

EXERGY ANALYSIS OF A LOW TEMPERATURE RADIANT HEATING SYSTEM

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ABSTRACT

The purpose of this study is to gain insight into the process of heating a room with a low-temperature radiant heating system and solar energy, considering energy conversion and heat transfer steps in the building (where heat is required), in the incident solar radiation (which supplies part of the heat required) and in the heating system (which provides for the additional heating needs, by using electricity from a gas-fired power plant to drive a heat pump). We applied a theoretical framework developed by Shukuya, et. al. to a dynamic simulation model and did numerical calculations for a room with an exterior wall, with and without a south-facing window, during a heating season in the Netherlands. The exergy analysis allows direct comparison between different energy types (e.g. heat, electricity, fuel) on a common basis, and the concept of exergy consumption is useful for expressing how and where energy is dispersed in the course of energy conversion and heat transfer steps. The results show that exergy consumption in the room (demand side) is relatively small compared to the supply side (fuel burned at the power plant and the sun reaching the ground and facade). The calculations also show that the total amount of exergy consumed during the heating season can be larger than the total amount of exergy supplied during the same period, as a result of heat storage in the building mass, and of changes in the outdoor temperature between the moment of heat storage and heat release.

INTRODUCTION

Mechanisms related to energy transfer and conversion in space heating/cooling and lighting systems in the built environment have been analyzed using the concept of 'Exergy' (e.g. Shukuya and Hammache 2002, Asada and Shukuya 1997, 1999, Nisikawa et al 1997, 1999, Takahashi et al 2000). Exergy is a concept that explicitly shows the 'usefulness (quality)' of energy and matter, in addition to 'what is consumed' in the course of energy transfer or conversion steps. The concept of 'Energy' does not show these quality and consumption aspects, because it is a concept aimed at 'quantity'; this quantity, being subject to a conservation law, cannot be consumed according to the

first law of thermodynamics. The concept of 'Exergy' provides us further understanding of 'how a system works', by pinpointing the subsystems where energy is degraded. An understanding of exergy consumption principles will lead us to a better understanding of resource and environment issues.

One of the important aspects of their exergy research is that all systems are able to work by feeding on and consuming their portion of exergy. According to the exergy analysis of a space heating system (Shukuya, 1994, 2002), it is important to reduce exergy consumption of a heating system by using warm water of minimal thermal exergy, i.e. as near as possible to the outdoor environmental temperature. The exergy analysis emphasizes the importance of first designing a building to minimize heating loads (e.g. by improving wall and window insulation) and then to compensate the remaining heat demand (heating load) by supplying heat at a low temperature.

In this paper, we applied exergy calculation methods to the analysis of a radiant heating system. We adapted a model developed by Shukuya (1993), Asada et al. (1999, 2002, 2003) to include a ceiling radiant heating panel, and performed a numerical calculation on non steady state during one heating season for the Netherlands.

The purpose of this study is to analyze exergy supply and consumption for a radiant heating system during a heating season in the Netherlands for a typical (office) room with an exterior wall. We consider the cases with and without a window. We first describe the whole system to be analyzed and define a number of subsystems and sub-subsystems. We, next, show how to set up energy, entropy, and exergy balance equations for a subsystem in question and show how to calculate the total amount of supplied and consumed exergy during a given period, based on the results of Shukuya and Komuro (1996) and of Nishikawa (1997, 1999). Finally, we show numerical calculation results for the two cases analyzed and discuss the path of exergy through the subsystems as a series of exergy consumption steps, from the supply side (solar or fuel exergy) to the demand side (room air and walls).

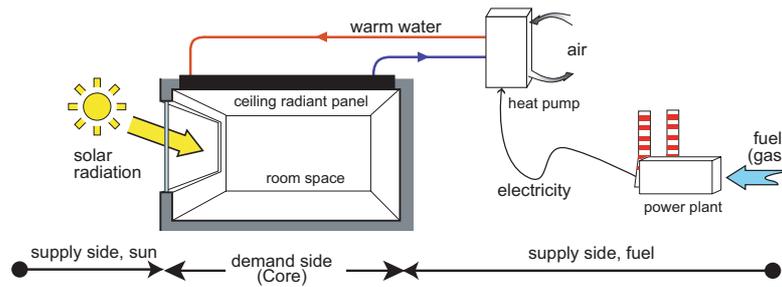


Figure 1 The system: a room in a typical office building with a ceiling radiant heating system, a heat source (electrically-driven heat pump) and a conventional gas-fired electric power plant.

