NUMERICAL ANALYSIS OF ANNUAL EXERGY CONSUMPTION FOR DAYLIGHTING, ELECTRIC-LIGHTING, AND SPACE HEATING/COOLING SYSTEM

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ABSTRACT

The purpose of this study is to show explicitly a series of exergy input, output, and consumption for daylighting, electric-lighting, and space heating/cooling system and hence to reveal how daylighting system consumes solar exergy and how electric-lighting, and heating, and cooling systems consume exergy originally contained by fossil fuel. The merit of exergy calculation is that we can explicitly and thoroughly show how different types of energy are used as a series of exergy consumption at different parts of a system. We first show how to calculate exergy consumed by a system during a given period. We, then, show the result of a calculation of annual exergy consumption for the whole of an architectural environmental system. We assumed two cases : one is a case of a double glazed window with interior Venetian blinds, and the other is a case of a double glazed window with exterior Venetian blinds. The results show the followings. The total amount of solar exergy consumption of the two cases are almost equal to each other, but the ways of solar exergy consumption are different. The consumed exergy, which originates from LNG, in the case of exterior Venetian blinds was smaller than that of the room with interior Venetian blinds.

INTRODUCTION

Turning off or dimming electric lamps in accord with available daylight on the workplane brings a reduction in the electricity consumption for lighting. But the thermal energy, which originates from solar radiation transmitted through windows for daylighting, may increase the space cooling load. The reduction in the electricity consumption for lighting, on the other hand, could cause a decrease in the space cooling load, while it may increase the space heating load. Therefore, it is necessary to evaluate a whole system which includes not only room space with windows and electric lighting systems, but also air conditioning systems and electric power plant. When analyzing such a whole system, it is not enough to reveal entire energy flow through it. Because different types of energy, such as solar radiation, electricity, fossil fuel, light emitted by lamps, and thermal energy, are involved and the concept of energy cannot show explicitly the difference between them.

For example, Figure 1 schematically shows energy flow of a fluorescent tube. The electricity of 40 W is supplied to the tube and converted into thermal energy of 31 W and visible radiation of 9 W, each flowing out from the tube surface. The total energy flows in and out are conserved in accord with the first law of thermodynamics. As far as looking at the numbers shown in Fig. 1, the fluorescent tube should be regarded as a *heater* rather than a *lighter* since the thermal energy flux is more than three times greater than the visible radiation, though this does not fit our sense.

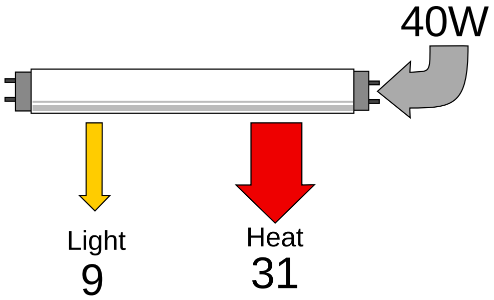

Figure 1 Energy flow of a 40 W fluorescent tube. Light is energy transfer by radiation in the visible range and heat is energy transfer by convection and long wave radiation in non-visible range from the tube surface.

For the reason above, it is important to take into account the quality of these different types of energy. To do this, we need to apply the concept of entropy in addition to that of energy and thereby derive exergy which can explicitly show how the resources are consumed (Shukuya and Komuro, 1996).

The purpose of this study is to show explicitly the energy use for daylighting, electric lighting, and space heating/cooling systems as a series of exergy input, output and consumption and reveal how a daylighting system consumes solar exergy and how an electric lighting and conventional space heating/cooling systems consume exergy originally contained from fossil fuel.

We fist show how to set up energy, entropy, and exergy balance equations for a system in question and how to calculate the total exergy consumption during a given period. We, then, show the results of a calculation of annual LNG exergy supply for a room having a window with interior or exterior Venetian blinds in Sapporo, Tokyo, and Kagoshima. Finally, We discuss annual exergy consumption at each stage of the whole system, for lighting, heating, and cooling.

