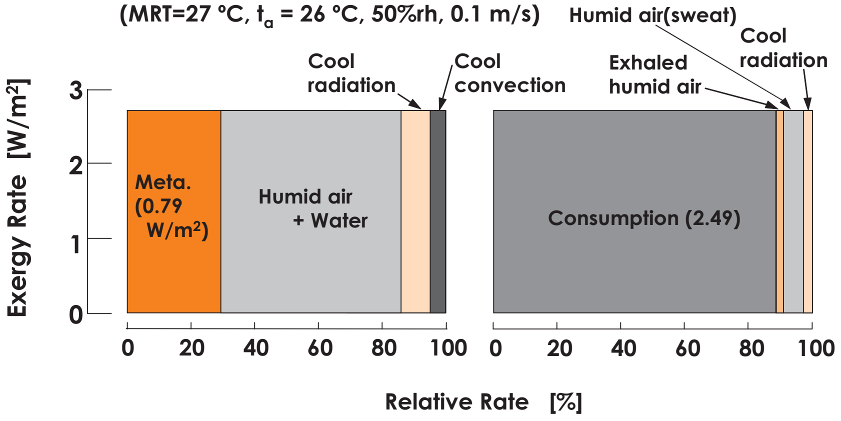
Figure 4.4.1: Three examples of the whole human-body exergy balance under typical winter condition(outdoor air temperature and relative humidity: 0°C and 40%). Exergy stored is negligibly small so that it is not shown in these graphs.

The height of each bar indicates the value of input exergy rate, which is exactly the same as the sum of exergy consumption rate, exergy stored rate, and the output exergy rate. The relative magnitudes of the components explained above are indicated by their corresponding widths in the horizontal direction.

The input exergy rates are different from each other, though the operative temperature of the three cases is the same. The smallest is given in the case of the mean radiant temperature lower than the surrounding air temperature, while on the other hand, the largest in the case of the mean radiant temperature higher than the surrounding air temperature.

More than 60% of the input exergy rate is the metabolic exergy of 7.6 W/m^2 for all three cases, 5 to 15 %, the warm/wet exergy contained by the inhaled humid air and the liquid water to be discharged mostly from the lung cells, and the rest, 25 to 35 % the warm radiant exergy absorption.

Convective cooling
(MRT=27 °C, t_a = 26 °C, 50%rh, 0.1 m/s)



Radiant panel + Natural ventilation
(MRT=27 °C, t_a = 30 °C, 65%rh, 0.3 m/s)

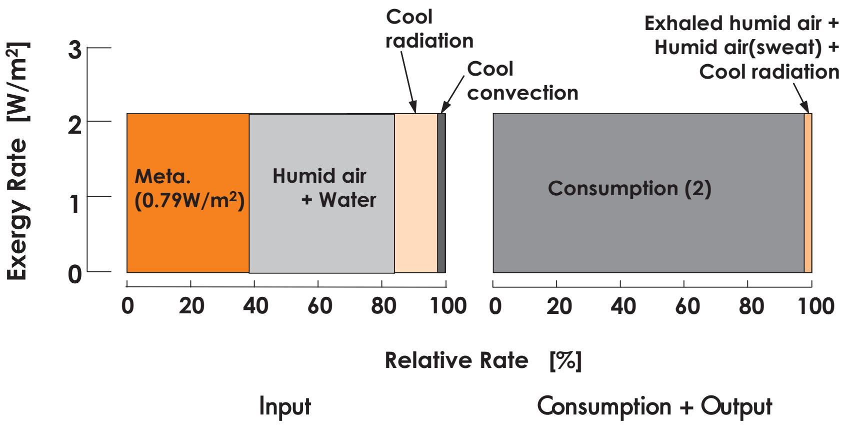


Figure 4.4.2: Two examples of the whole human-body exergy balance under typical summer condition(outdoor air temperature and relative humidity:33°C and 60%). Exergy stored and exergy contained by the inhaled air is negligibly small so that they are not shown in these graphs.

The exergy-consumption rate amounts to 20 to 30 % of the input exergy rate and they are different from each other in three cases, among which the smallest is in the case of the mean radiant temperature higher than the surrounding air temperature, while on the other hand, the largest in the case of the mean radiant temperature lower than the surrounding air temperature. In general, the smaller the difference in temperature between the core and the shell of the human body, the smaller also the exergy consumption rate is.

Relative rates of warm radiant exergy emission and convective warm exergy transfer are very large in the case of the mean radiant temperature higher than the surrounding air temperature, compared to those in the case of the mean radiant temperature lower than the surrounding air temperature.

In winter, it is very important to make both the absorption and emission of warm radiant exergy by raising the interior surface temperature so that the average temperature of the skin and clothing surfaces becomes sufficiently high and thereby the occupants do feel comfortable. The fact that the relative rate of warm exergy transfer by convection becomes larger in the case of higher mean radiant temperature than the surrounding air temperature is due to such skin and clothing surface temperature rise. This results in the above-mentioned consequence of a smaller exergy consumption rate.

Figure 4.4.2 shows two examples of the whole human-body exergy balance under a typical summer condition in hot and humid regions, outdoor air temperature and relative humidity of 33°C an 60%, respectively. How to read these twin-bar graphs are exactly the same as Figure 4.4.1. The twin-bar graph at the top shows a case of radiant cooling together with natural ventilation and that at the bottom a case of mechanical air cooling. For the former, the surrounding air temperature, humidity and air movement are assumed to be 30°C; 65% and 0.3 m/s, respectively, and for the latter, 26°C; 50 %, and 0.1 m/s, respectively. For both cases, the mean radiant temperature is assumed to be 27°C.

The profiles of exergy balance in summer cases are quite different from those in winter cases. There are four apparent differences. One is that the absolute values of exergy input rate in summer are much smaller than those in winter; this is because of a small temperature difference between indoors and outdoors in summer. The second is that the relative rates of wet exergy contained by liquid water, especially in the body-shell rather than in the body-core, are much larger than those in winter. The third is that there is cool exergy provided by convection in addition to radiation, though its relative magnitude is smaller than that of cool radiant exergy. The fourth is that the relative rates of exergy consumption are very large compared to the output exergy rate.

The metabolic exergy rate is warm exergy given inside the human body. With this fact in mind, all of the wet exergy of liquid water given inside the human body and the cool radiant exergy coming onto the human body in addition to cool exergy transferred by convection is to let this inevitable metabolic "warm" exergy be consumed in order to maintain the human body within a desirable thermally-well-being state.

The relative magnitude of the output exergy rates are small as mentioned above, but it does not imply that they are less important; they are essential in disposing of the generated entropy inside the human body due to exergy consumption of "warm" and "wet"/"cool" exergies. In other words, the output exergy rates are small, since they contain a lot of entropy to be discarded into the environmental space for the human body.

4.5 Human-body Exergy Consumption Rate in Winter and in Summer

As described in 3.3, the values of exergy consumption can only be obtained from the exergy balance equation, once all other terms of exergy inputs, storage and output are calculated. The exergy consumption rate is the function of the difference in temperature and also water-vapor pressure between the core of the human body and its surrounding space, so that it must relate much to the conditions of thermal comfort. Here, we show three numerical examples of the exergy consumption rate in relation to mean radiant temperature and air temperature in winter cases and mean radiant temperature and air movement in summer cases.

Figure 4.5.1 shows an example for winter condition[12][13]. 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 the human body. The metabolic condition is assumed to be for sedentary work, clothing for winter and room air is still, air velocity lower than 0.1 m/s.

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 4.5.1 must give a comfortable indoor thermal condition.

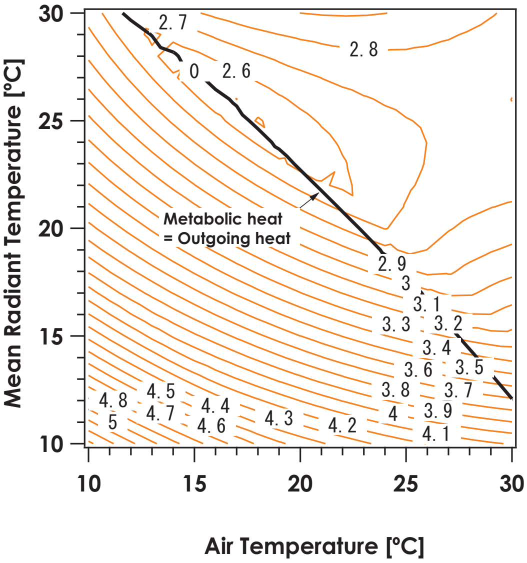


Figure 4.5.1: Relationships between human-body exergy consumption rate, whose unit is W/m^2 (body surface), and his/her environmental temperature under a winter condition (0ºC; 40%rh). There is a set of room air temperature (18 to 20 ºC) and mean radiant temperature (23 to 25 ºC) which provides him/her with the lowest exergy consumption rate. This relationship was first found by Isawa and Shukuya (2002, 2003).

