news

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Low Exergy Systems for High-Performance Buildings and Communities

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BENCHMARKING OF LOW "EXERGY" BUILDINGS

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The growing concern of environmental problems, such as global warming, which have been linked to the extended use of energy, has increased both the importance of all kinds of so-called "energy saving measures", and the necessity for an increased efficiency in all forms of energy utilisation. Despite the efforts made to improve energy efficiency in buildings, the issue of gaining an overall assessment and comparing different energy sources still exists [1]. Today's analysis and optimisation methods do not distinguish between different qualities of energy flows during the analysis. An assessment of energy flows from different sources is first carried out at the end of the analysis by weighting them against the primary energy factors included in the building codes of a number of countries. Primary energy factors are based neither on analytical grounds nor on thermodynamic process analyses, yet they have been derived from statistical material and political discussion.

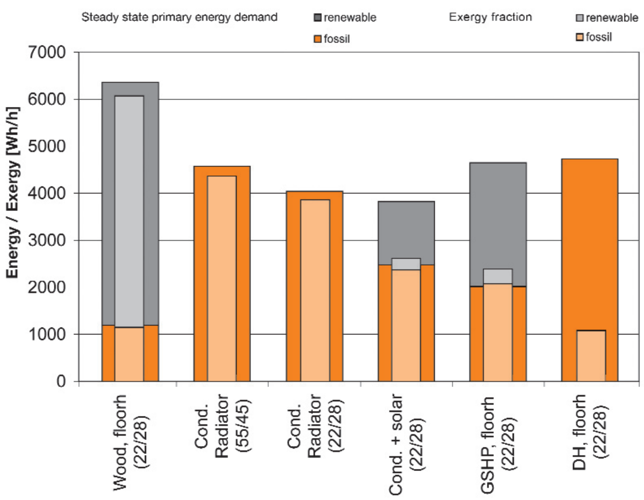

Figure 1: Calculated primary energy demand (fossil and renewable) for the chosen variants of the building service equipment (steady state calculation)

As described above, all our energy assessment of energy utilisation in buildings is based on quantitative considerations alone. By weighting different energy sources against primary energy factors, some aspects of a somewhat qualitative assessment are taken into consideration. Yet, principally, the design of supply structures is founded on the satisfaction of the quantitative demand within buildings. With the so-called LowEx approach, a further step is to be taken. Not only are the quantitative aspects of demand and supply considered, but the qualitative aspects are also included ([2], [3], [4], [5]).

To clarify these ideas, different uses of energy within buildings are explained: if we heat indoor space up to 20°C, we have to supply heat at a temperature slightly higher than 20°C. An exergetic analysis shows that the required energy quality, the exergy fraction or quality factor q, for this application is very low (q ≈ 7% only). If the production of domestic hot water is considered as heating water up to temperatures of about 55°C, the necessary energy quality is slightly higher (q ≈ 15%). For cooking or heating of, for example, a sauna, we need an even higher quality level (q ≈ 28%), and for the operation of different household appliances and lighting we need the highest possible quality (q ≈ 100%).

On the other hand, our energy supply structures are not as sophisticated as the use. Energy is commonly supplied as electricity or as a fossil energy carrier. The energy quality of the supply is the same for alll different uses are the same and unnecessarily high (q ≈ 100%).

An adaptation of the quality levels of supply and demand could be managed by covering, for example, the heating demand with suitable energy sources, as there is available district heating with a quality level of about 30%. There is a large variety of technical solutions on the market to supply buildings with the lowest possible supply temperatures (q ≈ 13%) on the market. Commonly known waterborne floor heating systems is one of these solutions.

In Germany, the typical primary energy efficiency for the heating of newly erected dwellings, equipped with good building service systems, is about 70%. If exergy is considered, the picture changes: the exergetic efficiency of the heating process is only about 10%.