SYSTEM DESCRIPTION

Figure 1 shows schematically the system to be analyzed, which consists of a room space in a typical office building with a ceiling radiant heating system, a heat source (electrically-driven heat pump) and a conventional gas-fired electric power plant. Pressure (Schmitz, 1999) and heat losses in the pipes are neglected. The demand for heating is located in the room, which is designated as the ‘core’ subsystem. The subsystems supplying this heat are designated as the ‘periphery’. Such a distinction between demand at the core and supply at the periphery is convenient for explaining the results in the item Results and Discussion.

EXERGY ANALYSIS

The analysis is based on the concept of ‘exergy consumption’ (Shukuya, 2002). Compared to thermal power plants and high-temperature industrial processes, space heating and cooling systems operate at temperatures relatively close to the outdoor conditions. The direct use of (fossil) fuels or electricity as a heat source thus entails degrading a high-grade energy source in order to generate low-grade heat, to meet the indoor space heating demand. While the first law of thermodynamics tells us that energy is conserved throughout this process, the second law (on which the exergy concept is based) can “articulate what is consumed” (Shukuya, 2002) during this degradation.

The subsystems

To calculate exergy consumption at the system shown in Figure 1, we first divide it into several subsystems. Each of the subsystems is a location or device where exergy is consumed as a consequence of energy transfer or energy conversion. We then define a sequential order for these subsystems, and set up energy, entropy, and exergy balance equations for each subsystem. The output energy, entropy, and exergy of each subsystem are used as the input for the next subsystem. Since exergy is gradually consumed in the course of the energy transfer and energy conversion processes involved, the output of the last system to the outdoor environment eventually decreases to zero.

For instance, in order to analyze how primary exergy

from fuel is consumed in a radiant heating system, we examine six subsystems: ‘Power plant’, ‘Heat pump’, ‘Ceiling radiant panel’, ‘Interior wall surface (fuel)’, ‘Floor surface (fuel)’, and ‘Room (air & enclosure)’. The exergy output from the power plant is the input for the heat pump; the output from the heat pump is the input for the ceiling radiant panel, etc.. The ‘Power plant’ subsystem converts the energy of fuel (natural gas) into electricity and heat. The ‘Heat pump’ subsystem uses electricity from the power plant and heat from the environment (outdoor air) to produce warm water. The ‘Ceiling radiant panel’ subsystem receives heat from warm water supplied by the ‘Heat pump’ subsystem and the ceiling panel surface emits long wave radiation. At the ‘Interior wall surface’ and ‘Floor surface’ subsystems, the long wave radiation emitted by the ceiling radiant panel is absorbed and converted into heat. In the ‘Room (air & enclosure)’ subsystem, this heat is transferred from the wall and floor surfaces to the room air (by convection) and to the inner part of the wall and floor constructions (by conduction).

Each subsystem can further be divided into several sub-subsystems, according to necessity. To illustrate the calculation procedure, we show energy, entropy, and exergy balance equations for the sub-subsystem ‘Inner part of the exterior wall’, which is a part of the ‘Room (air & enclosure)’ subsystem. The equations were derived by Nishikawa et. al. (1997). Figure 2 schematically shows the energy flows within a wall. The dashed line indicates the boundary of the sub-subsystem ‘Inner part of the exterior wall’.

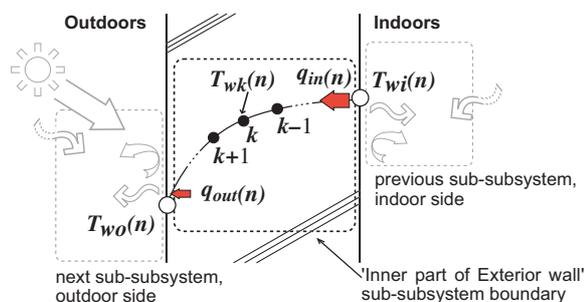


Figure 2 Energy flux in the sub-subsystem ‘Inner part of the exterior wall’, between the ‘outdoor surface of the wall’ and ‘inner surface of the wall’ sub-subsystems.

in the wall is modeled as multi node ($k = 1, 2, \dots, m$) and heat storage capacity of a node k is shown as $C_{pk}\rho_k V_k$ [J/(K·m²)]. The solar radiation incident on the exterior wall surface and the heat transfer on the exterior wall surface are considered at the next subsystem at the outdoor side, shown by gray line at the left hand side of the wall in Figure 2.