SYSTEM DESCRIPTION

Figure 2 shows schematically a combination of the systems to be analyzed. We assume a room space in a typical office building with daylighting, electric lighting, and space heating/cooling systems. An electric power plant is included within the whole system. The workplane inside the room space is illuminated both by daylight transmitted through the window and by the light emitted by the fluorescent lamps. The lamps are dimmed in accord with available daylight on the workplane. Heating and cooling are made by a heat pump air conditioner to keep room air temperature constant.

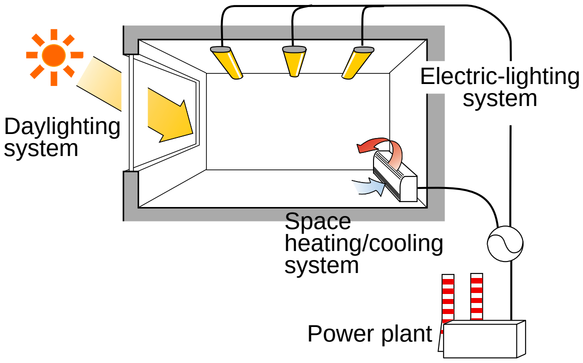

Figure 2 The whole system to be analyzed. The system includes not only daylighting, electric lighting, and space heating/cooling systems but also a power plant.

To calculate exergy consumption at various parts of the system, we first divide them into several subsystems. Each of the subsystems is a place or device where exergy is consumed as a consequence of energy transfer or energy conversion. The electric lighting system is divided into five subsystems : “Power plant”, “Fluorescent lamp”, “Interior wall surface (electric light)”, “Floor surface (electric light)”, and “Room air and building envelope”. The “Power plant” subsystem converts the energy of liquefied natural gas into electricity and heat. The “Fluorescent lamp” subsystem converts electricity into visible radiation, shortwave radiation in the range of 0.38 to 0.78 µm, and heat including long-wave radiation. The “Interior wall surface (electric light)” and the “Floor surface (electric light)” subsystems involve energy conversion of electric light into heat by absorption at the surface of interior wall and floor. The “Room air and building envelope” subsystem involves energy transfer between the surface of interior wall and room air by thermal convection.

In the same manner as in the case of electric lighting system, we divide daylighting system into five subsystems : “Outer surface of exterior wall”, “Window”, “Interior wall surface (solar rad.)”, “Floor surface (solar rad.)”, and “Room air and building envelope”.

Space heating/cooling system is divided into three subsystems : “Power plant”, “Heat pump”, and “Room air (heating/cooling)”.

The “Room air and building envelope” subsystem in the daylighting system is exactly the same as that already explained in the case of the electric lighting system. The same is true in terms of the “Power plant” subsystem in the space heating/cooling system. We have all together twelve subsystems.

ENERGY, ENTROPY, AND EXERGY BALANCE EQUATIONS

As an example, we show energy, entropy, and exergy balance equations for the “Fluorescent lamp” subsystem and then show how to calculate its exergy consumption during a given period.

The “Fluorescent lamp” subsystem consists of two

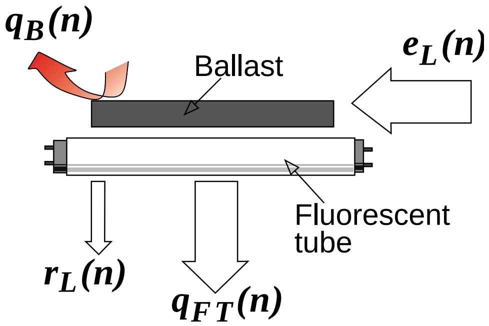

Figure 3 The energy input and output of the “Fluorescent lamp” subsystem. The “Fluorescent lamp” subsystem consists of two components ; ballast and fluorescent tube.

components ; ballast and fluorescent tube. Figure 3 shows schematically the energy input and output of the “Fluorescent lamp” subsystem. The energy balance equation of the “Fluorescent lamp” subsystem is given by the following equation.

$$e_L(n) = r_L(n) + q_B(n) + q_{FT}(n) \qquad (1)$$

where $e_L(n)$ is the electric power supplied to the ballast [W] ; $r_L(n)$ is the visible radiation emitted by the surface of fluorescent tube [W] ; $q_B(n)$ is heat released from the outer surface of the ballast [W] ; $q_{FT}(n)$ is heat released from the outer surface of fluorescent tube [W]. The variable appeared in each bracket denotes the time $n \bullet \Delta t$, where Δt is the increment in time. The left hand side of eq. (1) is the input energy flow and each term of the right hand side is the output energy flow.

