SOLAR HEATING AND COOLING SYSTEM FOR THERMAL COMFORT CONDITIONS AND LOWER BUILDING ENERGY USE

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1. Introduction

EPBD Recast Directive 2010/31/EU promotes the improvement of the energy performance of buildings within the Union, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness. Furthermore, it encourages architects and planners to properly consider the optimal combination of improvements in energy efficiency, the use of energy from renewable sources and the attainment of thermal comfort for the users (Directive 2010/31/EU). In this respect, the possibility to design a highly efficient heating and cooling (hereinafter H/C) system that attains thermal comfort conditions beside rational building energy use has to be well considered. Highly satisfied user and the attained minimal possible energy use for H/C purposes assure the favourization of low-temperature-heating and high-temperature-cooling systems as compared to conventional systems for H/C of buildings.

Good possibilities present H/C radiative panels that allow the use of low valued energy, which is delivered by renewable energy sources. A new direction in the development of a simple solar H/C system that uses solar exergy for warming up the water to be circulated within the panels was suggested by Hoshino and Shukuya (2008). It can be well upgraded also with solar cooling techology system. H/C radiative panels provide H/C energy at a temperature close to room temperature. They have been implemented into quite a few buildings, owning to their positive impact on thermal comfort conditions (Dijk et al., 1998; Krainer and Meletitiki-Alexandros, 2004; Olesen, 1997, 1998; Sammaljarvi, 1998; Shukuya, 2003, 2006, 2010), better indoor air quality (Lengweiler et al., 1997; Sammaljarvi, 1998; Schata et al., 1990) and lower building energy use (Krainer and Meletitiki -Alexandros, 2004; Krainer et al., 2007).

Experiences of architects and engineers working on the design of comfort conditions in winter show that higher mean radiant temperature (hereinafter T_{mr}) and lower room air temperature (hereinafter T_{ai}) can result in more acceptable comfort conditions. This coincides with the fact that thermally comfortable conditions equal to thermal neutrality seem to lead to lower human body exergy consumption rate. The relation was first investigated by Isawa et al. (2003) and Shukuya et al. (2003, 2006). Simone et al. (2011) studied the relation between the human body exergy consumption rate and the human thermal sensation. Results (Simone et al., 2011) showed that the minimum human body exergy consumption rate was related to the thermal sensation votes close to thermal neutrality, tending to slightly cooler side of thermal sensation. The whole human body exergy balance under typical summer conditions in hot and humid regions was analyzed by Iwamatsu and Asada (2009) and Shukuya et al. (2010). Tokunaga and Shukuya (2011) investigated the human-body exergy balance calculation under un-steady state conditions.

The paper presents the comparison between solar H/C system and conventional system regarding measured building energy use and exergy analysis of thermal comfort conditions. The presented approach of reciprocal consideration of building energy use and thermal comfort is important for the future design of H/C systems and for the improvement of energy performance of buildings.

2. Methods

Test room (163.4 m^3) is located at the Faculty of Civil and Geodetic Engineering, University of Ljubljana (year of contruction: 1969).

It has one exterior wall (1.29 W/m^{2}K) with a 15 m^2 window (classical double glazed, 2.9 W/m^{2}K, west oriented). Other constructional complexes are interior (0.83 - 1.17 W/m^{2}K). The test room is equipped with two systems for H/C: conventional and solar H/C system separated in time (Fig.1).

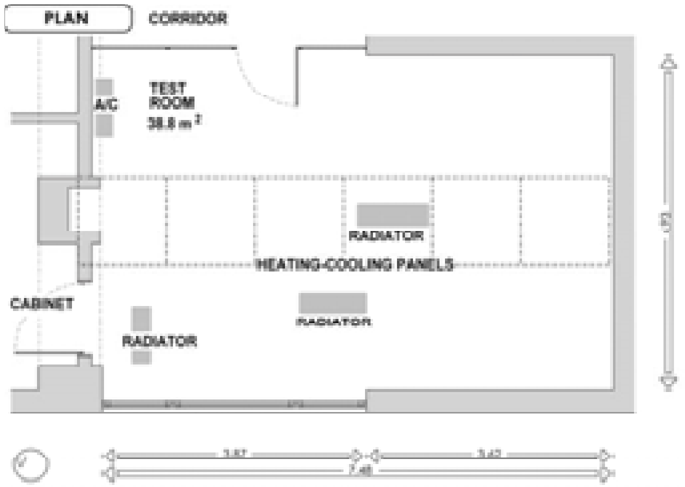

Fig. 1: Plan of test room with positions of conventional H/C system (oil-filled electric heaters and split system with indoor A/C unit) and solar H/C system (H/C ceiling radiative panels)