Energy, entropy and exergy balance equations

The energy balance equation (per unit area) for the sub-subsystem ‘Inner part of the exterior wall’ at a specific moment (n) is:

$$q_{in}(n) = \sum_{k=1}^m C_{pk}\rho_k V_k \frac{dT_{wk}}{dt} + q_{out}(n) \quad (1)$$

The left hand side of Eq. (1) is the rate of thermal energy inflow into the inner part of the exterior wall. The first term of the right hand side is the rate of thermal energy storage in the wall mass and the second term is the rate of energy outflow from the inner part of the exterior wall.

The entropy balance equation, based on the second law of thermodynamics, is derived from Eq. (1) by dividing each term by its corresponding temperature at the moment (n). This equation is used to derive that of exergy.

$$\frac{q_{in}(n)}{T_{wi}(n)} + s_g(n) = \sum_{k=1}^m \left\{ C_{pk}\rho_k V_k \frac{dT_{wk}}{dt} \cdot \frac{1}{T_{wk}(n)} \right\} + \frac{q_{out}(n)}{T_{wo}(n)} \quad (2)$$

The first term on the left hand side of Eq. (2) is the entropy of the thermal energy going into the wall, and the second term is the entropy generation within the wall by heat conduction from the indoor surface to the node and from the node to the outdoor surface. Although the first law of thermodynamics states that energy is conserved during heat conduction, the second law tells us that entropy is generated. The entropy generation term in Eq. (2) gives an indication of the extent to which thermal energy is degraded (from a higher to a lower temperature) in the course of heat conduction.

The exergy equation, Eq. (3), is derived by subtracting each term in Eq. (2) from the corresponding term in Eq. (1), and subsequently multiplying each term by a reference temperature T_o at the moment $T_o(n)$ [K]. One possible interpretation of these equations is that the exergy in Eq. (3) can be regarded as the ‘valuable’ portion, and the entropy in Eq. (2) as the ‘invaluable’ portion of the thermal energy terms expressed in Eq. (1).

The reference temperature in exergy analysis is usually taken as the outdoor temperature. The outdoor air environment can be regarded as a common heat sink for all systems. If, for example, a hot or warm system is allowed to thermally interact with the outdoor environment without any external input of heat, it will eventually reach a state of thermal equilibrium with

this environment. A system above or below environmental temperature contains thermal exergy relative to this environment. When in thermal equilibrium with the environment, however, the system has zero thermal exergy. Exergy can thus be used to express how far a system is from its environment and can show, for example, that warm water at 30 °C is more valuable on a cold winter day than on a warm summer day.

$$\begin{aligned} q_{in}(n) \left(1 - \frac{T_o(n)}{T_{wi}(n)} \right) - s_g(n) \cdot T_o(n) \\ = \sum_{k=1}^m \left[C_{pk}\rho_k V_k \frac{dT_{wk}}{dt} \left(1 - \frac{T_o(n)}{T_{wk}(n)} \right) \right] \\ + q_{out}(n) \left(1 - \frac{T_o(n)}{T_{wo}(n)} \right) \end{aligned} \quad (3)$$

The first term on the left hand side of Eq. (3) is the rate of thermal exergy input associated with heat q_{in} flowing from the indoor wall surface into the inner part of the exterior wall; the second term is the exergy consumption rate within the wall, which is associated with the entropy generation resulting from heat conduction within the wall. The first term on the right hand side is the exergy associated with heat storage within the wall; the second term is the rate of thermal exergy output associated with heat q_{out} flowing from inner part of the wall towards the outdoor wall surface.

The reference temperature in Eq. (3) is allowed to change according to the change of outdoor air temperature. Customarily, a constant reference temperature is used for high or low temperature systems far from the environmental temperature T_o (e.g. power plants, cryogenic systems); in such cases, fluctuations in T_o have relatively little effect on the exergy values. However, for near-environmental systems, these fluctuations can become significant. Nishikawa (1997) has investigated non-steady state thermodynamics and concluded that there is no need to define a constant reference temperature and it is possible to compare or to add exergies calculated with different reference (outdoor) temperatures.

The entropy flux accompanied with solar radiation, which is needed to calculate the exergy flux, was calculated by an empirical formula given by Kabelac and Drake (1992).