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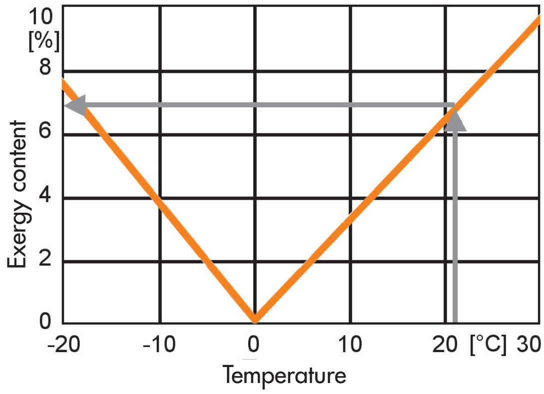

Figure 2: For a reference temperature of 0°C, the exergy content of an energy flow at the indoor air temperature of 21°C is 7%.

An exergy analysis has to start with the definition of the boundary conditions and with the estimation of the exergetic demand of the occupied zones. A typical outdoor ambient air temperature in winter is considered to be 0°C in central/northern Europe. This is also the reference temperature for the exergy analysis. With an indoor air temperature of 21°C within the heated spaces, the exergy fraction of the heating energy turns out to be 7% as shown in Figure 2. The quality factor is equal to the Carnot efficiency for this purpose.

This factor is dependent on the temperature inside the room and on the ambient environment. In addition, in extreme conditions, this does not exceed 15%. Although similar considerations can be made for summer and cooling conditions, this is not the subject of this paper and will be covered in future research activities.

Table 1: Cases analysed

Case	Heat generation system	Heat emission system
1	Condensing boiler	Standard radiators (55/45°C)
2	Condensing boiler	Floor heating (28/22°C)
3	Biomass boiler (e.g. wooden pellet burner)	Floor heating (28/22°C)
4	Condensing boiler and solar thermal system covering 40% of the heating load	Floor heating (28/22°C)
5	Ground source heat pump (GSHP) with ground heat exchanger	Floor heating (28/22°C)
6	CHP district heating system fired with renewable sources	Floor heating (28/22°C)

A Case Study

As a case study, a German single-family dwelling built between 1995 and 2000, has been chosen. For the building service equipment and the heating system of the building, six different variants (shown in Table 1) have been studied intensively.

A common energetic assessment of the building under steady state conditions is shown in Figure 1. Because of the different primary energy factors of the used fuel sources, the fossil part of the energy supply varies between the analysed variants. Taking the renewable amounts of used energy into consideration, the total energy consumption is about the same. This is self-evident, since the same building is presented in all cases. Only the efficiency of the chosen building service system may vary.

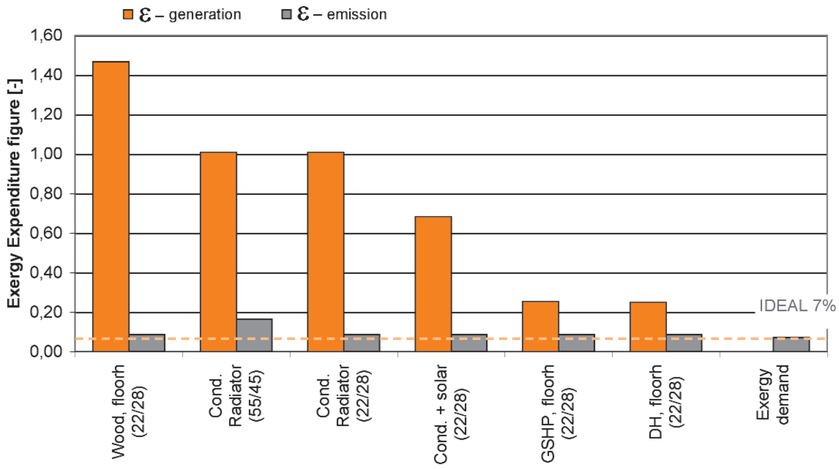

Figure 3: Assessment of the components "heat generation" and "emission system" with the exergy expenditure figure for the chosen variants of the building service system.

In considering the primary energy alone, saving measures for fossil energy sources and the related CO_2 emissions can be identified but can hardly give any real indication of the efficient use of energy.