Conventional H/C system presents three oil filled electric radiators (230 V – 50 Hz, 2000 W) and classical split system with indoor unit (2 cooling aggregates with 30.9 kW of cooling capacity, 35.3 kW of heating capacity; 1 indoor unit with 2kW of cooling power). Solar H/C system presents six radiative ceiling panels (9m^2) conected with solar collectors positioned on the top of the faculty (4 x 2 m^2; α= 95%; ε= 5%, 525 kWh/m^{2}day), cold water is supplied with cassical split system. Switching between hot and cold water entering into the panels is manual. The dimensions of H/C ceiling panels are 125 x 125 cm. They are constructed of 10 cm tick polystyrene thermal insulation with engraved pipes for hot or cold water. All panels are fixed with 4 steel screws into ceiling construction. Plan and section of H/C ceiling panels are shown in Figure 2. The comparison between conventional and solar H/C system will be investigated regarding calculated thermal comfort conditions and measured building energy use. For the purpose of on-line monitoring and control of indoor parameters and energy use, an integrated control system of internal environment on the basis of fuzzy logic (hereinafter ICSIE) was used.

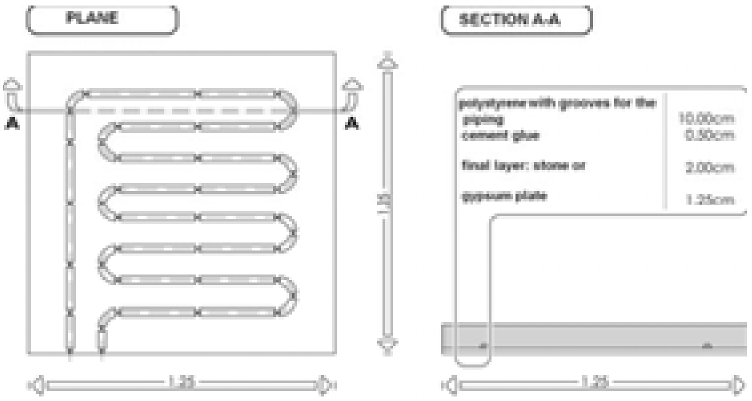

Fig. 2: Plan and section of H/C ceiling panels. The plan shows the grooves for the piping

It enables the control of indoor air temperature, CO$_2$ and illuminance under the influence of outdoor environment and users` requests. The ICSIE system is divided in three parts: sensor network system, regulation system and actuator system. Sensor network system enables recording of internal air temperature, external air temperature, internal relative air humidity, external relative air humidity, internal surface temperatures, black bulb temperatures, temperature of medium in panels, internal work plane illumination, external illumination, concentration of CO_2, direct solar radiation, reflected solar radiation, wind speed, wind direction, precipitation detection, energy use for heating, energy use for cooling. The selected time step was 0.5 s. The selected parameters for monitoring were: outdoor and indoor air temperature, outdoor and indoor relative humidity (hereinafter RH_{in}, RH_{out}), surface temperatures, black bulb temperature (hereinafter $T_{black\ bulb}$), temperature of the medium in panels, energy use for heating and cooling. Thermal comfort conditions are analyzed by calculated human body exergy consumption rates and predicted mean votes index using spread sheet software (Iwamatsu and Asada, 2009; Shukuya et al. 2010). For exergy analysis of thermal comfort conditions we assume individul user exposed to different combinations of T_{ai} and T_{mr}, which results in the same operative temperature (hereinafter T_o). In case of conventional system it was assumed that T_{ai} was equal to T_{mr} and in case of solar H/C system T_{ai} differs from T_{mr}. For calculations, the reference environmental temperature (T_{ao}) and RH_{out} were assumed to be equal to T_{ai} and RH_{in}. User characteristcs and experimental conditions are presented in Table 1 and Table 2.