Exergy over a given period

Eq. (3) shows exergy fluxes [W/m²] for a specific moment (n). We use Eq. (4) to calculate the total exergy quantities [J/m²] for a given period. In order to derive this equation, we first assume that the given period is a series of finite time increments Δt (from time $n - 1$ to time n) and that each Δt is small enough so that the temperatures, energy, entropy, and exergy values appearing in Eq. (1), (2), (3) can be assumed to be constant during each Δt . We integrate every term of Eq. (3) over Δt , to obtain the total exergy quantities

over the infinitesimally small time interval Δt . In order to obtain the total exergy amounts over a longer period, we then sum up the resulting terms over Δt ranging from $n=i$ to j .

$$\begin{aligned} & \Delta t \cdot \sum_{n=i}^j \left[q_{in}(n) \left(1 - \frac{T_o(n)}{T_{wi}(n)} \right) \right] - \Delta t \cdot \sum_{n=i}^j s_g(n) \cdot T_o(n) \\ &= \sum_{n=i}^j \sum_{k=1}^m C_{pk} \rho_k V_k \left((T_{wk}(n) - T_{wk}(n-1)) - T_o(n) \ln \left(\frac{T_{wk}(n)}{T_{wk}(n-1)} \right) \right) \\ & \quad + \Delta t \cdot \sum_{n=i}^j \left[q_{out}(n) \left(1 - \frac{T_o(n)}{T_{wo}(n)} \right) \right] \end{aligned} \quad (4)$$

Eq. (4) also refers to the sub-subsystem ‘Inner part of the exterior wall’. The first term refers to the total amount of exergy supplied to the inner part of the wall during the length of the entire period. The second term is the total amount of exergy consumed during the period due to heat transfer by conduction. The first term of the right hand side is the total amount of thermal exergy stored within the wall mass. The second term is the total exergy output towards the next sub-subsystem, the ‘outdoor surface of the wall’. From there, this exergy eventually dissipates into the outdoor air by convection and radiation. If the temperature of the outer surface is equal to that of the outdoor air, the second term of right hand side is zero.

The energy, entropy, and exergy balance equations for a ceiling radiant panel were shown in the references (Asada and Takeda, 2002, 2003). Equations for other subsystems can be derived in the same manner as described above (Asada and Shukuya, 1994, 1996, 1999)

NUMERICAL CALCULATIONS

Calculations were made for a room in a typical office building, assumed to be 6.0 m (width) x 6.0 m (depth) x 2.6 m (height) and to have an exterior wall with outside insulation (Figure 3). The ceiling radiant panel is assumed to have a constant surface temperature of 28 °C, and to be controlled based on a room operative temperature setpoint of 23 °C. A simple on/off control strategy assumes that warm water (35 °C) supply to the ceiling heating system is turned on when the operative temperature drops below 22 °C and is turned off above 24 °C. Thermal inertia of the water inside the system (ceiling panel and pipes) is neglected. The return water temperature from the radiant panel is assumed to be about 30 °C. A heat pump is used to produce warm water; its coefficient of performance (COP) is assumed to vary according to the outdoor temperature (Table A1). The fuel used at the power plant is natural gas (the ratio of the chemical exergy to the higher heating value of natural gas is 0.98). The thermal efficiency of the power plant is assumed to be 0.38.

We calculated hourly exergy quantities for the whole system during one heating season in the Netherlands

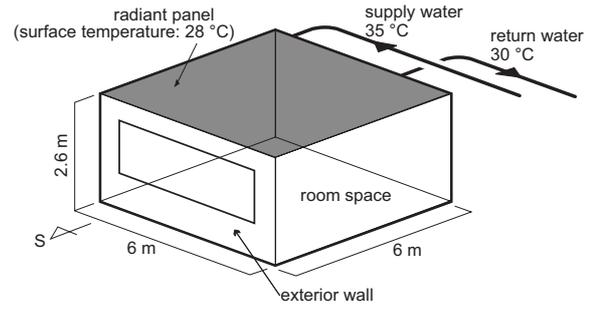


Figure 3 A room in a typical office building is assumed, 6.0 m x 6.0 m x 2.6 m, with a south-facing exterior wall. Temperatures are assumed to be 28 °C for the radiant panel surface, 35 °C for the warm water supplied to the panel and 30 °C for the return water.

(de Bilt: the city at northern part of NL), using hourly weather data for the standard year 1964 (e.g. outdoor air temperature, solar radiation, outdoor humidity). We calculated room air temperature, energy, entropy, and exergy flows for unsteady state heat transfer using central volume heat balance equations by the implicit type of finite difference method. We derived the thermal energy to be supplied to the ceiling radiant panel considering the solar radiation transmitted through the window, and the electricity supplied to the heat pump. We also took into account the fuel supplied to the power plant.