A comparison of an energetic and exergetic assessment of the primary energy demand from fossil and renewable sources is shown in Figure 1. It can be clearly seen that the different building service system configurations could handle the same requirements to fulfil the heating task of the same building, with a largely varying amount of exergy. Especially the condensing boiler, where natural gas is used and burned, utilises about 100% exergy for that task. This is also true for the wooden pellet burner. Other systems are able to satisfy the requirements with less than half of the exergy. This is shown in the results from, for example, the systems operating with a district heating supply.

The exergetic assessment of the regarded heating systems opens up the possibility of comparing the performance (and the efficient use of the different the energy sources) in an equal and thermodynamic way. This basis is free from the influence of political discussions and national borders. The potential of renewable energy sources has also correctly been taken into consideration. It can be concluded that a rational use of energy has to be assessed with an additional exergy analysis and that exergy use should be limited, as it is done today with primary energy. This has to happen under the consideration of the entire building as one system ([6], [7]).

A LowEx Benchmark

To make the exergy quantity manageable for building designers and to allow for engineering-based orientation for the choice of building service solutions, a new parameter is presented here. This parameter, the exergy expenditure Figure, is a quotient from the exergetic effort (produced by a component) and the energetic use of this component. It is defined as:

$$\varepsilon = \frac{effort}{use} = \frac{\dot{E}x_{in} + \dot{E}x_{aux}}{\dot{E}n_{out}}$$

A component, e.g. a radiator, is designed to supply a specified heating power. This implies it should heat the room with a certain amount of heat, which is to be delivered to the room space. Energy is transmitted and used within the space, and heat has been exchanged from the heat carrier, water, to the air within the room. A component should perform this task with the smallest possible amount of exergy. Furthermore, the use of high quality (auxiliary) energy, e.g. electrical power, should be low, as should unused losses to the environment.

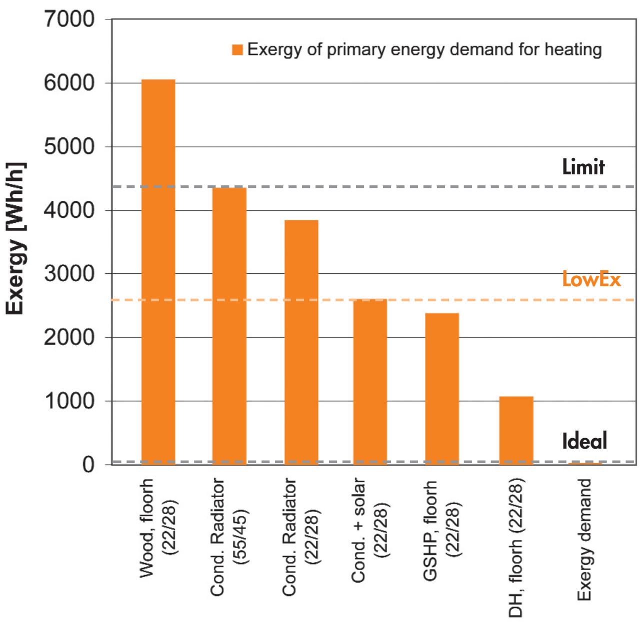

Figure 4: Calculated exergy fractions of total primary demand (fossil and renewable) for the chosen variants of the building service equipment (steady state) and a suggested possible classification.

As described above, the exergy demand, i.e. the exergy fraction of the needed energy, of a zone is only 7%. This value can be directly compared to the exergy expenditure Figures of the different components, as has been done in Figure 3. It is shown that different heat generators satisfy the demand with a more or less well-adapted supply. Heat generators, which utilise a combustion process, use much more exergy than required, and are thus less "LowEx". These differences can also be demonstrated for emission systems. The radiator system uses more exergy than the floor heating system to heat the same room. The floor heating system is close to ideal conditions.

Low Exergy Buildings

Since the exergy approach enables a comparison of different energy utilisation systems in buildings on an equal basis, a limitation of the exergy fraction of the primary energy demand is advisable.