There is a set of room air temperature (18 to 20 ºC) and mean radiant temperature (23 to 25 ºC) which provides him/her with the lowest exergy consumption rate. 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 sounds consistent with such an indoor condition that brings about the lowest exergy consumption rate within the human body as shown in Figure 4.5.1. It suggests that the human body as a biological system has evolved over long years since the birth of life on the earth so that humans can feel the most comfortable with the lower exergy consumption rate, at least in winter conditions.

The relationship given in Figure 4.5.1 is yet further to be investigated in relation to the preference of occupants by experiments in-vitro, laboratory tests, and in-vivo, field surveys.

We can make a similar chart to Figure 4.5.1 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 the 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 an indoor condition of a little lower mean radiant temperature than air temperature during daytime, which is comfortable enough especially in residential buildings. Figure 4.5.2 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[18].

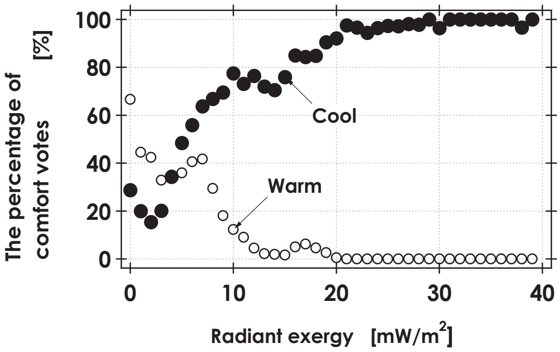


Figure 4.5.2: The percentage of comfort votes under the condition of no perceived air current as a function of radiant exergy emitted from interior wall surfaces.

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/m² results in the condition that no subjects vote for comfort. On the other hand, the same rate of "cool" radiant exergy results in a totally opposite condition in which most of the subjects vote for comfort. An amount of cool radiant exergy rate at 20mW/m² is available provided that the mean radiant temperature is lowered slightly compared to the outdoor air temperature. As can be seen in Figure 4.5.3, interior surfaces whose temperature is 31 ºC emit about 40 mW/m² of cool radiant exergy in the case of outdoor air temperature of 33 ºC.

These results confirm 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 realize 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, at least in Japan. 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 and humidity to be realized by high-exergy supply.

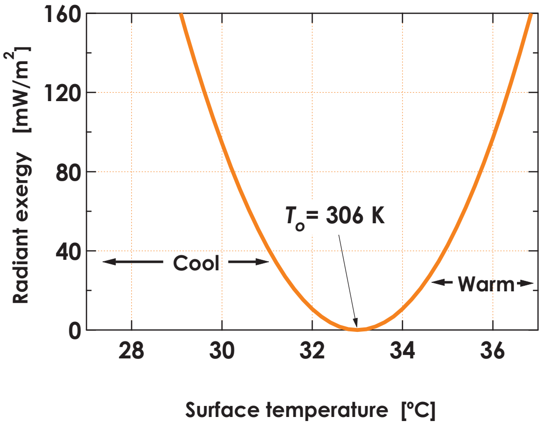


Figure 4.5.3: Radiant exergy available from the interior surfaces of building envelopes in a summer condition. Here in this example, the outdoor air temperature as the environmental temperature for exergy calculation is assumed to be 303 K(=33ºC). The amount of "warm" and "cool" radiant exergy rate ranges from 0 to 250 mW/m².

Recent study by Iwamatsu and Shukuya (2008) shows that there seems to be a set of mean radiant temperature and air-current velocity giving the lowest human-body exergy consumption rate[23]. What follows discusses briefly this result.

Figure 4.5.4 shows a relationship between the human-body exergy consumption rate, whose unit is W/m² (body surface), and the combination of mean radiant temperature and air movement under a summer condition (33ºC;60%rh) in the case of mechanical convective cooling. Room air temperature and relative humidity are assumed to be 26 ºC; 50%rh. The lowest exergy-consumption rate of 2.3 W/m² or less can be found for the range of 0.3 to 0.4 m/s of air movement with mean radiant temperature of about 26 ºC. But, such a rather high air velocity around the human body in a mechanically air-conditioned space must result in discomfort. This is usually due to the fact that the air current coming out from the outlet sweep the body surface directly or indirectly and thereby causes the draught or uncomfortable mechanical patterns of air movement, especially at the hands and foots. This may also cause dried eyes, sore throat and others. Therefore, the air current for mechanical cooling mainly by the use convection should be reduced to the air movement of 0.15 m/s at the highest.

If the air movement is assumed to be 0.1 m/s for this reason, the lowest exergy consumption rate of around 2.4 W/m^2 can be found with the mean radiant temperature of 24 °C, which is 2 °C lower than the room air temperature assumed for this calculation. This is an indoor environmental condition that is rather difficult to realize by a convective cooling system alone, whose task is not to cool the wall surfaces, but the room air. In addition, there are usually some radiant heat sources such as glass windows absorbing more or less the incident solar radiation and electric-lighting fixtures mounted on the ceiling, computer screens and so on.

Therefore, the mean radiant temperature is usually much higher than 24 °C, say 29 to 30 °C. There are some cases that it reaches even higher, almost 31 °C. If this is the case, we can see from Figure 4.5.4 that the human-body exergy consumption rate becomes even slightly larger and reaches around 2.5 to 2.7 W/m^2.

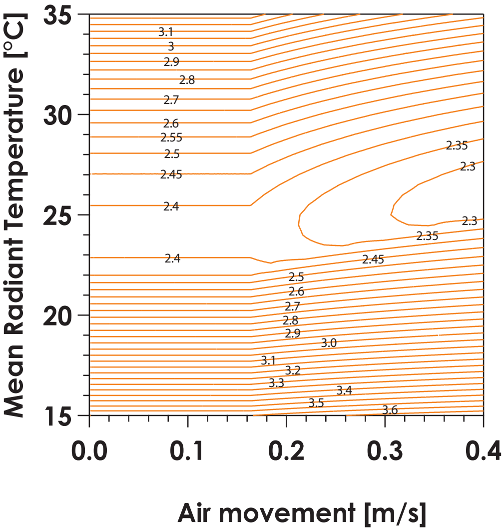


Figure 4.5.4 Relationships between human-body exergy consumption rate, whose unit is W/m^2 (body surface), and the combination of mean radiant temperature and air movement under a summer condition (33°C;60%rh) in the case of convective cooling. Room air temperature and relative humidity are assumed to be 26 °C; 50%rh. This relationship was first found by Iwamatsu and Shukuya (2008).

Figure 4.5.5 shows the same relationships as Figure 4.5.4, but assuming that room air temperature and relative humidity are different; here they are 30 °C and 65%. Such a room air condition during daytime at outdoor air temperature and relative humidity of 33 °C and 60% can be realized by natural ventilation together with radiative cooling wall or ceiling panels, thermally-activated building-envelope system, or with the cool storage by floor, walls and ceiling due to nocturnal ventilation by either an active system or a passive system made during the previous days[24][25].

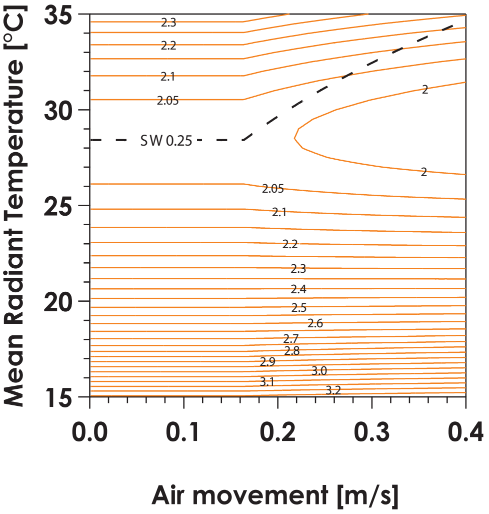


Figure 4.5.5: Relationships between human-body exergy consumption rate, whose unit is W/m^2 (body surface), and the combination of mean radiant temperature and air movement under a summer condition (33°C;60%rh). Room air temperature and relative humidity are assumed to be 30 °C; 65%rh for the indoor air condition by natural ventilation. This relationship was first found by Iwamatsu and Shukuya (2008).

A combination of mean radiant temperature controlled lower than 30 °C, say in the range of 28 to 29 °C, and air movement exceeding 0.2 m/s provides the human body with his/her lowest exergy consumption rate. The lowest exergy-consumption rate turns out to be about 2 W/m^2 for the air movement smaller than 0.2 m/s and even a little less than 2 W/m^2 for the air movement over 0.2 m/s.