In order to consider the effect of solar radiation transmitted through the window and the thermal characteristics of the exterior wall, we assume two cases (Figure 4). In case 1 we have a room with a south-facing window (4.0 m wide x 1.7 m high), and assume the heat transmission losses to be uniform over the entire facade. Hence, we assume the U-value of the exterior wall and that of the window to be equal, at 0.8 W/(m²·K). In case 2 we have a room without a window, and assume the same amount of thermal energy is supplied to the ceiling radiant panel (by warm

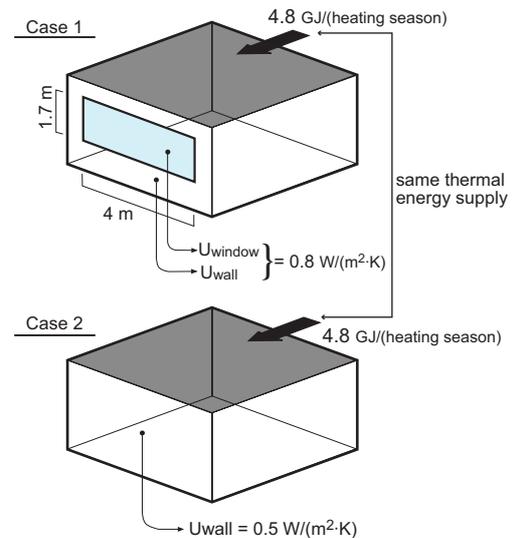


Figure 4 Case 1: south-facing window and $U=0.8$ W/(m²·K) for both the exterior wall and the window. Case 2: room without a window, $U=0.5$ W/(m²·K) for the exterior wall for both cases.

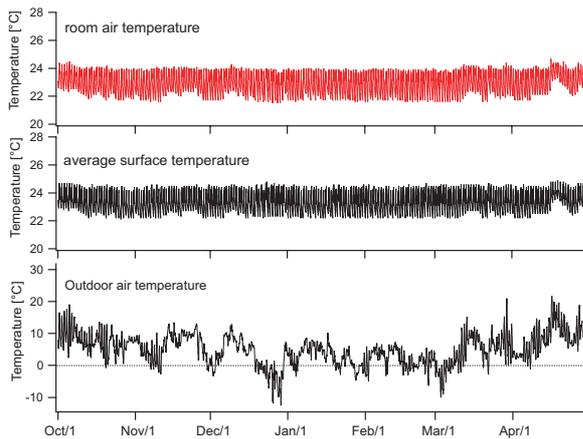


Figure 5 Time histories of room air, indoor surface (averaged), and outdoor air temperatures during a heating season (October to April) in the Netherlands, for a room with a window.

water) as in the room with a window. The thermal energy supplied to the radiant panel is about 4.8 GJ/(heating season) in both cases. Because in the windowless room there is almost no heat gain from the sun, the exterior wall has to be more insulated; an U-value of about 0.5 W/(m²·K) is required to compensate for the lack of solar heat gains into the room.

RESULTS AND DISCUSSION

In this item, calculation results are presented for a room (with and without a window) and for a wall. The analysis shows how exergy is consumed in the course of energy conversion and heat transfer processes.

We first did an annual calculation for the case of a room with a south-facing window. The heating loads between May and September were negligible, so we assumed the heating season to last from October to April.

Figure 5 shows the time histories of temperatures of room air, average interior surface, and outdoor air during heating season (October to April) in the Netherlands for the case of a room which has a window. Room air temperature and average interior surface temperature are the results of the calculation and the outdoor air temperatures are input data used for the calculation.

The outdoor air temperature (the lower graph) is about -10 °C to 15 °C during October to April. The room air temperature (the upper graph) and average interior surface temperature (the middle graph) are almost equal and are 21 °C to 24.5 °C.

Figure 6 shows the exergy input and consumption path for the case of a room which has a window.

The vertical axis shows the total exergy consumption during the heating season. [GJ/(heating season)]. Horizontal axis shows variations of subsystems where exergy is consumed.

The vertical arrow on the left side of Figure 6 shows the total exergy supplied by the sun to the facade, about 14 GJ/(heating season). The vertical arrow on the right side shows the total exergy supplied by the fuel (natural gas), about 3.8 GJ/(heating season). The black vertical bars in the figure show the amount of exergy consumed at each subsystem. Exergy supplied by the sun and by fuel is consumed step by step at each subsystem as a result of energy conversion and heat transfer steps. These exergy consumption steps are shown in the figure, from the supply sides (left and right sides of Figure 6), to the demand side at the ‘core’ of the system, the subsystems ‘Interior wall surface (solar)’, ‘Floor surface (solar)’, ‘Room (air + enclosure)’, ‘Floor surface (fuel)’, and ‘Interior wall surface (fuel)’ shown around the middle of the Figure. The term ‘solar’ and ‘fuel’ in the blackets show source of consumed exergy. The subsystems and phenomena which involved in exergy consumption are shown in the Appendix (Table A2).