An ideal line can be drawn based on the real exegetic demand of the regarded zone, as shown in Figure 4. Minimisations of this exergetic demand should first be taken into account, by implementing measures to decrease the energy demand of buildings. Subsequently, this exergetic demand should be satisfied with a suitable supply system, e.g. the exergy expenditure Figure should be oriented to the actual exergetic demand of the zone.

Furthermore, the upper limit of the exergy demand should be limited according to the demand with the use of a good building service equipment solution, similarly as done in the limitation of fossil primary energy demands. As the supply matches the needed demand and the exergy destruction in the regarded building is kept below a limit, this building can be regarded as a LowEx-building. Therefore, the exergy demand of fossil and renewable sources should be limited. This limitation could be done in a similar manner as already known from the procedure of limiting the primary energy demand.

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DYNAMIC EXERGY ANALYSIS ON BUILDING LEVEL

Timo Haase[2], Dirk Müller[3]

For the process of designing energy efficient buildings, the benefits of exergy analysis are indisputable. However, exergy analyses with constant ambient conditions are often not sufficient for complex systems that work on very low exergy levels.

Thermal exergy, for example, is computed on the basis of temperature differences between a heat flow and the ambient. If the aim of an exergy analysis is to assess a power plant process, the definition of the ambient dead state is normally fixed. This is reasonable because temperature differences between combustion chamber and ambient are so high that a varying ambient air temperature only causes small errors. If a system that works on a temperature level very close to the ambient temperature is to be analysed, the relative error of an exergy calculation with constant ambient conditions increases significantly. In order to assess such systems accurately, the variation of the ambient dead state must be taken into account. If exergy flows of a system are calculated in small time steps with changing ambient dead state, the process of assessment is called dynamic exergy analysis.

An example shall render the usability of dynamic exergy analysis at the building level. As it has been stated before, energy analysis of a building and its technical installations is not sufficient for choosing the best heating system [1]. A better approach is to assess the building's thermal exergy demand and to find a heat source that meets that demand.

The example case of the following exergy calculation is a single room with a dimension of 4 m x 4 m, representing a typical office room with average insulation standards. The room is equipped with a 3 m^2 south facing window. The heat is transferred to the room air by a floor heating system working at a water supply temperature of 40 °C. In the base case, a condensing boiler combusting liquefied natural gas (LNG), serves as the heat source. The whole simulation set-up consists of a room, a thermo hydraulic heating and ambient weather model using Modelica. The object oriented simulation environment Modelica/Dymola [2] allows very detailed and fully time resolved calculation runs. By this means, the simulation model is able to take into account accurate weather data as well as the dynamic interaction of room and technical systems.

The calculated exergy demand leads to a required exergy flow from the floor heating system. In most cases, the heat generator does not have to accommodate the whole exergy demand – solar gains and other heat sources inside the room (e.g. appliances and occupants) already satisfy a certain part of the heating demand. In this example, only solar gains are taken into consideration.

Heat losses of the distribution system are calculated on the basis of pipe insulation standard, mass flow, fluid temperature, and ambient temperature. The exergy balance is completed by assessing the consumption of auxiliary exergy by pumps and control system components.

The system's boundary must defined accurately. In the base case, two energy sources enter the system: electric energy (i.e. pure exergy), and liquefied natural gas, for which we can compute the chemical exergy.

To be able to compare the results of the exergy analysis of the LNG-fired boiler to a heat source with lower exergy level, a second case is also examined. In this second case, the heat source is waste heat from the return flow of a district heating network with a temperature of 60 °C.

Here, the exergy analysis of the building connected to the district heating network is assessed by regarding only the exergy portion of the incoming heat flow as a function of the reference temperature and the supply temperature from the network.