In a naturally ventilated room space, almost random natural fluctuation of soft air movement, namely breeze, brings about pleasant coolness, which is called "Suzushisa" in Japanese; this is rather a dynamic condition different from static neutrality of neither hot nor cold. It is interesting that the human-body lowest exergy consumption rate given by convective-cooling conditions is larger than that by natural ventilation with some "cool" radiant exergy to be available from the interior wall surfaces in the room space.

This suggests that passive strategies for indoor thermal environment control such as solar control by external shading device over glass windows and natural ventilation should come to the first priority and then there need to be an active cooling system, which can well suit them. The development of low-exergy cooling systems is to be made on this direction, which is consistent with that of low-exergy heating systems[24][25].

5. CONCLUDING REMARK

This report has described an application of one of the core concepts of thermodynamics, "exergy", to the human-body thermoregulatory system in order to have a better understanding of thermal comfort in the built environment. In due course, we believe that we could demonstrate such a thermodynamic approach to be fruitful in strengthening our thought on the development of sustainable future technology with the rational scientific basis.

The science of thermodynamics has been usually considered to be one of the completed classical sciences and to have no room for a further development, but it is not necessarily true as demonstrated through our discussion in this report.

The important points described in this report are as follows:

1. The concept of exergy can quantify what is consumed for a system to work. It is derived by combining the concept of energy necessarily to conserve, that of entropy necessarily to generate, and that of environmental temperature for the system in question.

2. Any thermodynamic systems work as "exergy-entropy" process, in which exergy is supplied, consumed and thereby entropy is generated and the resultant entropy is discarded into the environmental space for a system in question.

3. With the image of "exergy-entropy" process in mind, we can set up the human-body exergy balance equation with the basis of water-, energy-, and entropy-balance equations with the environmental temperature for exergy calculation.

4. In winter, "warm" radiant exergy supplied to the human-body surface from the surrounding surfaces such as the ceiling, the floor, the walls and the windows plays a key role in providing the human body with a lower exergy consumption rate. Thermal insulation of building envelope such as walls and windows is usually considered for the purpose of reducing the overall heat loss and thereby decreasing the thermal energy requirement, but its role for the purpose of raising the interior surface temperature should be highlighted since it is equivalent to install a passive type of radiant heating panels. In this sense, thermally-activated building envelope systems should be recognized to be attractive as rational low-exergy heating systems.

5. In summer especially in hot and humid regions, it is of vital importance to decrease "warm" radiant exergy available from windows and walls in order to bring about a lower human-body exergy consumption rate. The installation of exterior shading devices over glass windows is essential, while at the same time the role of daylighting should be re-evaluated since the reduction of the internal heat generation caused by electric lighting is also essential. The installation of radiant cooling panels as an active system to provide "cool" radiant exergy indoors is in harmony with the passive strategy for decreasing the "warm" radiant exergy. Therefore, thermally-activated envelope systems are considered to be on the right track. The reduction of "warm" radiant exergy together with providing with a small amount of "cool" radiant exergy makes natural ventilation very effective and attractive.

6. Exergetic research on human-body thermoregulatory system in relations to space heating and cooling confirmed not only what the rational type of built-environmental conditioning for human thermal comfort is, but also the usefulness of the exergy concept itself.

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24) T. Iwamatsu, Y. Hoshino, E. Kataoka, and M. Shukuya, “An Experimental Study on the Feasibility of SAIREI-A Way of Radiative Cooling- in Naturally Ventilated Room Space, Journal of Environmental Engineering, Architectural Institute of Japan, No.618, August 2007, pp.45-52.
25) M. Shukuya, “Radiant Exergy and its Importance for Thermal Comfort in the Built Environment”, IEA/ECBCS/Annex 49 Newsletter No.3, 2008, pp.5-7.

APPENDICES

Described here is the concise, but still detailed, derivation of mathematical formulae necessary for the numerical calculation of thermal exergy. Those interested in the fundamentals of thermodynamics and heat transfer and their applications to exergy calculation are welcome to go through what follows below. In due course, the equations given in Table 3.2 for wet/dry exergies, warm/cool radiant exergies and warm/cool exergy transfer by convection are explained thoroughly.

The first three sections below deal with moist air and liquid water. Then, the following two sections describe how to deal with radiation and convection.

A.1 Wet/Dry Exergy Contained by Moist Air

Suppose that there is an amount of liquid water, whose upper surface bounds up with an amount of moist air above as shown in Figure A.1.1. We assume two tiny systems sharing the boundary surface each other: one is the liquid water below the boundary surface of liquid water and moist air the most air and the other the most air above. This shared boundary surface is open to the heat transfer and also to the transportation of water molecules from liquid to vapor phase or vice versa. Therefore, both systems are typical open systems, but we can simplify the systems to be closed, namely those systems not allowing mass transfer but heat transfer alone. This makes easier the derivation of wet/dry exergy formulae.

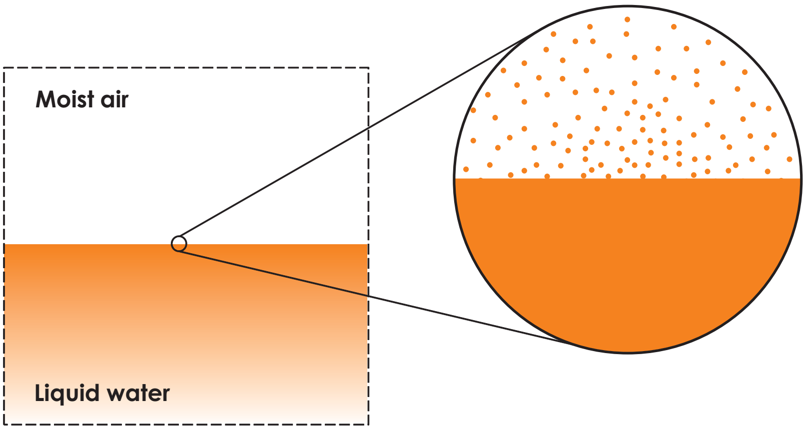

Figure A.1.1: Two tiny systems near the liquid water surface: one consists of moist air above the surface and the other of liquid water below the surface. They are surrounded by huge spaces above (moist air) and below (liquid water), which are the environment for them. Although the system size is very small relative to the environment, they still have enormous number of molecules. See also the footnote a) in the last page 38.

The reason for enabling us to assume two closed systems is that, although there is always the constant supply of water molecules into the moist-air system through the shared boundary surface from the liquid-water system below, there is also the corresponding constant release of exactly the same amount of water molecules as vapor phase into the surrounding moist-air space across the upper round-shaped boundary surface. While on the other hand, the same amount of liquid-water molecules as that of evaporated is also always constantly supplied from the surrounding liquid water across the lower round-shaped boundary surface into the liquid-water system.

In short, the input and output of water molecules are constant so that it is equivalent to assume that there is neither input nor output of water molecules to either of the two systems. These two closed systems are tiny[a] so that we consider that they are in equilibrium. For this condition, the amounts of internal energy and entropy and also the number of molecules are constant for either system.

Infinitesimal energy balance equations for the two systems are first expressed with the quantities of state alone, namely temperature, pressure, entropy and volume and then they are combined with the conditional equations representing the equilibrium in which the sum of infinitesimal increase in entropy of both systems is null.

These series of mathematical operation yields the exact condition of three system variables for the equilibrium: temperature, pressure, and molecular free-energy (chemical potential). They are related to thermal equilibrium, mechanical equilibrium, and chemical equilibrium, respectively. For the thermally equilibrium condition, the temperature of both systems has to be equal to each other. The same is true for pressure to have the mechanically equilibrium condition. The last is unique with respect to phase change from liquid water to water vapor or vice versa. The molar free energy of the two systems is equal to each other for the chemically equilibrium condition.

The next step starting with this last condition is to combine an infinitesimal energy change of both systems with an infinitesimal change in molar free-energy. Once these infinitesimal changes are expressed as two mathematical equations, we can then reduce them into one equation having infinitesimal changes of temperature and pressure, entropy and volume of liquid water and those of water vapor, namely all together six variables. This operation finally brings us a differential equation indicating that the rate of an infinitesimal change in saturated vapor pressure with respect to that change in temperature is exactly expressed as the ratio of the difference in entropy between the tiny systems to that in volume: this important relationship is called Clapeyron-Clausius[b] equation.