The entropy balance equation corresponding to eq. (1) is given by

$$s_{eL}(n) + s_{gL}(n) = s_{rL}(n) + \frac{q_B(n)}{T_B(n)} + \frac{q_{FT}(n)}{T_{FT}(n)} \qquad (2)$$

where $s_{eL}(n)$ is entropy flux accompanied with electricity [W/K], which is zero since the electric power is the transfer of energy without dispersion of energy from the electricity grid to the ballast ; $s_{gL}(n)$ is the rate of entropy generation within the “Fluorescent lamp” subsystem [W/K] ; $s_{rL}(n)$ is entropy flux accompanied with visible radiation emitted by the surface of the fluorescent tube [W/K] ; $T_B(n)$ is the surface temperature of the ballast [K] ; $T_{FT}(n)$ is the surface temperature of the fluorescent tube [K].

The entropy flux accompanied with visible radiation emitted by a fluorescent lamp, $s_{rL}(n)$, can be calculated by a method discussed by Asada and Shukuya (1996). The second and third terms of the right hand side of eq. (2) are entropy flux given off from the “Fluorescent lamp” subsystem.

Extracting each term of eq. (2) multiplied by environmental temperature, $T_O(n)$ [K], from the corresponding term of eq. (1) yields the following exergy balance equation. Here we assume that the outdoor air environment is regarded as a common heat sink for all subsystems, so that environmental temperature is outdoor air temperature in Kelvin.

$$\begin{aligned}\left\{e_L(n) - s_{eL}(n)\cdot T_O(n)\right\} - e_{CL}(n) &= e_{XrL}(n) + \left\{1 - \frac{T_O(n)}{T_B(n)}\right\} q_B(n) \\ &\quad + \left\{1 - \frac{T_O(n)}{T_{FT}(n)}\right\} q_{FT}(n) \qquad (3)\end{aligned}$$

$$e_{CL}(n) = s_{gL}(n)\cdot T_O(n) \qquad (4)$$

$$e_{XrL}(n) = r_L(n) - s_{rL}(n)\cdot T_O(n) \qquad (5)$$

where $e_{CL}(n)$ is the rate of exergy consumption at the “Fluorescent lamp” subsystem [W] ; $e_{XrL}(n)$ is exergy flux of visible radiation emitted by the fluorescent tube [W]. The second and third terms of right hand side of eq. (3) are thermal exergy flux.

Equation (3) implies that the exergy of visible radiation is produced as a result of the consumption of a portion of input exergy. The thermal exergies produced as by-product are considered to be useful for giving off the entropy produced within the “Fluorescent lamp” subsystem, which appeared in the second term of the left hand side of eq. (2).

As the consequence of the use of the fluorescent lamp during a given period, a certain amount of exergy is consumed. We calculate this amount of exergy consumption at the “Fluorescent lamp” subsystem by the following equation.

$$\begin{aligned}E_{CLtotal} &= \sum_{n=0}^{N} e_{CL}(n)\cdot \Delta t \\ &= \sum_{n=0}^{N} s_{gL}(n)\cdot T_O(n)\cdot \Delta t \qquad (6)\end{aligned}$$

where $E_{CLtotal}$ is total exergy consumption during a given period, from 0 to $N \bullet \Delta t$, [J].

The energy, entropy, and exergy balance equations for other subsystems can be derived in the same manner as described above (Asada and Shukuya, 1994 and 1996).