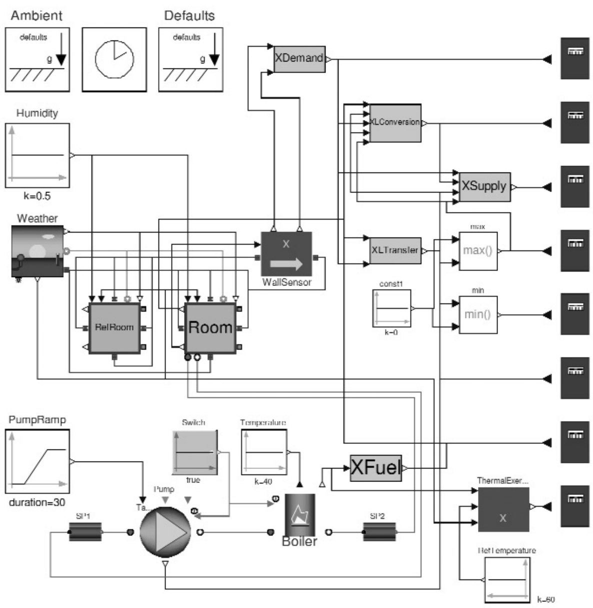

Figure 5: Components and model for the dynamic simulation in Modelica/Dymola.

Figure 6 shows the results of a dynamic exergy analysis of the system carried out over a period of 90 days. The dark grey indicates the exergy demand of the room, which is equal to the exergy flow connected to heat losses due to transmission and air exchange to the ambient. The light grey line indicates the feed on exergy which is consumed by the condensing boiler; the exergy flow associated with the usage of waste heat at 60 °C is shown by the orange line.

The amount of exergy consumed by the boiler is always much higher than the demanded exergy of the heat flow to the room. The difference in exergy flows is destructed or dispensed to the ambient.

Quite contrary to the condensing boiler, the heat supply with waste heat shows only small differences in consumed and demanded exergy flows. In some

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time steps, the exergy supply is even lower than the demand – this is the case when the heating system is considerably supported by solar or internal gains.

The results clearly show the merits of exergy analysis in contrast to energy analysis. Since the latter only accounts for the energy flows to and from the room, which are the same in both cases, it shows no difference between the two possibilities of heat supply. The dynamic exergy calculation approachevaluates the quality of the energy flows and therefore the good system design can be distinguished from the poor one. The outcome of such analyses should be a reasonable use of the whole energy chain.

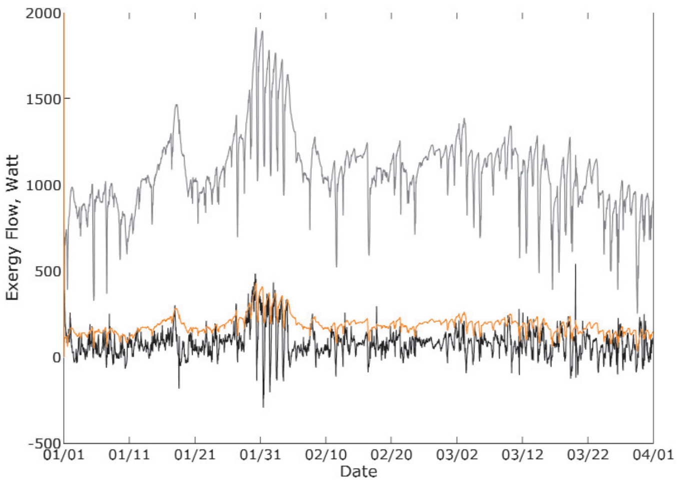

Figure 6: Exergy demand of the room (dark grey), exergy flow of LNG (light grey), and exergy flow of district waste heat supply (orange).

In the presented case, the high exergy flow from the combustion of fossil fuel (LNG) should be used to feed industrial processes working at high temperature levels or to produce electricity and heat. The amount of heat energy that is dispensed in connection with high temperature or power plant processes permits the heat supply of offices or residential buildings. A direct use of fossil fuels for heating purposes means a waste of exergy, which is ecologically as well as economically counterproductive.

Additionally, dynamic exergy analysis allows very detailed studies on all components of the supply system. System parts producing high exergy losses can be replaced by new components. A recalculation of the building and the updated supply system will deliver pros and cons of the new set-up.

In the future, dynamic exergy analysis should be applied to cooling, ventilation and air conditioning cases. More complicated supply systems offer many possibilities, in terms of exergy, for optimisation.