Combining the Clapeyron-Clausius equation together with the ideal gas equation based on Boyle-Gay-Lussac[c] theorem and the thermal energy necessary for vaporization, the specific latent heat value of water vapor as a constant of 2450 kJ/kg[d], in the range of 0 to 40 °C yields the saturated water-vapor pressure, p_{vs} in the unit of Pascal, as a function of temperature, T in the unit of Kelvin, in the form of

$$p_{vs} = e^{(25.89 - \frac{5319}{T})} \qquad (A.1.1)$$

If the values of relative humidity and temperature of a certain moist-air system is given, then its vapor pressure can be calculated as the product of eq.(A.1.1) and the value of relative humidity in percentage divided by 100.

Eq.(A.1.1) is useful in numerical calculation of wet/dry exergy of moist-air systems and also of wet exergy of liquid water. The Clapeyron-Clausius equation is used again to derive the exergy balance equation for a liquid-water surface to be discussed in A.3. What has been so far described is the preparation for deriving the exergy formula with respect to moist air. Let us move into the core of this derivation.

Based upon the fact that a moist-air system, whose pressure within the atmospheric pressure value can be characterized very well by the ideal-gas equation according to the Boyle-Gay-Lussac theorem, we assume that this is also true for each of either saturated water vapor or dry air system since their partial pressure values are smaller than the atmospheric pressure value. As shown in Figure A.1.2, let us suppose a system of water-vapor alone with the volume of V_v and also another system of dry air alone with the volume of V_a. If they are mutually dispersed into the volume of V, which is exactly equal to the sum of V_v and V_a, then this brings about the entropy increase of both systems and their total is just equal to their sum. This is based on Gibbs[e] theorem claiming that neither work nor heat needs for either mutual dispersion or separation due to a careful thought experiment with a schematic drawing as shown in Figure A.1.3.

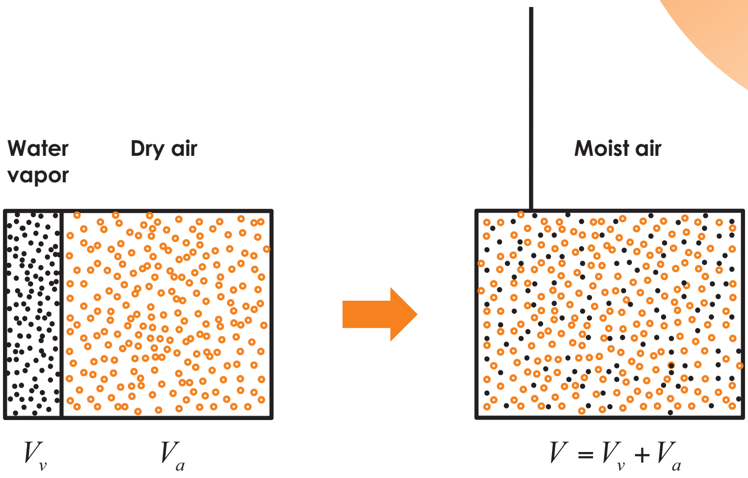

Figure A.1.2: Mutual dispersion of water vapor and dry air to bring about moist air. The entropy of the moist air is larger than the sum of respective values of entropy with respect to each of water vapor and dry air alone. Their difference is exactly the summation of the entropy increase in water vapor and dry air due to free expansion, namely the increase in respective volumes.

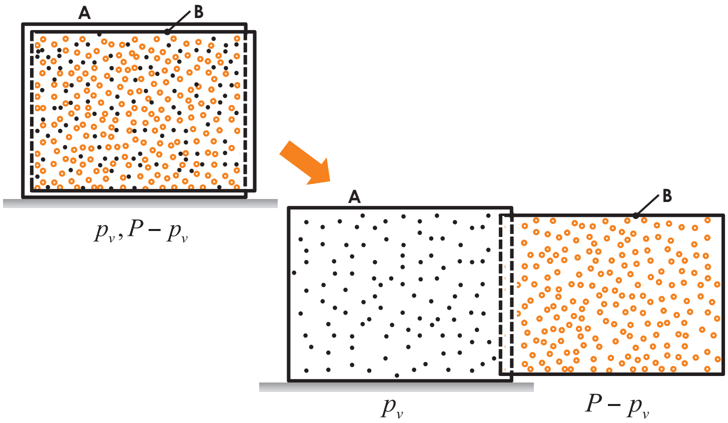

Figure A.1.3: Two compartments, A and B, are in the positions as overlapped in the beginning as shown on your left. The right partition of A allows the air molecules to transmit freely, while on the hand, the left partition of B allows the water vapor to transmit freely. Since neither work nor heat is required to separate the air and the water vapor molecules, the entropy of the moist-air system is exactly equal to the sum of the entropy values of the independent systems of water vapor and dry air as shown on your right,. This is called Gibbs theorem.

What we are aiming at here in this discussion is to derive a formula for wet or dry exergy contained by an amount of moist air whose relative humidity is different from its surrounding moist air. For this purpose, the discussion so far has to be extended as follows.

As can be seen in Figure A.1.4, suppose that there are a system and the environment: the former has water-vapor pressure of p_v and dry-air pressure of $P - p_v$, where P is the atmospheric pressure; the latter has p_{vo} and $P - p_{vo}$. The sum of the entropy contained by the system and the environment can be expressed by following exactly what was described above, based upon Gibbs theorem.

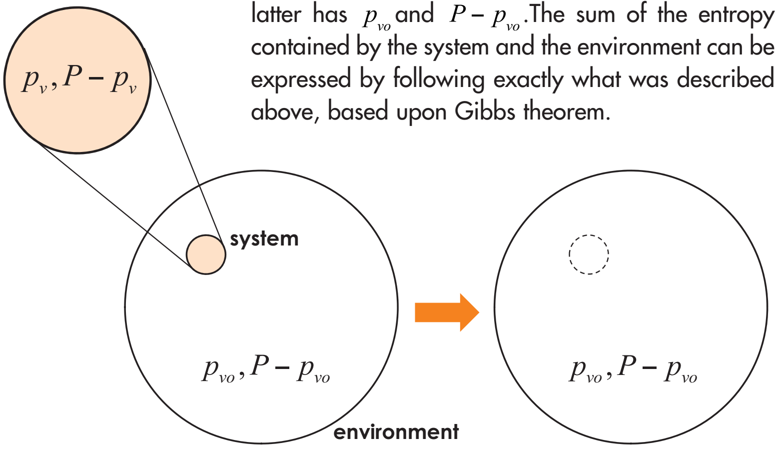

Figure A.1.4: A moist-air system whose vapor pressure, p_v, is different from that of its environment, p_{vo}. The atmospheric pressure is P and the pressure denoted by $P - p_v$ in the system is the dry-air pressure. The same applies to the dry-air pressure in the environment. We assume that the relative size of the environment to the system is large so that the dispersion of moist air contained by the system into the environment causes little change in the environmental vapor pressure, p_{vo}. The moist air system contains "wet" exergy, if p_v is higher than p_{vo}, while on the other hand, it contains "dry" exergy, if p_v is lower than p_{vo}.

If the relative size of the environment is huge enough, then the vapor pressure of the environment remains unchanged even after the moist-air system has dispersed. In this particular case, the whole change in the entropy contained by the system and the environment between before and after the moist-air system dispersing into the environment, ΔS, can be reduced to the following equation with a little bit of mathematical operation.

$$\Delta S = nR\left\{\frac{P - p_v}{P}\ln\frac{P - p_v}{P} + \frac{p_v}{P}\ln\frac{p_v}{p_{vo}}\right\} \quad , \quad \text{(A.1.2)}$$

where n is the whole number of water and dry-air molecules in the unit of mol and R is gas constant, which is equal to 8.314 J/(mol·K). An important feature of this equation is that ΔS is always greater than null for both cases of $p_{vo} < p_v$ and $p_v < p_{vo}$.

According to the "exergy-consumption" theorem, we can express the general form of exergy balance equation as follows.

$$X - S_g T_o = 0 \ . \qquad \text{(A.1.3)}$$

Let us suppose that X is an amount of exergy contained by the moist-air system shown in the left of Figure A.1.4, and then the entropy generation, S_g, corresponds exactly to the entropy increase mentioned above. The product of the entropy generation, S_g, and the environmental temperature, T_o, is the exergy consumption. Therefore, the exergy contained by the moist-air system can be expressed as follows.

$$X = nRT_o\left\{\frac{P - p_v}{P}\ln\frac{P - p_v}{P} + \frac{p_v}{P}\ln\frac{p_v}{p_{vo}}\right\} . \quad \text{(A.1.4)}$$

It is convenient to express the moist-air exergy as a volumetric intensive value as follows.

$$x = \frac{T_o}{T}\left\{(P - p_v)\ln\frac{P - p_v}{P} + p_v\ln\frac{p_v}{p_{vo}}\right\} \quad , \quad \text{(A.1.5)}$$

where T is the temperature of the moist-air system.