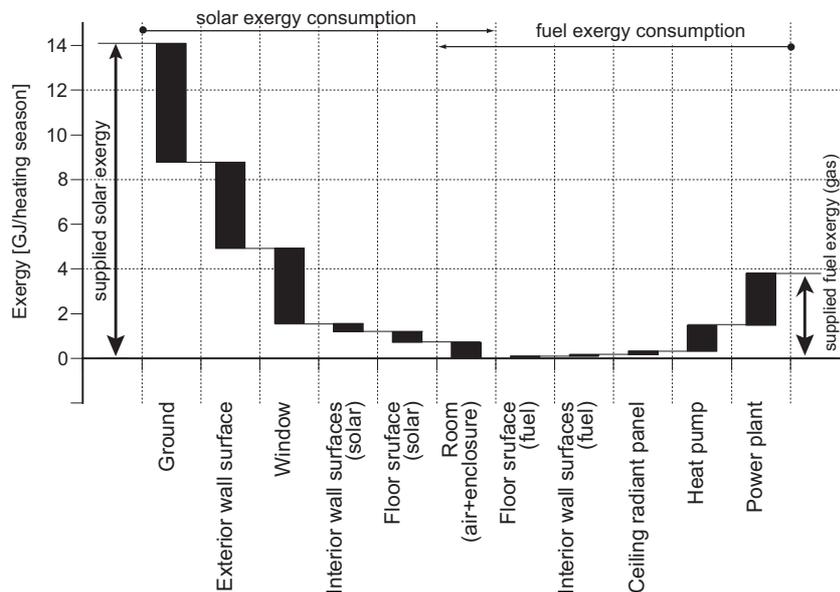


Figure 6 Exergy input and consumption path for a room with a south-facing window.

An example is presented to illustrate how exergy consumption can be read from Figure 6. The first black bar on the left side of the figure corresponds to the 'Ground' subsystem. It shows the first exergy consumption step, as a result of solar radiation being reflected by the facade, reaching the ground, being absorbed and then converted to heat. This exergy consumption, about 5 GJ/(heating season), corresponds to the length of the black bar for the 'Ground' subsystem. The remaining solar exergy is also consumed by absorption and conversion to heat at the subsystems 'Exterior wall surface', 'Interior wall surface (solar)', and 'Floor surface (solar)'. These exergy consumption steps are similarly expressed as black bars, the length of each bar indicating the amount of exergy consumed per subsystem. On the right hand side of the figure, exergy consumption steps are shown in a similar way for the exergy supplied by the fuel and consumed by energy conversion and heat transfer at the subsystems 'Power plant', 'Heat pump', 'Ceiling radiant panel', 'Interior wall surface (fuel)', and 'Floor surface (fuel)'. Finally, exergy consumption at the subsystem 'Room (air & enclosure)' is due to heat transfer by convection and conduction to and from the indoor air and the room enclosure (walls and floor).

The results show that relatively large exergy consumptions take place at the supply side, from the sun and from fuel. Solar exergy consumption at the subsystems 'Ground', 'Exterior wall surface', and 'Window' is due to energy conversion from high-grade solar radiation to low-grade heat. Fuel exergy consumption at the 'Power plant' and 'Heat pump' subsystems is also comparatively large; this is attributed to the relatively complex energy conversion steps involved in electricity generation, and to the use of electricity to produce low-grade heat in the heat pump.

At the 'core' of the system, the subsystem 'Room

(air & enclosure)', consumes a relatively small amount of exergy. This is because energy conversion and transfer occur at temperatures near to that of the environment.

Figure 7 shows the result for the room without a window. The same amount of solar exergy is supplied to the facade as in the case of the room with a window, since both rooms have the same facade area. However, practically all the solar exergy is consumed at the subsystems 'Ground' and 'Exterior wall surface' by absorption on the ground and facade. This example shows how solar exergy is consumed whether we harness it or not.

Because the same amount of thermal energy is supplied to the radiant panel, the total supplied fuel exergy and its consumption path are the same as for the room with a window. The lower U-value of the facade and the absence of a window have no noticeable effect on the path of exergy consumption from fuel to heating panel shown on the right-hand side of the graph. For the subsystem 'Room (air & enclosure)', however, about two-thirds of the exergy consumption appears under zero (shown as vertical grey bar). This does not show negative exergy but indicates that more exergy is consumed than supplied during the heating season, reflecting the relation between the amount of stored thermal exergy in the building mass and variation of reference (outdoor air) temperature.