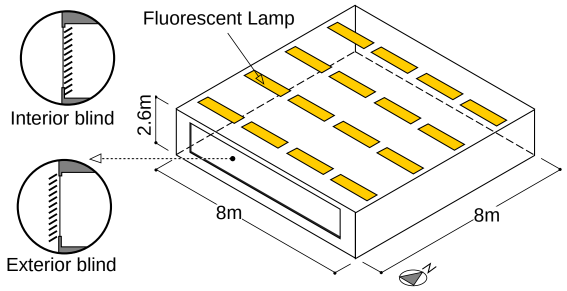

Figure 4 A room in a typical office building is assumed. The room is 8.0 m (width) × 8.0 m (depth) × 2.6 m (height) and has one exterior window with a double glazing and interior or exterior Venetian blind. Sixteen fittings with two 40 W fluorescent tubes each are mounted on the ceiling.

NUMERICAL CALCULATION

Calculation was made for a room shown in Figure 4 This is a room in a typical office building. The size is assumed to be a 8.0 m (width) × 8.0 m (depth) × 2.6 m (height) ; it has one exterior wall with a window. There are sixteen fittings, each with two fluorescent tubes of 40 W, mounted on the ceiling . The lamps are dimmed so that the total illuminance on the workplane becomes 500 lx if daylight illuminance on the workplane is smaller than 500 lx. The heat pump air conditioner is assumed to keep the room air temperature during occupied hours at 22 °C in winter season, 26 °C in summer season, and 24 °C in spring and autumn season. The coefficient of performance (COP) of the heat pump is assumed 3.5 for heating and 2.5 for cooling. The fuel used at the power plant is assumed to be liquefied natural gas (LNG). The ratio of the chemical exergy to the higher value of combustion of LNG is 0.98. Thermal efficiency of the power plant is assumed to be 0.38.

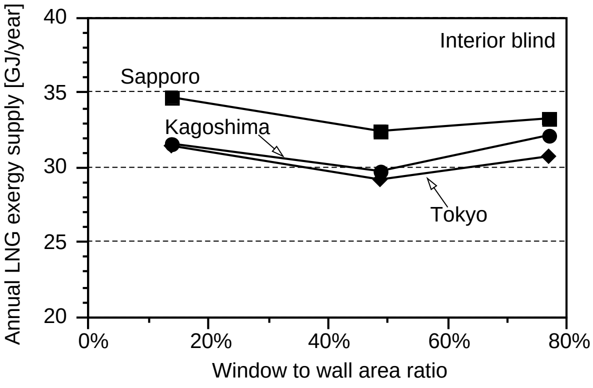

Figure 5 Annual LNG exergy supply to a room having a window with double glazing and interior Venetian blind.

The entropy flux accompanied with solar radiation, which is necessary to calculate exergy flux, was obtained from an empirical formula given by Kaberac and Drake (1992).

Before calculating annual exergy consumption of the whole system, we first calculated the interior daylight illuminance on the workplane on hourly basis for one year, using direct sunlight factor method (Shukuya and Kimura, 1982). We, then, calculated the amount of electric-light to be supplied on the workplane to reach at least 500 lx by electric lamps and calculated electricity supply for the lamps. Heating or cooling exergy load for the heat pump air conditioner were determined by solving control volume heat balance equations by the implicit type of finite difference method.

RESULTS AND DISCUSSION

We, first, show a comparison of annual exergy supply to the power plant for three different sizes of windows : one is a large window, 7 m (width) × 2.3 m (height), whose window to wall area ratio is 77 % ; the second is a medium sized window, 6 m (width) × 1.7 m (height), whose window to wall area ratio is 49 % ; the third is small window, 6 m (width) × 0.5 m (height), whose window to wall area ratio is 14 %. All of these windows have double glazing with interior or exterior Venetian blinds. We assumed that the slat of Venetian blinds are fixed at 45˚ during occupied hours in any seasons.

Figures 5 and 6 show the result of the calculation in the case of a window with interior Venetian blinds and in the case of exterior Venetian blinds. In both figures, there are three lines : they are for Sapporo, Tokyo, and Kagoshima respectively.