Equation (A.1.5) can also be obtained from the general formula of chemical exergy to be contained by an open system, which is expressed as the summation of the respective products of the difference in molar free-energy (chemical potential) of molecular components between the system and the environment and the number of molecules in the unit of mol. We reach exactly the same result as eq.(A.1.5).

A.2 Wet Exergy Contained by Liquid Water

An amount of liquid water as an open system, whose temperature is equal to the environmental temperature, T_o, still has an amount of exergy called "wet" exergy, since it can disperse into its environment by mass diffusion. What follows describes how to derive the formula of wet-exergy for liquid water.

First, suppose that there is an amount of moist air which contains n_v mol of water molecules and their pressure is p_{vo} in the unit of Pascal. These molecules can be separated in accordance with Gibbs theorem, as shown in Fig. A.1.3.

Let us regard this water-vapor system separated to be a closed system consisting of water molecules alone. Starting with this condition, we may consider a thought experiment, a series of 'work' to compress the system from vapor phase until saturated isothermally, namely with outgoing 'heat' whose amount exactly equals that of work given, and then 'cool' by extracting heat to condense further the saturated water vapor into the liquid phase. During these processes, we assume that the temperature of the system remains unchanged at T_o. The whole thought experiment is schematically shown in Figure A.2.1.

The differences in energy (enthalpy), ΔH_l, and entropy, ΔS_l, contained by the closed system before and after becoming liquid phase, are expressed as

$$\Delta H_l = -n_v M_v L(T_o) \ , \tag{A.2.1}$$

$$\Delta S_l = -n_v R \ln \frac{p_{vs}(T_o)}{p_{vo}} - n_v M_v \frac{L(T_o)}{T_o} \ . \tag{A.2.2}$$

where M_v is the molar mass of water molecules (18.05 g/mol), $L(T_o)$ is specific latent-heat value at the environmental temperature, T_o, whose unit is J/g and $p_{vs}(T_o)$ is saturated water vapor pressure at the environmental temperature, T_o, to be calculated by eq.(A.1.1). Eq.(A.2.1) indicates that the thermal energy, namely latent heat, is given off in the course of condensation and eq.(A.2.2) the sum of entropy given off in the course both of isothermal compression and of condensation.

Substitution of eqs.(A.2.1) and (A.2.2) into the general form of exergy formula yields the following equation.

$$\begin{aligned} X_w &= \Delta H_l - T_o \cdot \Delta S_l \\ &= n_v R T_o \ln \frac{p_{vs}(T_o)}{p_{vo}} \ . \end{aligned} \tag{A.2.3}$$

Since $n_v M_v$ is equal to $\rho_w V$, where ρ_w is the density of liquid water and V its volume and also the relative humidity, φ_o, in percentage value is equal to the ratio of p_{vo} to $p_{vs}(T_o)$ multiplied by 100, we can express the volumetric wet exergy of liquid water as

$$x_w = \frac{\rho_w R}{M_v} T_o \ln \frac{100}{\varphi_o} \ . \tag{A.2.4}$$

Substituting the values of ρ_w(=1000kg/m³), R (=8.314J/(mol·K)), and M_v(=18.05g/mol), x_w is expressed simply as

$$x_w = 460609 T_o \ln \frac{100}{\varphi_o} \tag{A.2.5}$$

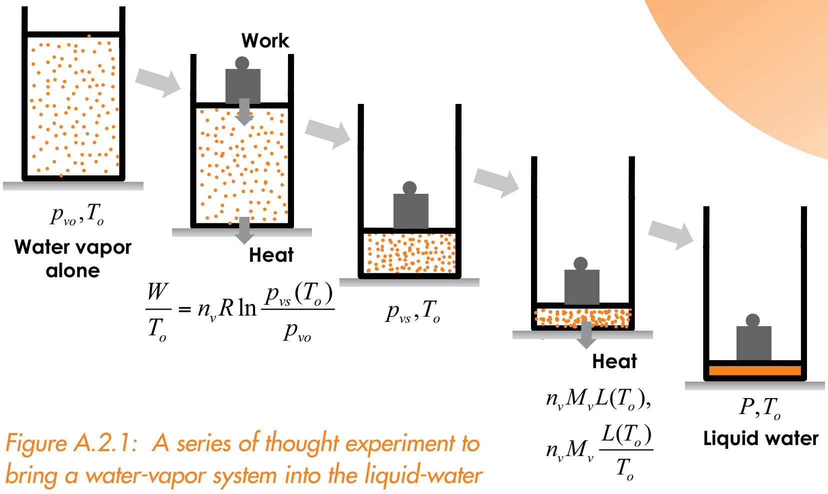

Figure A.2.1: A series of thought experiment to bring a water-vapor system into the liquid-water system. In the course of isothermal compression, in which the temperature of the system is kept constant, $n_v R \ln \frac{p_{vs}(T_o)}{p_{vo}}$ *of entropy is given off and in the course of cooling,* $n_v M_v L(T_o)$ *of energy and* $n_v M_v \frac{L(T_o)}{T_o}$ *of entropy are given off.*

For example, x_w turns out to be 96.8MJ/m³ for T_o =303.15K(=30˚C) and φ_o=50%.

This is huge if comparing with the order of wet/dry exergy, 50 to 200 J/m³ to be calculated from eq.(A.1.5). The volumetric wet-exergy values of liquid water are one-million time larger than those of moist air. This fact that liquid water is very rich in wet exergy suggests that its consumption plays very important role in thermo-regulation of human body especially under hot and humid conditions.

A.3 Exergy Balance at the Boundary Surface of Moist Air and Liquid Water

Let us suppose a liquid-water surface, whose temperature is T, surrounded by moist air, as shown in Figure A.3.1.

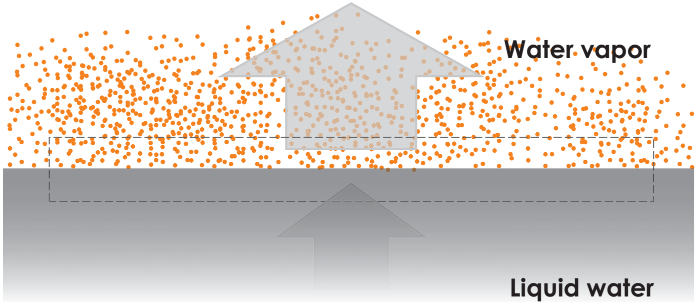

Figure A.3.1: Liquid water surface where evaporation is taking place. In due course, water vapor carries away an amount of entropy in addition to energy.

We assume that an amount of liquid water, whose molecular number is n_v mol, has the energy (enthalpy) level of ΔH_l, which is exactly the difference in energy at the liquid-water surface temperature, T, and at the environmental temperature, T_o. If this liquid water evaporates, namely all of the molecules turn into the vapor phase, then the energy level becomes ΔH_v, which is greater than ΔH_l, by an amount of latent heat, $n_v M_v L(T)$. Namely,

$$\Delta H_l + n_v M_v L(T) = \Delta H_v \; . \qquad \text{(A.3.1)}$$

The specific latent-heat, $L(T)$, which is in the unit of J/kg, at an arbitrary value of temperature, T, can be approximated very well by the following equation:

$$L(T) = L(273.15) + (c_{pv} - c_{pw})(T - 273.15) \;, \qquad \text{(A.3.2)}$$

where c_{pv} and c_{pw} are specific heat capacity of water vapor (=1846J/(kg·K)) and liquid water (=4186J/(kg·K)), respectively. Substituting T_o into eq.(A.3.2), we get the following equation:

$$L(T_o) = L(273.15) + (c_{pv} - c_{pw})(T_o - 273.15) \; . \qquad \text{(A.3.3)}$$

Subtraction of eq.(A.3.3) from eq.(A.3.2) and multiplication of $n_v M_v$ over the whole resultant equation yields,

$$n_v M_v \left\{ -L(T_o) + c_{pw}(T - T_o) \right\} + n_v M_v L(T) = n_v M_v c_{pv}(T - T_o) \; . \qquad \text{(A.3.4)}$$

The first term of the left-hand side of eq.(A.3.4) is exactly ΔH_l and the right-hand side is ΔH_v. The fact that ΔH_l and ΔH_v can be expressed by the respective corresponding terms is that the energy(enthalpy) contained by water vapor and liquid water is a quantity of state.

The equation with respect to entropy, which is parallel to eq.(A.3.4) for energy, can be derived starting from the Clapeyron-Clausius equation described in A.1, to which we substitute the relationship of eq.(A.3.3) instead of substituting a constant value to derive eq.(A.1.1) for saturated water-vapor pressure[f)].