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RADIANT EXERGY AND ITS IMPORTANCE FOR THERMAL COMFORT IN THE BUILT ENVIRONMENT

Masanori Shukuya[4]

Low exergy systems for heating and cooling in buildings are those which make use of low-valued energy as sources of heating and cooling. This article is focused on the control of "radiant exergy" in order to create a more comfortable indoor environment.

Warm radiant exergy and its positive effect in winter

Well-designed passive solar buildings usually show small temperature fluctuations throughout the day. A sufficient amount of heat capacity in the walls and floor with external insulation allows the temperature to stay well below the upper limit for comfort, namely avoiding overheating, and the temperature does not fluctuate much with changes in weather conditions. Thermal insulation of building envelopes reduces the space-heating load allowing for a downsized heater, having larger emission areas with a lower surface temperature, thereby sustaining the supply temperature of the heating medium at only a slightly higher level than the desired level for indoor temperature.

Figure 7 shows a typical example of human-body exergy consumption rate in winter as a function of mean radiant temperature on the ordinate and air temperature on the abscissa [1], [2]. A human body, as one of the biological systems, performs the "exergy-entropy process", in which a large portion of exergy, supplied as food, is consumed for metabolism, thus maintaining a variety of body functions and structures. The exergy consumption rate shown in Figure 7 is for thermo-regulation.

Each of the fine lines with numbers represents an equi-exergy-consumption rate. The bold line drawn from the upper-left down to the lower-right corresponds to the state of the human body, which has a metabolic thermal energy emission rate equalling the energy outflow from radiation, convection, evaporation, and conduction. According to the previous knowledge of human thermal physiology, such a condition provides the human body with thermal comfort, i.e. any sets of room air temperature and mean radiant temperature on the bold line in Figure 7 must give a comfortable indoor thermal condition. Nevertheless, according to experienced architects and engineers concerned with designing comfortable built environments, a set of relatively high mean radiant temperatures and relatively low air temperatures brings about a better indoor thermal quality during the winter. This is consistent with such an indoor condition that brings about the lowest exergy consumption rate within the human body, as shown in Figure 7. Yet, the preference of occupants, with respect to the combination of radiant temperature and air temperature, should be proved more extensively through experiments.

In order to have higher mean radiant temperature, it is vitally important to make windows and walls thermally well insulated. For example, the surface temperatures of a concrete wall with no thermal insulation and of a single-paned window would turn out to be around 10°C and 5°C, respectively, for the condition of indoor and outdoor air temperatures of 20°C and 0°C. Provided that their thermal insulation level is improved, the surface temperature can be raised to around 19°C and 15°C, respectively.

An exergy-wise implication of this fact can be explained by Figure 8, which shows a quantitative relationship between warm and cool radiant exergies as a function of surface temperature under the condition of outdoor air temperature of 0°C. The surfaces emit "warm" or "cold" radiant exergy depending on whether their temperature is higher or lower than that of outdoor air. Most walls and windows emit "warm" radiant exergy in winter. Figure 8 shows that a better insulation makes three to almost four times larger the amount of warm radiant exergy emission rate in the case of walls and ten-times in the case of windows.

If the "warm" radiant exergy-emission rate from the walls and the windows is small, then the clothing and skin temperatures becomes lower. This results in a large temperature difference between bodycore and shell, thereby increasing human-body exergy consumption rate. The larger the warm radiant exergy emitted by the surrounding surfaces, the easier for the human body to dissipate the thermal exergy for entropy disposal from the skin and the clothing surface into its surroundings, hence reducing the exergy-consumption rate within the human-body.

For summer conditions, it also holds true that a combination of higher mean radiant temperature and lower air temperature gives the lowest exergy consumption rate.

A recent investigation on the role of radiant exergies, focused on residential buildings, shows that radiant cooling seems to allow the subjects to be tolerant to a little higher air temperature and humidity, though more detailed studies are required [3], [4].