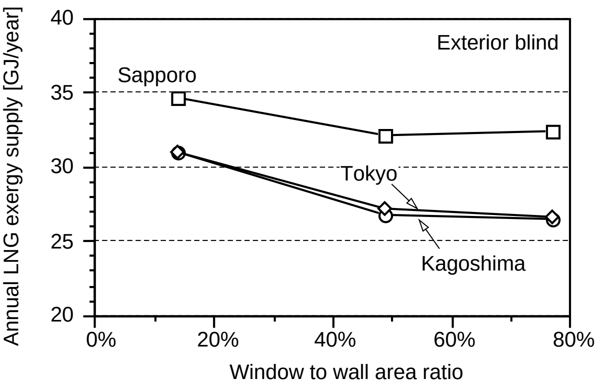

Figure 6 Annual LNG exergy supply to a room having a window with double glazing and exterior Venetian blind.

The LNG exergy supply to the room with interior Venetian blinds is the smallest in the case of medium sized window in every regions. On the other hand, the LNG exergy supply to the room with exterior Venetian blinds is the smallest in the case of large window in every regions, even in Sapporo whose winter is very cold.

Figure 7 shows annual exergy consumption at each subsystem in the case of large window in Tokyo : upper figure shows the case of interior Venetian blinds and lower figure exterior Venetian blinds.

Horizontal axis of upper and lower figures indicates the subsystems where exergy is consumed. Table 1 summarizes the phenomenon which causes exergy consumption at each of the subsystems. The vertical axis of the left-hand side indicates the amount of exergy consumption. The amount of exergy consumption at each subsystem is indicated by the corresponding shaded bar with the number above. Exergy consumption shown under the shaded bars enclosed by dashed line are the sum of exergy consumption from the left-hand side to right hand side. The total exergy consumption of the whole system is the number shown above the dot-and-dashed line. This total exergy consumption is 82.2 GJ/year in the case of interior Venetian blinds and 78.0 GJ/year in the case of exterior Venetian blinds.

Exergy consumption under the dashed horizontal line shown in the middle of the both figures are all originated from solar radiation, namely solar exergy consumption. Their totals in the case of interior and exterior Venetian blinds are equal because there is no difference in the incident solar radiation on the windows between interior and exterior Venetian blinds.

The amounts of exergy consumption indicated by the two horizontal dashed line in the middle of both figures, shown by the vertical arrow, are all originated from the