The result is as follows:

$$\Delta S_l + n_v \left\{ M_v \frac{L(T)}{T} + R \ln \frac{p_{vs}(T)}{p_{vr}} \right\} = \Delta S_v \;, \qquad \text{(A.3.5)}$$

where $$\Delta S_l = -n_v R \ln \frac{p_{vs}(T_o)}{p_{vo}} - n_v M_v \left\{ \frac{L(T_o)}{T_o} - c_{pw} \ln \frac{T}{T_o} \right\} \;, \qquad \text{(A.3.6)}$$

$$\Delta S_v = -n_v R \ln \frac{p_{vr}}{p_{vo}} + n_v M_v c_{pv} \ln \frac{T}{T_o} \; . \qquad \text{(A.3.7)}$$

The second term of the left-hand side of eq.(A.3.5) is necessarily greater than zero, since $0 < n_v$, $0 < M_v$, $0 < L(T)$, $0 < T$, $0 < R$, $0 < \ln \dfrac{p_{vs}(T)}{p_{vr}} = \ln \dfrac{100}{\varphi}$, where φ is relative humidity in percentage of the surrounding moist air at its temperature of T[9)].

This confirms that the evaporation of water, a typical mass-diffusion phenomenon, is exactly accompanied by entropy generation quantified by the second term of eq.(A.3.5). We may regard eq.(A.3.5) to be an entropy balance equation as $\Delta S_l + S_g = \Delta S_v$, where S_g is entropy generation to be expressed by the second term of eq.(A.3.5).

The water vapor does not exist itself alone after its evaporation, but it disperses spontaneously with the moist air nearby. Assuming that the evaporated water molecules of n_v mol does not change the water-vapor pressure in the surrounding moist air, p_{vr}, in other words, the relative-humidity value of the surrounding air is given to be constant, then the number of dry-air molecules in the unit of mol can be expressed as follows by applying the ideal-gas equation based on Boyle-Gay-Lussac theorem.

$$n_a = \frac{P - p_{vr}}{p_{vr}} n_v \qquad \text{(A.3.8)}$$

For the reason that the evaporated water molecules cannot exist themselves alone, we add the entropy value of dry air for the number of molecules to be given by eq.(A.3.8) to both sides of eq.(A.3.5); it is actually the addition of negative value of dry-air entropy to be measured from the entropy state corresponding to the environmental condition, since the dry air which also cannot exist alone has lower entropy value than the dry air as a portion of the environment. This operation yields the following equation. Namely,

$$\begin{aligned} &(\Delta S_l - \frac{P - p_{vr}}{p_{vr}} n_v R \ln \frac{P - p_{vr}}{P - p_{vo}}) + S_g \\ &= (\Delta S_v - \frac{P - p_{vr}}{p_{vr}} n_v R \ln \frac{P - p_{vr}}{P - p_{vo}}) \end{aligned} \; . \qquad \text{(A.3.9)}$$

Using ΔH_l appeared in eq.(A.3.1), which was finally expressed by the first term of eq.(A.3.4), and ΔS_l expressed by eq.(A.3.6) together with the term attached to it as indicated in the first term of eq.(A.3.9), and the environmental temperature, T_o, the molar exergy of liquid water, x_l, can be expressed by

$$x_l = M_v c_{pw}\left\{(T - T_o) - T_o \ln\frac{T}{T_o}\right\} + RT_o \ln\frac{p_{vs}(T_o)}{p_{vo}} + RT_o\frac{P - p_{vr}}{p_{vr}}\ln\frac{P - p_{vr}}{P - p_{vo}} \quad . \qquad \text{(A.3.10)}$$

The first term of the right-hand side of eq.(A.3.10) is thermal exergy, which is either warm or cool, and the rest is wet exergy contained by liquid water and its associated dry air. The latter, the sum of wet exergy contained by liquid water and its associated dry air, was drawn as a numerical example in Figure 4.1-a). See p. 19.

The same procedure as for eq.(A.3.10) brings us the molar exergy of moist air expressed as follows:

$$x_v = M_v c_{pv}\left\{(T - T_o) - T_o \ln\frac{T}{T_o}\right\} + RT_o \ln\frac{p_{vr}}{p_{vo}} + RT_o\frac{P - p_{vr}}{p_{vr}}\ln\frac{P - p_{vr}}{P - p_{vo}} \quad . \qquad \text{(A.3.11)}$$

The sum of the second and the third terms of the right-hand side of eq.(A.3.11) is wet or dry exergy of moist air, which was drawn as the other numerical example of Figure 4.1-b).

Let us confirm how the exergy balance equation for an amount of liquid water with n_v mol can be expressed for a special case that the water temperature, T, is equal to the environmental temperature, T_o,

$$n_v x_l - S_g T_o = n_v x_v \quad . \qquad \text{(A.3.12)}$$

Substituting eqs.(A.3.10) and (A.3.11) to eq.(A.3.12) yields,

$$S_g T_o = n_v R T_o \ln\frac{100}{\varphi_o} \quad . \qquad \text{(A.3.13)}$$

Eq.(A.3.13) indicates that "wet" exergy contained by liquid water is consumed by evaporation even if the liquid-water temperature is exactly equal to the environmental temperature unless the relative humidity in the environment is 100%.

A.4 Thermal Radiant Exergy

Suppose that there is a room as shown in Figure A.4.1. Environmental temperature for this room is T_o in the unit of Kelvin. There is one external wall and its interior surface temperature is T_1, again in the unit of Kelvin. The rate of radiant energy emitted from 1m^2 of this surface towards the interior space can be expressed as

$$q_r = \varepsilon\sigma T_1^4 \quad . \qquad \text{(A.4.1)}$$

where ε is the emittance of the surface, which is usually very close to unity, say 0.9 to 0.95 in the cases of ordinary building walls, and σ is Stephan-Boltzmann constant, which is equal to 5.67×10^{-8} W/(m^2·K^4)[h].

The 4th power equation given by eq.(A.4.1) can be derived by performing a series of algebraic operation for the energy balance equation of a closed system filled only with electromagnetic wave whose pressure against the interior surface of the walls of the system is exactly one-third of the volumetric internal energy value.

The emission rate of radiant entropy parallel to eq.(A.4.1) can also be derived in a similar manner and is expressed as follows:

$$s_r = \frac{4}{3}\varepsilon\sigma T_1^3 \qquad \text{(A.4.2)}$$

The theoretical consideration to arrive eqs.(A.4.1) and (A.4.2) was first made by Boltzmann.

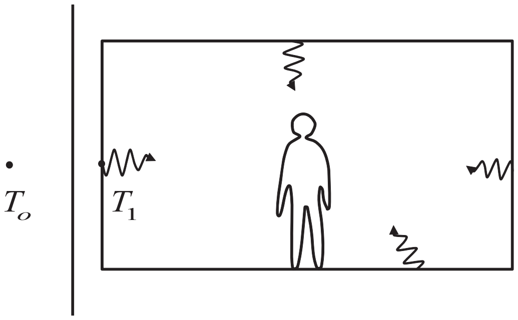

Figure A.4.1: A room with an external wall, whose interior surface temperature is T_1, assumed for theoretical consideration of radiant exergy calculation. The room is surrounded by the environmental space whose temperature is T_o.

In order to have radiant exergy equation, we need to combine both eqs.(A.4.1) and (A.4.2) and the environmental temperature. For its simplest description, let us suppose a case of two surfaces facing each other, both surrounded by the environmental space in vacuum, as shown in Figure A.4.2. The two surfaces as a whole are surrounded by their environmental space whose temperature is T_o. Unless the emittance of the surfaces is unity, there is mutual reflection of radiation, but for simplicity of discussion here, we neglect it. This is all right as far as the ordinary wall surfaces are concerned[i].

Assuming that the temperature of these two surfaces is constant and regarding surface 1 to be a system in question, its input is $\varepsilon\sigma T_2^4$ and its output is $\varepsilon\sigma T_1^4$. Energy balance equation for this system is therefore described as follows:

$$\varepsilon\sigma T_2^4 = \varepsilon\sigma T_1^4 \quad . \qquad \text{(A.4.3)}$$

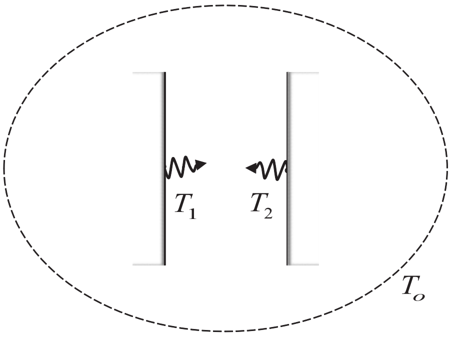

Figure A.4.2: Two surfaces emitting radiant energy and entropy each other in accordance respectively with the 4th and 3rd powers of the absolute temperature of the two surfaces.