Tab. 1: User characteristics

Metabolic rate [met]	Effective clothing insulation [clo]	T_{cr} [°C]	T_{sk} [°C]	T_{cl} [°C]
2.0	0.5	36.9	34.2-34.4	29.2-29.6

T_{cr}=body core temperature, T_{sk}=skin temperature, T_{cl}=clothing temperature. T_{cr}, T_{sk} and T_{cl} are calculated due to experimental conditions.

Tab. 2: Experimental conditions

System	T_{ai}[°C]	T_{mr}[°C]	RH_{in}[%]	v_a [m/s]
Conventional	24	24	50	0.07
Solar H/C system	20	28	50	0.07

T_{ai}=room air temperature, T_{mr}=mean radiant temperature, RH_{in}=relative humidity of indoor air, v_a=air velocity.

3. Measured energy use for heating and cooling and characteristics of temperature profiles

Energy use was measured for the same test room equipped with conventional system and solar H/C system in time separation. Energy use for heating was measured for winter period (5.03. - 23.03.2010) and summer period (18.06. - 24.06.2010) and it presents overall 528 heating hours. Heating was performed also for summer period, because in many occupied spaces with special procedures higher temperatures can be required. Energy use for cooling was measured for summer period 10.06. - 24.06.2010 and 5.07. - 10.07.2010 and presents overall 453 cooling hours.

2.2. Measured energy use for conventional system and solar H/C system

For the systems` comparison approximately the same conditions were selected (equal set-point T, time period, T_{out} and T_a variate among systems ±0.5°C; 0.4% assumed error). The measured energy use is presented in MJ for heating or cooling, as shown in Table 3. The measured energy use for heating was by 11.0-26.8% lower for solar H/C system than for conventional system. The energy use for cooling was by 41.2-61.5% lower for solar H/C system. For the whole measured cooling period (187 cooling hours) the energy use for solar H/C system was 1.15 MJ, and for conventional system 3.02 MJ. However, the efficiency of solar H/C system during heating period could be increased with higher surface area of panels. The calculated energy use for heating in case of four times higher surface area of panels was 40% lower energy use than for the conventional system.

Tab. 3: The measured energy use for two heating and cooling systems [MJ]

H/C system	T_{ao} [°C]	T_{ai} [°C]	Energy use [MJ]
Conventional system			
H winter	-2.6	23.7	2.95
H summer	13.2	25.4	1.33
C summer	20.0	25.3	3.24
C summer	26.4	20.9	3.42
Solar H/C system			
H winter	-2.6	23.3	2.63
H summer	13.5	25.5	0.97
C summer	20.2	25.7	1.44
C summer	26.5	20.7	2.02

H-heating, C-cooling.

2.1. Temperature profiles for heating and cooling with conventional and solar H/C system

Figures 3-6 present 24-hour temperature profiles for heating and cooling with conventional and solar H/C system.