Let us discuss the negative and positive effects of radiant exergies on indoor environment, supposing a typical summer afternoon of outdoor air temperature of 33°C. Assuming a bare concrete wall, with an external surface which absorbs solar-radiant energy of 300 W/m^2, and an indoor air temperature of 27°C, the internal surface temperature would be around 35°C. This internal surface temperature can be decreased to 28°C by sufficient thermal wall insulation. A similar consideration applies to the location of shading devices relative to the glass windows. Assuming an internal shading device (e.g. a roller shade) with solar-energy transmittance and reflectance of 0.15 and 0.25 respectively, along with a glass window pane, its surface temperature would be around 40°C. However, if the same roller shade is located just outside the glass pane, the surface temperature can be decreased to 35°C or lower. Such appropriate thermal insulation of the wall and the window decreases overall internal surface temperature, thereby dramatically decreasing the warm exergy available in the room space. Furthermore, the use of external solar shading devices, together with nocturnal natural ventilation and the use of moderate thermal mass of floors and walls, combined with good external insulation, can even allow for the production of cool radiant exergy during the daytime in summer.

Figure 9 shows the warm and cool radiant exergies available in summer conditions. Values of radiant exergy are much lower in summer than in winter. This is due to a much smaller temperature difference between indoors and outdoors in summer than in winter. Due to the characteristic of mathematical expression of radiant exergy [3], [5], radiant exergy in summer is 15 to 50 times smaller in summer

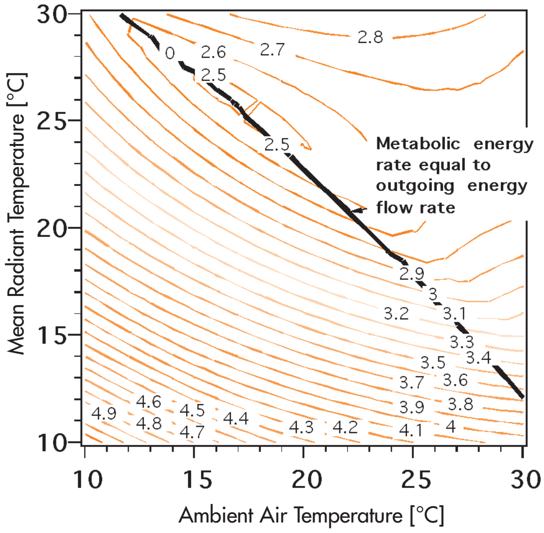

Figure 7: Relationships between human-body exergy consumption rate, whose unit is W/m^2 (body surface), and the outdoor environmental temperature under winter conditions (0°C; 40%rh). There is a set of room air temperatures (18 to 20°C) and mean radiant temperatures (23 to 25°C) which provide him/her with the lowest exergy consumption rate.

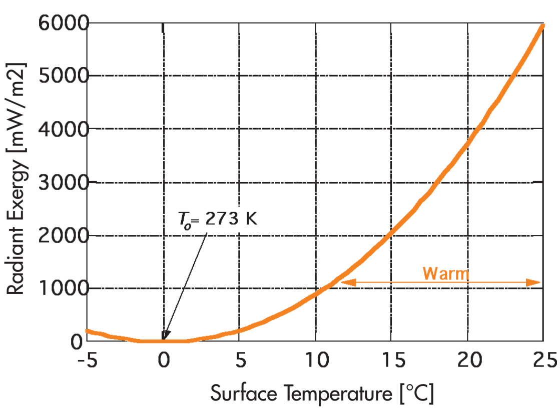

Figure 8: Radiant exergy available from the interior surfaces of building envelopes under winter conditions. In this example, the outdoor temperature as the environmental temperature for exergy calculation is assumed to be 273 K. The amount of "warm" radiant exergy ranges from 2 to 4 W/m^2; this is much larger than that available in summer. See also Figure 9 for comparison.

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than in winter, even though the temperature difference in winter is only about three times more than in summer.

Figure 10 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 were open for cross ventilation. This result was obtained from an in-situ experiment carried out in two small wooden buildings with natural ventilation in summer [3].