Due to our assumption that the two surface elements are surrounded by the environmental space at its temperature of T_o, their portions of radiant energy to irradiate at the environmental temperature, T_o, is already "dispersed". Taking this into consideration, eq.(A.4.3) can be rewritten as follows to get the amount of energy that is not yet dispersed[i],

$$\varepsilon\sigma T_2^4 - \varepsilon\sigma T_o^4 = \varepsilon\sigma T_1^4 - \varepsilon\sigma T_o^4 \quad . \qquad \text{(A.4.4)}$$

In the calculation of thermal radiant energy, entropy and exergy for built environment, the temperature level that we encounter with ranges from -10 to 40°C. It allows us to use linearized approximation of eq.(A.4.4).

Let us show this linearization below taking the case of surface 1 as an example, referring to a schematic drawing shown in Figure A.4.3. Take the average of two temperatures, T_1 and T_o, as T_m, namely,

$$T_m = \frac{T_1 + T_o}{2} \quad . \qquad \text{(A.4.5)}$$

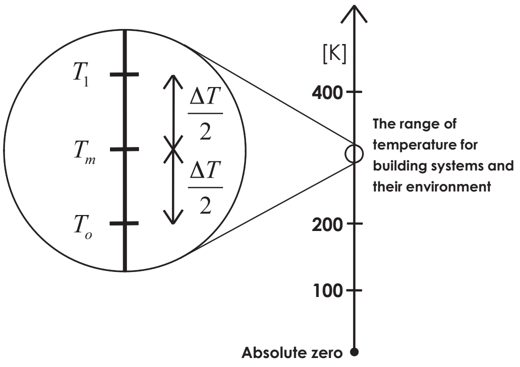

Figure A.4.3: The relationship between the system temperature, T_1, and the environmental temperature, T_o, with their average, T_m, and their difference, ΔT.

Take also the temperature difference between surface 1 and the environment as $\Delta T = T_1 - T_o$. Then we can express two temperatures, T_1 and T_o, as follows

$$T_1 = T_m + \frac{\Delta T}{2} \quad \text{and} \quad T_o = T_m - \frac{\Delta T}{2} \quad . \qquad \text{(A.4.6)}$$

Substituting the relationships expressed by eq.(A.4.6) into the right-hand side of eq.(A.4.4) and a little bit of algebraic operation yields the following equation.

$$\begin{aligned}&\varepsilon\sigma T_1^4 - \varepsilon\sigma T_o^4 \\ &\quad = \varepsilon\sigma\left\{8T_m^3\left(\frac{\Delta T}{2}\right) + 8T_m\left(\frac{\Delta T}{2}\right)^3\right\}\end{aligned} \quad . \qquad \text{(A.4.7)}$$

Since $\Delta T \ll T_m$, the above equation can be reduced to

$$\begin{aligned}&\varepsilon\sigma T_1^4 - \varepsilon\sigma T_o^4 \approx (\varepsilon\sigma 4T_m^3)\Delta T \\ &\quad = \varepsilon h_b(T_1 - T_o)\end{aligned} \quad , \qquad \text{(A.4.8)}$$

where h_b equal to $4\sigma T_m^3$ is radiative heat-transfer coefficient of a black surface in the unit of W/(m²·K).

The equation for entropy, which is parallel to eq.(A.4.3) for energy, can be written as follows:

$$\varepsilon\left(\frac{4}{3}\sigma T_2^3\right) + s_g = \varepsilon\left(\frac{4}{3}\sigma T_1^3\right) \quad . \qquad \text{(A.4.9)}$$

where s_g is entropy generation rate due to the absorption of the incoming radiation from surface 2 to surface 1. We apply the same operation as we did from eq.(A.4.4) to eq.(A.4.7) and reach the following equation,

$$\begin{aligned}&\varepsilon\left(\frac{4}{3}\sigma T_1^3\right) - \varepsilon\left(\frac{4}{3}\sigma T_1^3\right) \\ &\quad = \varepsilon\left(\frac{4}{3}\sigma\right)\left\{6T_m^2\frac{\Delta T}{2} + 2\left(\frac{\Delta T}{2}\right)^3\right\}\end{aligned} \quad . \qquad \text{(A.4.10)}$$

Again, since $\Delta T \ll T_m$,

$$\begin{aligned}&\varepsilon\left(\frac{4}{3}\sigma T_1^3\right) - \varepsilon\left(\frac{4}{3}\sigma T_2^3\right) \\ &\quad = \varepsilon(4\sigma)T_m^2\Delta T = \varepsilon h_b\frac{T_1 - T_o}{T_m}\end{aligned} \quad . \qquad \text{(A.4.11)}$$

Now, we have the radiant energy emission rate expressed by eq.(A.4.8) and the corresponding radiant entropy emission rate expressed by eq.(A.4.11). The general form of exergy can be written with the difference in energy between the system and its environment, ΔE, that in entropy, ΔS, and the environmental temperature, T_o, as follows:

$$x_r = \Delta E - T_o \cdot \Delta S \quad . \qquad \text{(A.4.12)}$$

For ΔE, we can substitute eq.(A.4.8) and for ΔS, eq.(A.4.11). Namely,

$$\begin{aligned} x_r &= \varepsilon h_b (T_1 - T_o) - T_o \left(\varepsilon h_b \frac{T_1 - T_o}{T_m} \right) \\ &= \varepsilon h_b (T_1 - T_o)(1 - \frac{T_o}{T_m}) \end{aligned} \quad . \qquad \text{(A.4.13)}$$

Taking the relation expressed by eq.(A.4.5) into consideration, eq.(A.4.13) can finally be expressed by the following equation.

$$x_r = \varepsilon h_b \frac{(T_1 - T_o)^2}{T_1 + T_o} \quad . \qquad \text{(A.4.14)}$$

Due to the fact that $0 < \varepsilon$, $0 < h_b$, $0 < T_1 + T_o$, and $0 < (T_1 - T_o)^2$, the radiant exergy is necessarily larger than zero except a case that the surface temperature equals the environmental temperature. For the cases of $T_o < T_1$, there is "warm" radiant exergy and for the cases of $T_1 < T_o$, there is "cool" radiant exergy.

A.5 Warm/Cool Exergy Transfer by Convection

Thermal energy transfer by convection from 1m² of the human body, q_c, is calculated by,

$$q_c = f_{cl} h_{ccl} (T_{cl} - T_{ra}) \quad , \qquad \text{(A.5.1)}$$

where f_{cl} is the ratio of human body area with clothing to the naked human body area (=1.05~1.5), h_{ccl} is average convective heat-transfer coefficient over clothed body-surface in the unit of W/(m²·K)), T_{cl} is clothing surface temperature in the unit of Kelvin, and T_{ra} is room air temperature in the unit of Kelvin. The entropy transfer, s_c, parallel to the energy transfer expressed by eq.(A.5.1) is given by

$$s_c = \frac{q_c}{T_{cl}} = \frac{f_{cl} h_{ccl} (T_{cl} - T_{ra})}{T_{cl}} \quad . \qquad \text{(A.5.2)}$$

Exergy transfer by convection is therefore expressed as follows, using the environmental temperature of T_o in the unit of Kelvin:

$$x_c = f_{cl} h_{ccl} (T_{cl} - T_{ra})(1 - \frac{T_o}{T_{cl}}) \quad . \qquad \text{(A.5.3)}$$

The clothing temperature, T_{cl}, varies with the conditions of six variables: mean radiant temperature; ambient air temperature; ambient relative humidity; overall average air velocity around the human body surface; the thermal resistance of clothing ensembles; and metabolic energy emission rate. If the five variables except room air temperature are assumed to be constant, then we can regard the clothing temperature to be a function of the single variable of room air temperature or vice versa. We can get this relationship by solving the energy balance equation set up for the clothing ensembles as a system. Figure A.5.1 shows schematically the general relationship between clothing temperature, T_{cl}, and room air temperature, T_{ra}; the higher the clothing temperature is, the higher also the room air temperature is.

With what has been described so far in mind, we may regard the rate at which thermal exergy transferred by convection to be calculated from eq.(A.5.3) as a function of two variables: room air temperature, T_{ra}, and the environmental temperature, T_o, since we now regard the clothing temperature, T_{cl}, as a function of room air temperature, T_{ra}.

If the values of warm- or cool-exergy transfer by convection are given for various sets of room air temperature, T_{ra}, and the environmental temperature, T_o, then they could be given as equi-convective exergy lines as shown in Figure 4.3. See p.21.