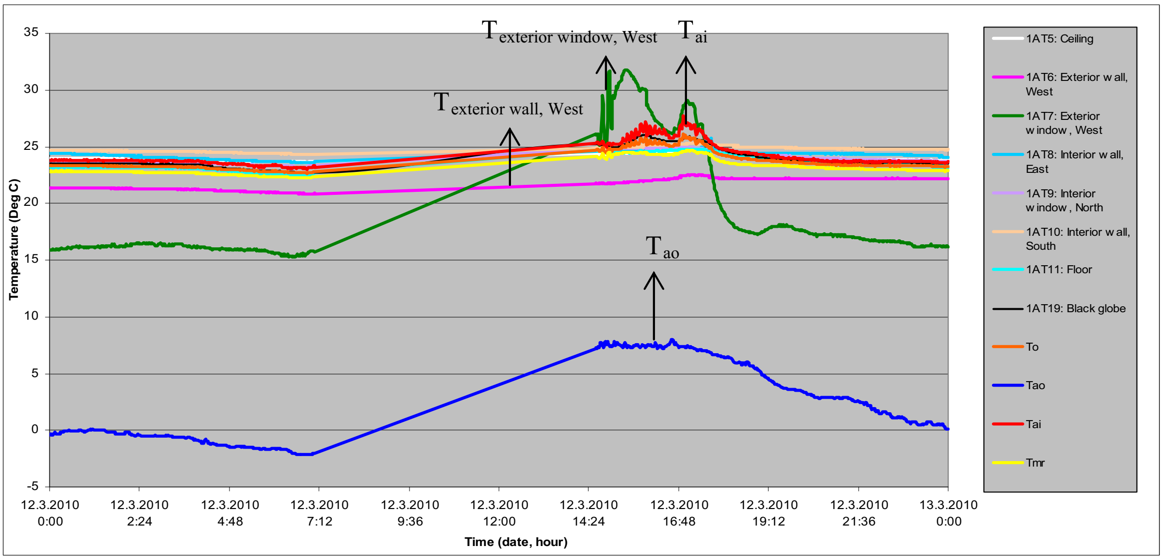

Fig. 3: Heating with conventional system, 12.3.2010 (00:00) - 13.3.2010 (0:00), 5.70 kWh, $T_{ai,avg}$=24.2°C, $T_{o,\ avg}$=23.7°C, $T_{ao,\ avg}$=2.2°C

For conventional system, temperature measurements show that interior constructional complexes have the highest surface temperatures, such as interior south wall, interior east wall, ceiling, interior north window and floor (Fig. 3). Lower heat flux occurs through interior building complexes due to lower ΔT (1°C) and lower U-value ($U_{interior\ wall}$=1.17 W/m^{2}K, $U_{ceiling,\ floor}$=0.83 W/m^{2}K) than through exterior building complexes (ΔT=24.0°C, $U_{exterior\ wall}$=1.29 W/m^{2}K). Exterior building complexes have the lowest surface temperatures, such as exterior west window and exterior west wall. The reason is higher U-value ($U_{exterior\ wall}$=1.29 W/m^{2}K, U_{window}=2.90 W/m^{2}K), which results in larger transmission heat losses and presents a weak part of building system.

In the room with solar H/C system similar conclusion about surface temperatures of building envelope could be made as in the room with conventional system (Fig. 4).

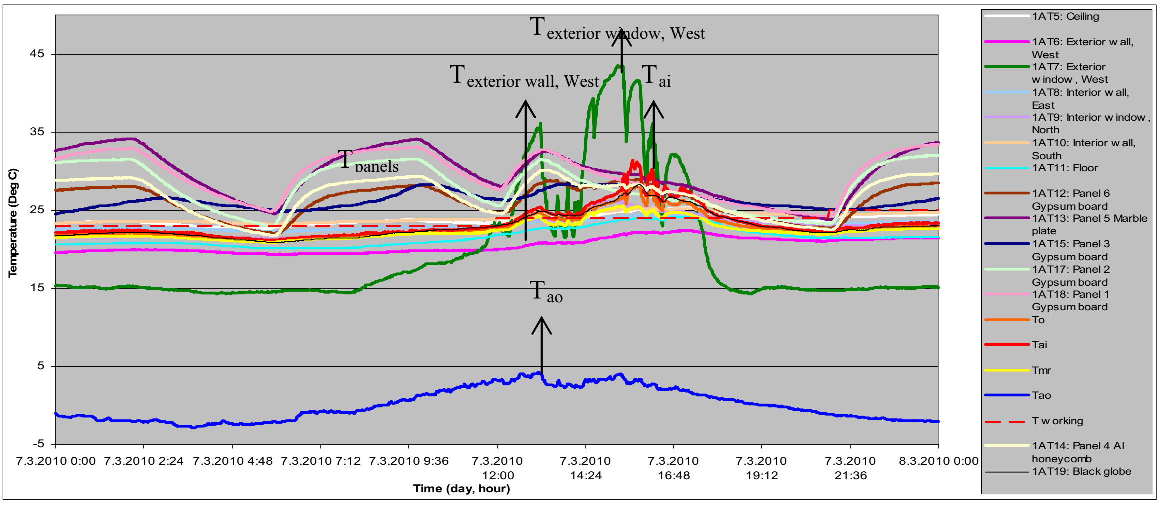

Fig. 4: Heating with solar H/C system, 7.3.2010 (00:00) - 8.3.2010 (0:00), 13.00 kWh, $T_{ai,avg}$=23.3°C,$T_{o,\ avg}$=22.8°C, $T_{ao,\ avg}$=0.05°C