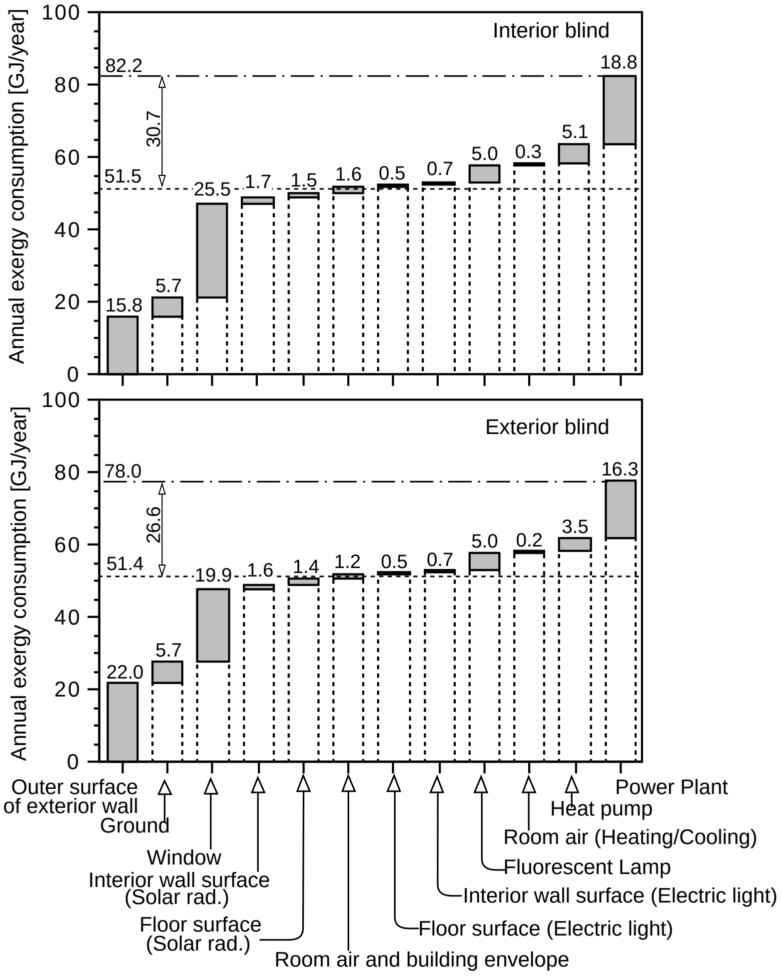

Figure 7 Annual exergy consumption of lighting, heating, and cooling systems in Tokyo for two rooms : one has a double glazed window with interior Venetian blinds and the other with exterior Venetian blinds.

Table 1 The phenomena causing the exergy consumption at subsystems shown in Fig. 6.

Subsystems	Phenomena
Outer surface of : exterior wall	Absorption of solar radiation incident on the surface of exterior wall.
Ground:	Absorption of solar radiation, which is reflected by the window and by the surface of the exterior wall and then incident on the surface of the ground.
Window:	Absorption of solar radiation at the glass pane and shading.
Interior wall surface: (Solar rad.)	Absorption of solar radiation at the interior wall surfaces except the floor.
Floor surface: (Solar rad.)	Absorption of solar radiation at the floor surface ; This directly contributes to the illumination.
Room air and : building envelope	Heat conduction within walls and heat convection between the wall surface and room air.
Floor surface: (Electric light)	Absorption of the electric light at the floor surface (workplane).
Interior wall surface: (Electric light)	Absorption of the electric light at the interior wall surfaces except the floor surface.
Fluorescent lamp:	Conversion of electricity to light, which is visible radiation, and to heat.
Room air: (Heating/cooling)	Heating and cooling room air with the supplied air from the heat pump.
Heat pump:	Compression and expansion of the refrigerant inside the heat pump.
Power plant:	Burning of liquefied natural gas and production if work with steam at the power plant.

liquefied natural gas (LNG) supplied to the power plant, namely LNG exergy consumption. Their total is 30.7 GJ/year in the case of interior Venetian blinds and 26.6 GJ/year in the case of exterior Venetian blinds.

Solar exergy consumption at the “Ground” in the case of exterior Venetian blinds is larger than that in the case of interior Venetian blinds since the solar exergy is reflected more by the window with exterior Venetian blinds than with interior Venetian blinds. On the other hand, solar exergy consumption at the “Window” in the case of exterior Venetian blinds is smaller than that in the case of interior blinds since less solar exergy is absorbed by the window with exterior blinds than that with interior blinds.

There is no significant difference in solar exergy consumption at the “Interior wall surface (daylight)” and “Floor surface (daylight)” between exterior and interior Venetian blinds. The same is true in terms of exergy consumption at “Floor surface (Electric light)”, “Interior surface (Electric light)”, and “Fluorescent lamp”. This implies that either exterior or interior Venetian blinds could bring almost the same amount of daylight for interior illumination.

Exergy consumption at the “Fluorescent lamp”, 5.0 GJ/year whether exterior or interior Venetian blinds, is about ten times larger than the exergy consumed at the “Floor surface (Electric light)”, which contributes essentially to the illumination of the workplne. The reason that the “Fluorescent lamp” consumes a lot of exergy is that there is a complex process within the fluorescent tube. The process involves energy conversion and transfer and they accompany exergy consumption. This results in the fluorescent tube inevitably consuming a lot of exergy supplied to the tube.

Figure 8 schematically shows exergy input, output, and consumption of a 40 W fluorescent tube installed in each of the fittings mounted on the ceiling. The input exergy as electricity is 40 W and the tube consumes 29 W, about 70 % of the supplied exergy, for producing visible radiation. Exergy output from the tube surface as visible radiation is 7 W. The rest 4 W (=40–29–7) is the exergy accompanied by the thermal energy flux. The exergy of visible radiation is about 1.8 times larger than that of heat. This proves that a fluorescent tube is a *lighter* rather than a *heater*.