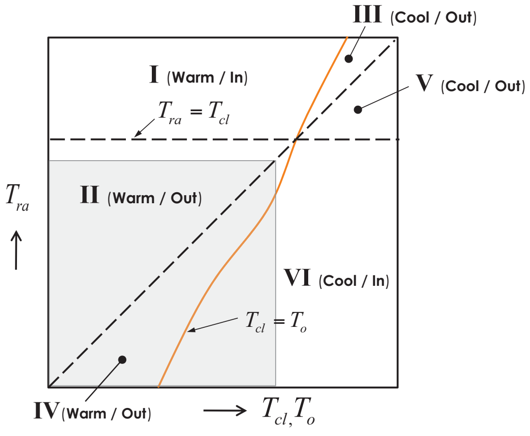

Figure A.5.1: The relationship between clothing temperature and room air temperature together with the environmental temperature. There are six cases depending on the conditions among the temperature values of the clothing, the room air, and the environment. They are different in whether exergy is warm or cool and also in whether exergy is outgoing or incoming. See also Table A.5.1 for the detail of the conditions. The shaded area corresponds to an actual example given in Figure 4.3.

Theoretically speaking, there are six cases depending on the order of three temperature values: the clothing temperature, T_{cl}, room air temperature, T_{ra}, and the environmental temperature, T_o. These six cases are different in whether a given exergy value implies "warm" or "cool" and also different in whether they are outgoing from or incoming onto the human body. These six cases correspond to the six areas denoted by the symbols from I to VI, which are bordered by three lines in Figure A.5.1; the three lines are as follows: one is the line representing the relationship between room air temperature, T_{ra}, and the clothing temperature, T_{cl}, which also indicates the cases of the clothing temperature equal to the environmental temperature, T_o; one other is the horizontal line crossing the point where room air temperature equals clothing temperature; and the last is the diagonal line representing room air temperature equal to the environmental temperature. Table A.5.1 summarizes the conditions of the respective cases with respect to thermal exergy transfer by convection.

Table A.5.1: The details of six cases of exergy transfer by convection

	Temperature	$\alpha = T_{cl} - T_{ra}$	$\beta = 1 - \frac{T_o}{T_{cl}}$	$\alpha \times \beta$	**Warm/ Cool**	**In/Out**
I	$T_o < T_{cl} < T_{ra}$	-	+	-	**Warm**	**In**
II	$T_o < T_{ra} < T_{cl}$	+	+	+	**Warm**	**Out**
III	$T_{cl} < T_o < T_{ra}$	-	-	+	**Cool**	**Out**
IV	$T_{ra} < T_o < T_{cl}$	+	+	+	**Warm**	**Out**
V	$T_{cl} < T_{ra} < T_o$	-	-	+	**Cool**	**Out**
VI	$T_{ra} < T_{cl} < T_o$	+	-	-	**Cool**	**In**

Whether exergy transfer by convection turns out to be "warm" or "cool" is determined by the sign of Carnot[k] factor, β, and whether it becomes outgoing as defined in eq.(3.6) or incoming is determined by the sign of the product of temperature difference, α, and Carnot factor, β.

In the cases of II and IV, where the clothing temperature is necessarily higher than room air temperature, there is outgoing warm exergy, while on the other hand, in the case of VI, there is incoming cool exergy due to the fact that the room air temperature is lower than the clothing temperature and both are lower than the environmental temperature.

Other three cases of I, III, and V are very extreme and rarely encountered in reality: in case I, there is incoming warm exergy due to the corresponding room air temperature higher than both the environmental temperature and the clothing temperature; in cases III and V, there is outgoing cool exergy due to the clothing temperature lower than room air temperature.

An actual example with numerical values shown in Figure 4.3 corresponds to the shaded area indicated within Figure A.5.1.

Footnotes for Appendices

a) If each of the tiny systems is a cube whose edge is 0.1 mm, it contains about 34×10^{15} water molecules for the liquid-water system and 2.5×10^{15} molecules of oxygen, nitrogen and water molecules for the moist-air system. These numbers are large enough to assume thermodynamic systems.

b) Clapeyron was a French scientist and engineer who contributed to the establishment of this relationship in addition to his re-discovery of Carnot's work; and Clausius was a German scientist who first conceived and discovered the concept of entropy. They worked in the mid of 19th century. With respect to Carnot, see k).

c) Boyle was a British scientist who did a series of experiment, with the help of another British scientist Hooke, to clarify the relationship between the pressure and the volume of gas. Boyle's name is famous for his contribution to this pressure volume relationship, but Hooke's contribution should not be disregarded. Hooke is also famous for his book "Micrographia" and also his discovery of the proportionality of the spring length to the weight. More than one-hundred years later, Gay-Lussac found the quantitative proportional relationship between the pressure-volume product and the temperature.

d) The actual latent-heat value at 0 ℃ is only 2.1% larger and that at 40 ℃ only 1.8% smaller than 2450 kJ/kg.

e) Gibbs was an American scientist in the 2nd half of 19th century who is very famous for his memorial work in the foundation of statistical thermodynamics.

f) If we use the specific latent heat expressed by eq.(A.3.2) instead of a constant value, 2450kJ/kg, then we reach the following equation: $p_{vs} = e^{(59.866 - 5.0802 \ln T - \frac{6815.26}{T})}$, which is a little more complicated than eq.(A.1.1), but it induces only 0.1% of error at maximum for the range of 0 to 70 ℃. On the other hand, eq.(A.1.1) induces 1% of error at maximum for the range of 0 to 40 ℃. Nevertheless, eq.(A.1.1) having a simple form is applicable to most cases in the built environment.

g) Note that the water vapor pressure of a certain moist air, p_{vr}, is given as the product of the saturated water vapor, $p_{vs}(T)$, and the relative humidity, φ, divided by 100.

h) The name of this constant, σ, comes from the commemorating works of the two scientists in the 2nd half of 19th century. Stephan, a German experimental scientist, found that overall thermal radiant energy emission rate is proportional to the fourth power of the absolute temperature of radiant sources investigating high-temperature furnaces, while on the other hand, Boltzmann, an Austrian theoretical scientist, derived the 4th power equation of radiant energy from his then unique consideration trying to forge a bridge between the electromagnetic-wave equations and the thermodynamic energy and entropy equations for a closed system.

i) What we should be careful is a case of an aluminum surface or a low-emissivity glass surface, but either of them can be treated as an application of what is described here.

j) This mathematical operation is similar to that for obtaining eq.(A.3.9) from eq.(A.3.5) with respect to water vapor and dry air.

k) Carnot was a French scientist who was active for a rather short period of time in early 19th century; he passed away at the age of thirty six. His theoretical considerations were all very much related to the fundamentals of thermodynamics. He clarified that there is the upper limit of 'work' output to be obtained from an imaginary ideal 'heat' engine. This implies that it is of vital importance to have 'cold' source in addition to 'heat' source. It is worthwhile keeping in mind that both 'heat' and 'cold' sources are equally important, since the former is well recognized by many of those concerned about so-called energy and environmental problems, but the latter has not yet been well recognized. With the latter in mind, it becomes easier to understand thermodynamic systems. Although implicitly, it seems that Carnot's work already included the concept of energy to be conserved, entropy to be generated, exergy to be consumed and the environmental temperature for a thermodynamic system.

IEA ECBCS ANNEX 49

Annex 49 is a task-shared international research project initiated within the framework of the International Energy Agency (IEA) programme on Energy Conservation in Buildings and Community Systems (ECBCS).

Annex 49 is a three year project. About 22 research institutes, universities and private companies from 12 countries are involved.

The main objective of this project is to develop concepts for reducing the exergy demand in the built environment, thus reducing the CO_2-emissions of the building stock and supporting structures for setting up sustainable and secure energy systems for this sector.

Annex 49 is based on an integral approach which includes not only the analysis and optimisation of the exergy demand in the heating and cooling systems but also all other processes where energy/exergy is used within the building stock. In order to reach this aim, the project works with the underlying basics, i.e. the exergy analysis methodologies.

These work items are aimed at development, assessment and analysis methodologies, including a tool development for the design and performance analysis of the regarded systems. With this basis, the work on exergy efficient community supply systems focuses on the development of exergy distribution, generation and storage system concepts.

For the course of the project, the generation and supply is as interesting as the use of energy/exergy. As a result, the development of exergy efficient building technology depends on the reduction of exergy demand for the heating, cooling and ventilation of buildings. Finally, all results of Annex 49 are to be made public information. The knowledge transfer and dissemination activities concentrate on the collection and spreading of information on ongoing and finished work.

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Annex 49

Low Exergy Systems for High-Performance
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International Energy Agency
Energy Conservation in
Buildings and Community
Systems Programme