The highest surface temperatures appear for interior south wall, ceiling, interior east wall, interior east window and floor. Average floor temperature in a room with solar H/C system is by 1.5°C lower than in a room with conventional system, mainly because of the position of radiators and radiative and convective heat flux on floor surfaces. Lower T_{ao} causes lower surface temperatures on exterior west window than in a room with conventional system. Other surface temperatures and room conditions (exterior west wall, T_o $T_{mr,avg}$, $T_{black\ globe}$) are almost the same as in the room with conventional system. Because in a room with solar H/C system additional surface area is heated to higher temperatures (28.0-33.9°C), much higher T_{mr} could be expected. The reason is the surface area of panels that affects T_{mr} (9 m^2). T_{mr} is affected by all room surfaces, not just panels. However, for both cases, almost the same room conditions are created, but in the case of solar H/C system energy use is by 11% lower. More precise look at T_{ai}, T_{mr}, T_o, $T_{black\ globe}$ (Figs. 3 and 4) shows that temperatures are much more constant in the room with solar H/C system than in the room with conventional system. Temperature measurements with black globe thermometer are close to the calculated temperature T_o.

Figure 5 presents temperature measurements in the room cooled with conventional system. For the room with conventional system exterior west wall has the highest and exterior window has the lowest surface temperatures, because they are highly affected by outdoor temperature variations. The surface temperatures are similar as $T_{ao.}$ The curve of T_{ai} and T_o changes approximately by 0.5°C/0.5h.

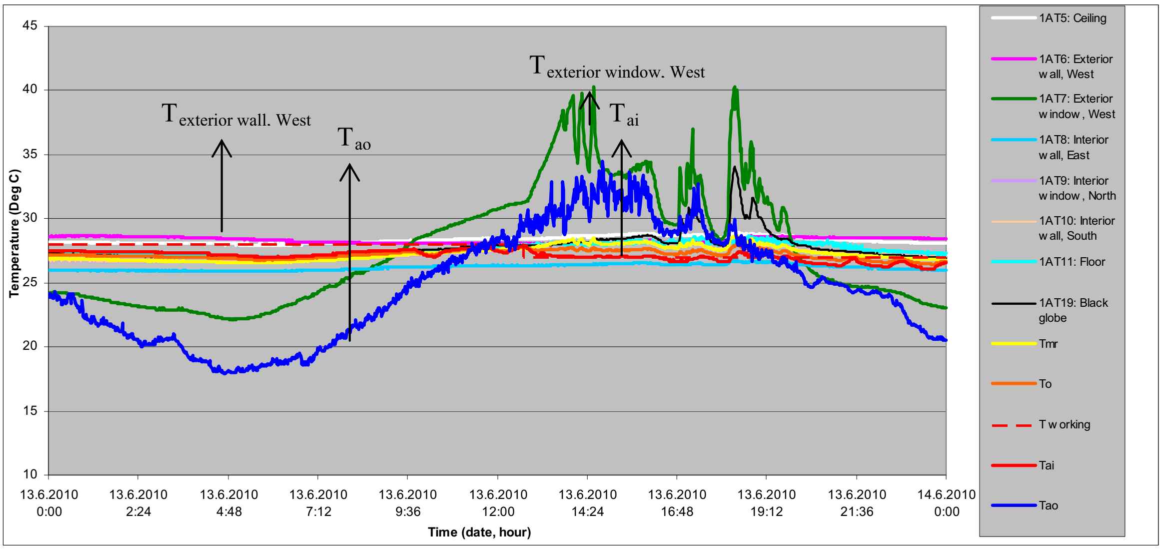

Fig. 5: Cooling with conventional system, 13.6.2010 (00:00) - 14.3.2010 (0:00), 10.00 kWh, $T_{ai,avg}$=27.1°C, $T_{o,\ avg}$=27.2°C, $T_{ao,\ avg}$=24.7°C

The comparison with solar H/C system shows that interior south wall has the highest and exterior west window the lowest surface temperatures (Fig. 6). Panel 5-marble plate had the lowest and panel-3 gypsum board the highest surface temperature. T_o, T_{mr}, $T_{black\ globe}$ are more constant in case of solar H/C system than for conventional system.