This effect is discussed below, based on the exergy input and consumption in the sub-subsystem 'Inner part of the exterior wall'.

Exergy analysis of a wall

Figure 8 shows time histories of temperatures (upper graph), and exergy supply and consumption (lower graph), for the sub-subsystem 'Inner part of the exterior wall' during two consecutive days, March 2nd and 3rd. In the upper figure, the two dashed grey lines show

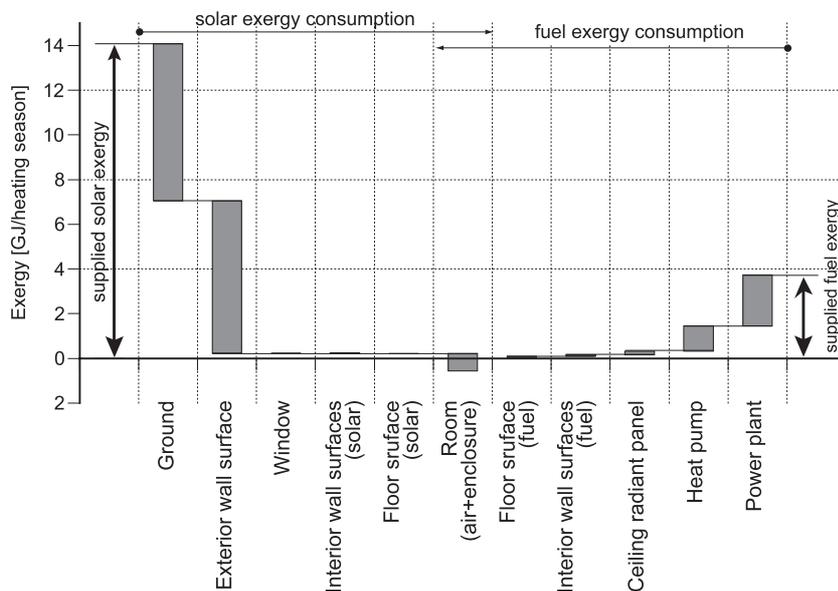


Figure 7 Exergy input and consumption path for a room without a window.

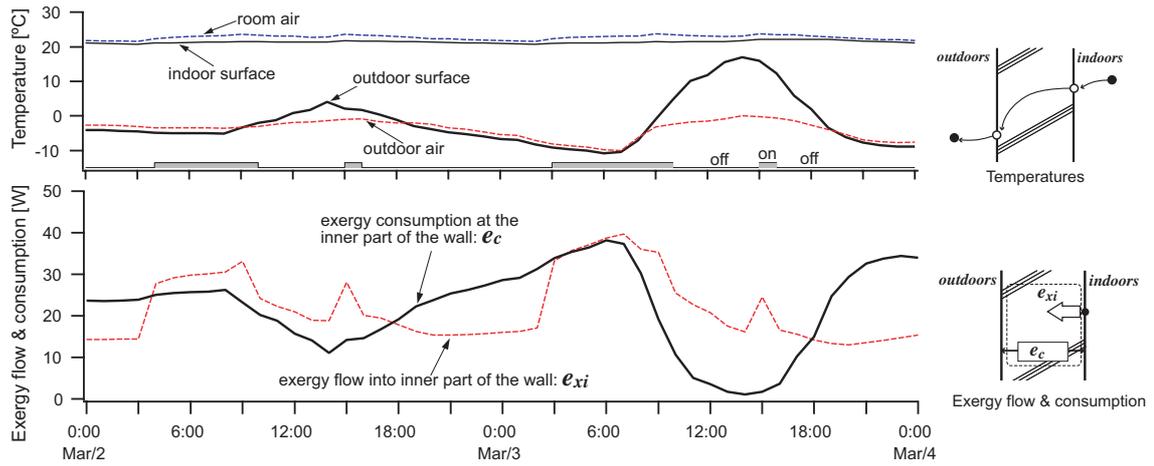


Figure 8 Exergy flow and consumption by heat conduction: inner part of the exterior wall

room air (the upper) and outdoor air temperatures (the lower); the two lines (non dashed) show indoor (the upper) and outdoor wall surface temperatures (the lower); the line at the bottom shows whether hot water is being supplied to the ceiling radiant panel or not (on or off).