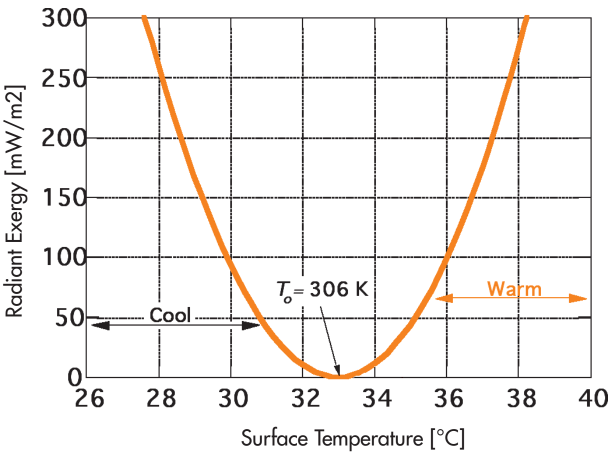

Figure 9: Radiant exergy available from the interior surfaces of building envelopes in summer conditions. In this example, the outdoor temperature as the environmental temperature for exergy calculation is assumed to be 306 K. The amount of "warm" and "cool" radiant exergy ranges from 0 to 250 mW/m².

The closed circles "•" denote the cases in which 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 emission rate reaching 20 mW/m² results in the condition that no subjects vote for comfort. The same rate of "cool" radiant exergy results in the opposite condition in which most of the subjects vote for comfort. An amount of cool radiant exergy rate at 20mW/m² is available if the mean radiant temperature is slightly lower than the outdoor air temperature (see Figure 9).

What can be seen from a simple example of surface-temperature calculation together with Figures 9 and 10 assures that the use of external solar shading is the first priority in creating a comfortable built environment which effectively uses natural ventilation, even in hot and humid summer situations.

Concluding remarks

Warm radiant exergy plays an important role in thermal comfort in winter and is enhanced by appropriate thermal insulation of walls, floor, ceiling, and windows. On the other hand, it plays a negative effect on thermal comfort in summer so that it must be decreased as much as possible by external solar-shading devices on windows, together with thermally well-insulated walls, ceiling, etc.. If there is a good amount of heat capacity within the walls and floor, and thereby nocturnal natural ventilation is used, then the cool radiant exergy could be provided by the wall and floor surfaces during the day.

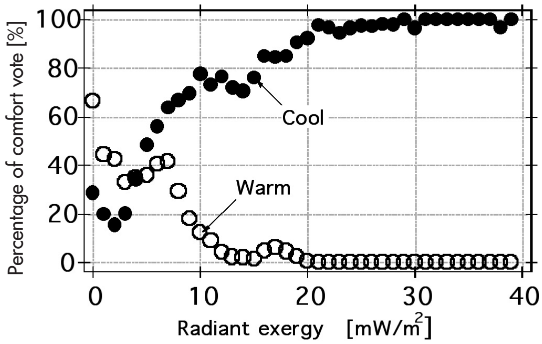

Figure 10: The percentage of comfort votes under the condition of no perceived air current as a function of radiant exergy emitted from interior wall surfaces in a small experimental house in Tsukuba, Japan.

Convection, of course, plays another key role in thermal comfort, but it should be minimised to avoid draughts, especially in winter. In summer, such convection delivering the cold air around the occupants' bodies should also be avoided, but if the moderate air current can be obtained by rationally-designed natural ventilation, then it plays a good role in sweeping away the resultant entropy disposal due to exergy consumption in the human body.

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Low Exergy Systems for High-Performance Buildings and Communities

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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 starting in November 2006, following a preparation phase of one year. About 12 countries are currently participating.

For up-to-date date information see:

www.annex49.com

Announcements

- **4th Expert Meeting** in Reykjavik (Iceland) on August 27-28, 2008
- **Joint Workshop** with IEA DHC "Future energy saving potential from DHC and LowEx activities", on August 29, 2008 in Reykjavik (Iceland)
- **LowEx Joint Annex 49 – CosteXergy Conference**, in Limburg region, the Netherlands, April 21st, 2009
- **5th Expert Meeting** in Limburg region, the Netherlands April 22-23, 2009
- **6th Expert Meeting** in Helsinki/Espoo, Finland September 2-4, 2009

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Energy Conservation in Buildings and Community Systems Programme
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