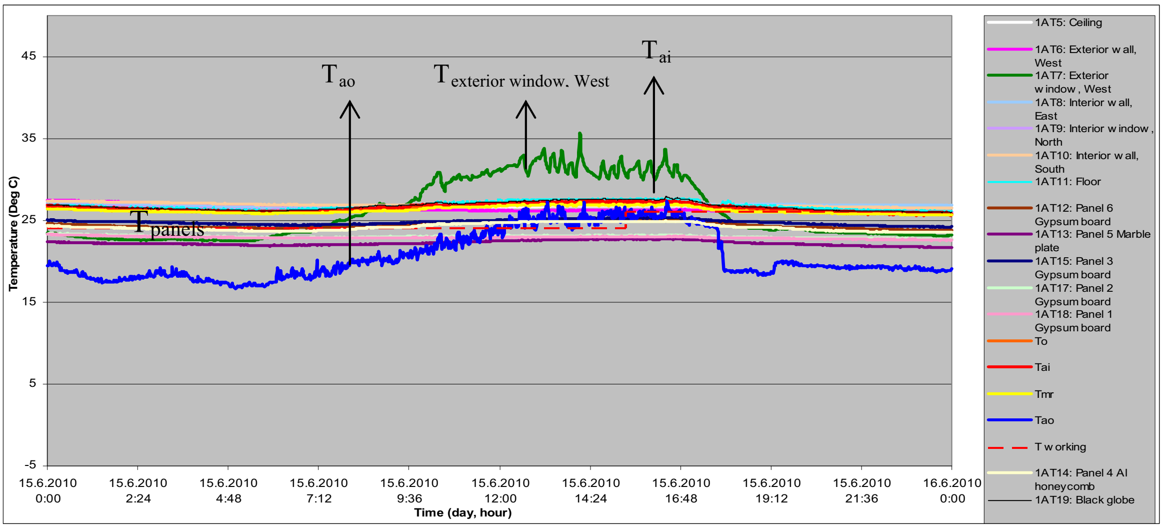

Fig. 6: Cooling with LowEx system, 15.6.2010 (00:00) - 16.3.2010 (0:00), 11.60 kWh, $T_{ai,avg}$=26.5°C, $T_{o,\ avg}$=26.4°C, $T_{ao,\ avg}$ = 20.7°C

4. Results of exergy analysis of thermal comfort conditions

3.1. Human body exergy balance

Human body is treated as a thermodynamic system based on exergy-entropy processes. The system consists of a core and a shell and is situated in a test room with an environmental temperature. The general form of the exergy balance equation for a human body as a system is represented in Eq. (1) (Shukuya et al., 2010):

$$[Exergy\ \ input]-[Exergy\ \ consumption]=[Exergy\ \ stored]+[Exergy\ \ output] \qquad \text{(eq. 1)}$$

The exergy input consists of five components: 1) warm exergy generated by metabolism; 2) warm/cool and wet/dry exergies of the inhaled humid air; 3) warm and wet exergies of the liquid water generated in the core by metabolism; 4) 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; 5) warm/cool radiant exergy absorbed by the whole skin and clothing surfaces.

The exergy output consists of four components: 1) warm and wet exergy contained in the exhaled humid air; 2) warm/cool and wet/dry exergy contained in resultant humid air containing the evaporated sweat; 3) warm/cool radiant exergy discharged from the whole skin and clothing surfaces; and 4) warm/cool exergy transferred by convection from the whole skin and clothing surfaces into surrounding air (Shukuya et al., 2010). To maintain thermally comfortable conditions, it is important that the exergy consumption and stored exergy are at optimal values with a rational combination of exergy input and output.

3.1. Thermal comfort in experimental conditions created with solar H/C system and conventional system

Table 4 presents the comparison between solar H/C system and conventional H/C system regarding the analysed thermal comfort conditions. Human body exergy consumption rates and PMV index are calculated for user, exposed to different combinations of T_{ai} and T_{mr} that result in the same operative temperature 24°C (hereinafter T_o). RH_{in} is assumed to be 50%. The data show that the human body exergy rates and PMV index vary between systems, even user is exposed to the same perceived temperature. Optimal conditions are created in the room with solar H/C system, where higher surface than air temperatures (Tmr 28° C; Tai 20°C) are reflected in more comfortable conditions (PMV=0.2) than in the room with conventional system (PMV=0.5). However, comfortable conditions in the room with solar H/C system do not always result in lower human body exergy consumption rates, as it was proven with previous studies (Isawa et al. 2003; Iwamatsu and Asada, 2009; Shukuya et al. 2003, 2006, 2010; Simone et al. 2011; Tokunaga and Shukuya, 2011). The human body exergy consumption rates depend significantly on user characteristics and will be considered further on.