The lower figure shows time histories of exergy input and exergy consumption at the sub-subsystem ‘Inner part of the exterior wall’. The black line shows the rate of exergy consumption and the gray (dashed) line the exergy input rate; they correspond to the first and second terms on the left hand side of Eq. (3). Exergy consumption (non dashed line) is smaller than exergy input (dashed line) between 4:00 and 18:00 hours on March 2nd. This shows a portion of input thermal exergy is being stored within the wall. On the other hand, exergy consumption is larger than exergy input from 18:00 (March 2nd) to 3:00 (March 3rd). The fact that exergy consumption can exceed exergy input is attributed to the effect of previously stored exergy within the exterior wall, which is gradually consumed by heat conduction within the wall. The time lag and the change in outdoor air temperature T_o between exergy storage and consumption contribute to this effect. Assuming that all stored heat in the inner part of the wall at the moment n (the first term of right hand side of the Eq. (1)) is released at the next moment $n+1$ and outdoor air temperature has changed during this period, the exergy of heat which is being stored to the wall at the moment n is different from that of heat being released from the wall at the next moment $n+1$, because the exergy factor of heat being stored at the moment n (which is $(1-T_o(n)/T_{wk}(n))$ shown at the first term of right hand side of Eq. (3)), has changed to $(1-T_o(n+1)/T_{wk}(n+1))$. at the moment $n+1$.

CONCLUSION

In this paper, we review some key aspects of the exergy consumption concept, and illustrate how to set up energy, entropy, and exergy balance equations for a radiant heating system. We did a numerical calculation

for one heating season in the Netherlands for a room with an exterior wall, with and without a south-facing window. The path of exergy consumption through the radiant heating system is shown as a series of exergy consumption steps from the supply side (sun and fuel) to the demand side (room air and walls). Exergy consumption in the room is relatively small (compared to the supply side), since energy conversion and heat transfer take place at near-environmental temperatures. For the room without a window, more exergy is consumed than supplied at the exterior wall, reflecting the heat storage effect in the building mass.

ACKNOWLEDGMENT

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NOMENCLATURE

$C_{pk}\rho_kV_k$	heat storage capacity of the node k in the wall [J/(K·m ²)]
dt	finite time interval [s]
dT_{wk}	temperature difference of the node k within a finite time interval [K]
k	specific node [-]
n	specific moment [-]
m	number of nodes in the wall [-]
$q_m(n)$	heat flow from the surface to the inner part of the wall [W/m ²]
$q_{out}(n)$	heat flow from the inner part to the outer surface of the wall [W/m ²]
$s_g(n)$	entropy generation at the sub-subsystem ‘Inner part of the exterior wall’ [W/(m ² ·K)]
T_H	temperature of the water leaving the heat pump [K]
$T_o(n)$	temperature of the outdoor air [K]
$T_{wk}(n)$	temperature of the node k where the heat storage mass is concentrated [K]

$T_{wo}(n)$ temperature of the outer surface of the wall [K]
 $T_{wi}(n)$ temperature of the inner surface of the wall [K]
 Δt increment in time [s]

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Table A1 Heat pump and power plant efficiencies

Heat pump	Power plant
$0.35 \cdot \left(1 - \frac{T_o}{T_H}\right)$	0.38*

* (output electricity)/(input fuel energy)

Table A2 The main phenomena causing exergy consumption at the subsystems shown in Fig.6 and 7

subsystems	phenomena
Ground	Absorption of solar radiation, reflected by the facade, on the surface of the ground.
Exterior wall surface	Absorption of solar radiation incident on the exterior wall surface.
Window	Absorption of solar radiation at the glass panes.
Interior wall surface (solar)	Absorption of solar radiation, directly and indirectly incident on the indoor wall surfaces. (excluding the floor surface)
Floor surface (solar)	Absorption of solar radiation directly and indirectly incident on the floor surface.
Room air & enclosure	Heat transfer by conduction within walls and by convection between wall surfaces and room air.
Floor surface (fuel)	Absorption of long wave radiation emitted by surrounding wall surfaces, including radiant panel, and energy conversion on the floor surface.
Interior wall surface (fuel)	Absorption of long wave radiation emitted by surrounding wall surfaces, including radiant panel, and energy conversion on the wall surfaces, excluding the floor surface.
Ceiling radiant panel	Heat transfer from water to the radiant panel surface, and into the room by radiation and convection.
Heat pump	Compression, expansion and phase change of the refrigerant inside the heat pump; heat transfer.
Power plant	Energy conversion from natural gas at the power plant into electricity and heat.