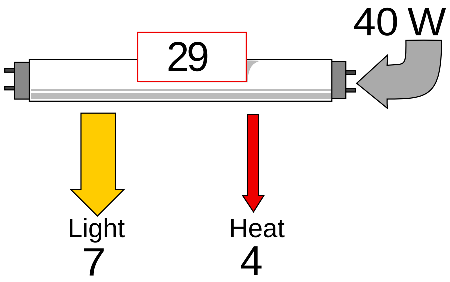

Figure 8 Exergy input, output, consumption of a 40 W fluorescent tube. Light is exergy flux of visible radiation and heat is exergy flux of heat convection and long wave radiation in non-visible range from the tube surface. The number in the square indicates the amount of exergy consumption within the tube.

The subsystem “Room air” consumes thermal exergy supplied by the heat pump air conditioner for heating or cooling room space with hot or cool air. The exergy consumption at this subsystem in the case of interior Venetian blinds is 0.3 GJ/year, while in the case of exterior Venetian blinds is 0.2 GJ/year. The difference is only 0.1 GJ/year. The exergy consumption at the subsystem “Heat pump” to produce hot or cool air is 5.1 GJ/year in the case of interior Venetian blinds, while in the case of exterior Venetian blinds is 3.5 GJ/year. The difference, 1.6 GJ/year, is brought installing Venetian blinds on exterior side of a window.

Replacing the interior Venetian blinds with the exterior Venetian blinds brings about a change in the path of solar exergy consumption and thereby a large reduction in LNG exergy consumption at the power plant system.

CONCLUSIONS

We fist discussed how to set up energy, entropy, and exergy balance equations for an architectural environment system consisting of daylighting, electric-lighting, and space heating/cooling systems and how to calculate the total exergy consumption during a given period. Numerical calculation of exergy input, consumption, and output was made for three cases in terms of window size, two cases in terms of shading, and three cases of locations : Sapporo, Tokyo, and Kagoshima. Annual LNG exergy supply to a room with a large-sized window with exterior Venetian blinds in Sapporo becomes smaller than others.

A comparison of annual-exergy-consumption patterns in the case of interior and exterior Venetian blinds showed that installing Venetian blinds on exterior side of a window brings about a change in the path of solar exergy consumption and thereby a large reduction in LNG exergy consumption at the power plant system, which is for electric lighting, heating, and cooling systems.

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NOMENCLATURE

$e_{CL}(n)$	rate of exergy consumption at the “Fluorescent lamp” subsystem [W].
$E_{CLtotal}$	total exergy consumption at the “Fluorescent lamp” subsystem during a given period, $i \cdot Dt$ to $j \cdot Dt$, [J].
$e_{XrL}(n)$	exergy flux of visible radiation emitted by the fluorescent tube [W].
$e_L(n)$	electricity supplied to the ballast of the lamp [W]
n	a certain time $n \cdot \Delta t$ [s].
$q_B(n)$	heat released from the outer surface of the ballast [W].
$q_{FT}(n)$	heat released from the outer surface of the fluorescent tube [W].
$r_L(n)$	energy output from fluorescent lamp as visible radiation [W].
$s_{eL}(\mathrm{n})$	entropy flux accompanied with electricity supplied to the fluorescent lamps [W/K].
$s_{gL}(n)$	rate of entropy generation at the “Fluorescent lamp” subsystem [W/K].
$s_{rL}(n)$	entropy flux accompanied with visible radiation emitted by the fluorescent lamp [W/K].
$T_{FT}(n)$	temperature of the surface of the fluorescent tube [K].
$T_O(n)$	outdoor air temperature at the time n [K].
$T_B(n)$	temperature of the surface of the ballast [K].
Δt	increment in the time $n \cdot \Delta t$ to $(n+1) \cdot \Delta t$ [s].