Tab. 4: PMV index and exergy consumption rate for individual user exposed to experimental conditions created with conventional and solar H/C system

User	T_{ai} [°C]	T_{mr} [°C]	PMV index	Exergy consumption rate [W/m^2]
Conventional system				
User	24	24	0.5	5.61
Solar H/C system				
User	20	28	0.2	5.76

For our calculations T_{ai} was assumed to be equal to T_{ao}. RH_{in} was assumed to be 50% and equal to RH_{out}.

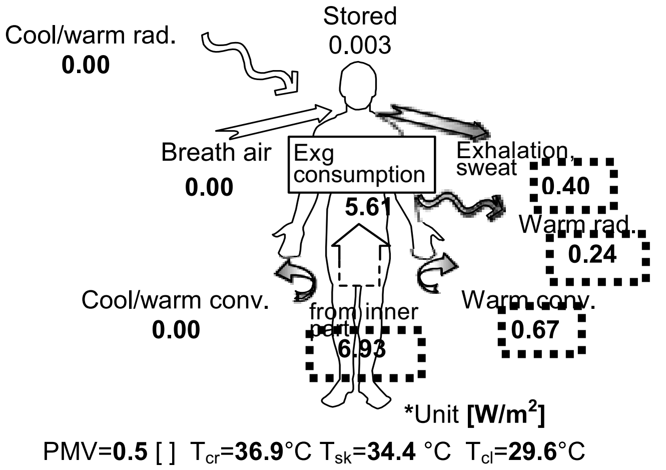

Fig. 7: Exergy balance of the human body for conventional H/C system (T_{ai} 24°C, T_{mr} 24°C, RH_{in} 50%)

Figure 7 shows the example of the whole human body exergy balance in the following conditions: T_{ai} 24°C , T_{mr} 24°C, RH_{in} 50%. Input exergy presents thermal radiative exergy exchange between the human body and the surrounding surfaces of active space, which influences on thermal comfort. Warm/cool radiant exergy absorbed by the whole skin and clothing surfaces is zero, because T_{ai} is equal to T_{mr}. The sum of exergies contained by the inhaled humid air is also zero (breath air in Fig. 7), because room T_{ai} and RH_{in} are equal to outside conditions T_{ao} and RH_{out}. Warm/cool convective exergy absorbed by the whole skin and clothing surfaces is also zero, because T_{ai} is equal to T_{ao}, and even T_{cl} is higher than T_{ai}. The main input exergy (100%) is presented by metabolic thermal exergy (inner part in Fig. 7). This means that 6.93 W/m^2 of thermal exergy are generated by bio-chemical reactions inside the human body. It is important to keep the body structure functioning and to get rid of the generated entropy. Thus, 6.93 W/m^2 have to be released into ambient environmental space by radiation, convection, evaporation, and conduction that present output exergies. Warm exergy stored in the core and in the shell is 3 mW/m^2 and presents a part of metabolic thermal exergy. Of that, 2 mW/m^2 of thermal exergy is stored in the core and 1 mW/m^2 in the shell. Because the moisture contained in the room air is not saturated, the water secreted from sweat glands evaporates into the ambient environmental space. Exhalation and evaporation of sweat are 0.40 W/m^2 (5.8% of output exergies and stored exergy). Warm radiant exergy discharged from the whole skin and clothing surfaces emerges because of higher T_{cl} than T_{ai} and presents 0.24 W/m^2 (3.5%). Exergy of 0.67 W/m^2 (9.7%) is transferred by convection from the whole skin and clothing surfaces into surrounding air, mainly due to the difference between T_{cl} and T_{ai}. The rate of exergy consumption that presents the difference between exergy input, exergy stored and exergy output is 5.61 W/m^2 (81%) for conditions created with conventional system.

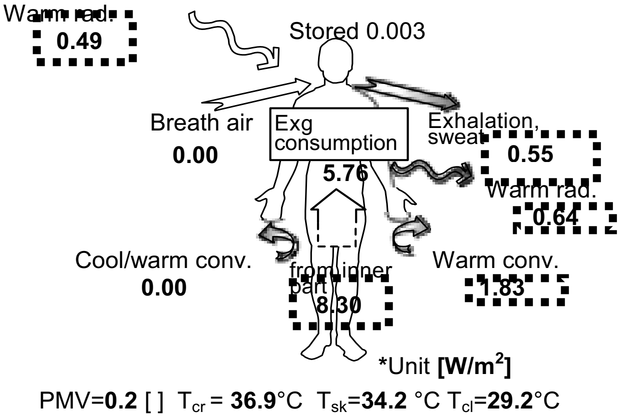

Fig. 8: Exergy balance of the human body for solar H/C system (T_{ai} 20°C, T_{mr} 28°C, 50%)

If a user was exposed to the conditions created with solar H/C system (T_{ai} 20°C, T_{mr} 28C, RH_{in} 50%), the input exergies, output exergies and exergy consumption would differ (Fig.8). Lower T_{ai} and higher T_{mr} than at conditions created with conventional system cause higher input exergies by metabolic thermal exergy (8.30 W/m^2, 94.5%) of input exergies. Also in case of solar H/C system, the metabolic thermal exergy does not present the only input exergy. Warm radiant exergy absorbed by the whole skin and clothing surfaces is 0.49 W/m^2 (5.5%), because T_{mr} is higher than T_{ai}. Cool/warm convective exergy absorbed by the whole of skin and clothing surfaces is zero, because T_{ai} was equal to T_{ao}. Output exergies are warm exergy transferred by convection from the whole skin and clothing surfaces into the surrounding air, warm radiant exergy discharged from the whole skin and clothing surfaces and exhalation and evaporation of sweat (0.55 W/m^2, 6.2% of output exergies and stored exergy). Higher T_{mr} than T_{ai} results in higher warm radiant exergy discharged from the whole skin and clothing surfaces (0.64 W/m^2, 7.3%) and higher warm exergy transferred by convection (1.83 W/m^2, 20.8%). However, lower input exergy consequently results in lower exergy consumption rate in case of conventional system (5.76 W/m^2, 65.6%).

If the building envelope is poorly insulated, lower surface temperatures appear, as it can be seen from Figs. 3-6. The influence of lower surface tekmperatures on human body exergy balance is presented in Figure 9.

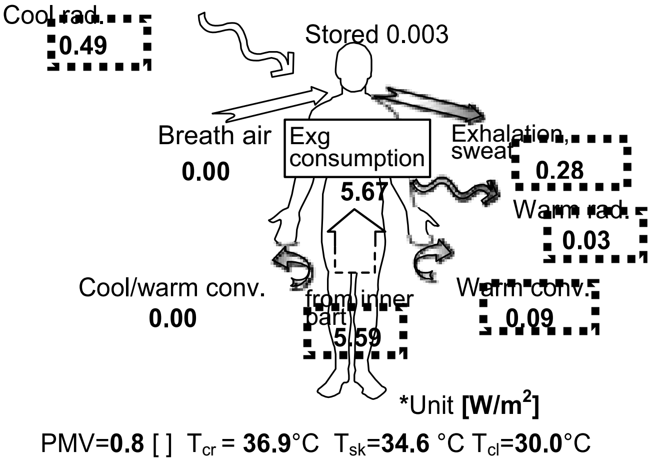

Fig. 9: Exergy balance of the human body in a room with poorly insulated builing envelope (T_{ai} 28°C, T_{mr} 20°C, 50%).

Lower surface temperatures result in cool radiant exergy absorbed by the whole of skin and clothing surfaces. These conditions often lead to discomfort.

5. Conclusions

From the results of comparison between conventional and solar H/C system the following conclusions can be drawn:

- The measured energy use for heating was by 11.0-26.8% lower for solar H/C system than for conventional system, and by 41.2 – 61.5% lower for cooling. The efficiency of solar H/C system during heating period could be increased with higher surface area of panels.
- Optimal thermal comfort conditions are created in the room with solar H/C system, where higher surface than air temperatures are reflected in more comfortable conditions than in the room with conventional system.
- Comfortable conditions in the room with solar H/C system do not always result in lower human body exergy consumption rates, as it was proven with previous studies. The human body exergy consumption rates depend significantly on user characteristics.
- To maintain thermally comfortable conditions, it is important that the exergy consumption and stored exergy are at optimal values with a rational combination of exergy input and output.
- Results of on-line monitoring show that temperatures are much more constant in a room with solar H/C system than in a room with conventional system.
- Poorly insulated building envelope presents a weak part of building system and results in lower surface temperatures.
- Lower surface temperatures result in cool radiant exergy absorbed by the whole of skin and clothing surfaces and lead to discomfort.

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