AN INNOVATIVE BUILDING BASED ON ACTIVE THERMAL SLAB SYSTEMS

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ABSTRACT

The rising demand of primary energy for heating and cooling of residential and commercial buildings implies the design and the realization of energy efficient buildings with a minimal impact on the environment.

Many new technologies allowing low supply temperature with low specific emissions and new buildings envelopes (good insulation and solar shadings) seem powerful, but there is the need to optimise control strategies for achieving this aim. The use of active thermal slab systems is a promising solution. Active thermal slab systems are being increasingly used in the centre and in the north of Europe, but some uncertainties still remain, especially as far as the control strategy is concerned. Moreover the operation of these buildings has to be investigated more in depth and the resort to field measurements is needed.

In this work the use of active thermal slabs systems is described and an innovative pilot project, the building of ZUB (The Centre for Sustainable Building) at the University of Kassel (Germany), is presented. Through a detailed description of its integrated heating and cooling system and its complex measurement system, which allows to collect temperature, comfort and air quality, the efficiency of different solutions and control strategies may be investigated. Up to now data on the operation of the active thermal slab system are being collected and analyzed. Therefore and in order to foresee the best working condition and control strategy, a simulation made by the commercial software TRNSYS 15 has been carried out. Finally, for a seek of completeness, a parametric study for different European climatic conditions is reported (Kassel/Germany, Venice and Palermo/Italy) to look at the possibility to use active thermal slab systems in similar buildings in different countries.

1. INTRODUCTION

During the last years energy problems, the deterioration of the environment and the adoption of new technologies have focussed the attention on radiant systems, and particularly on thermally activated slab systems. As a consequence, new studies have been carried out and new perspectives of their use are being investigated. In this work attention is paid on this new type of radiant systems, discussing their possibilities and limitations.

Active thermal slab systems, as the other radiant systems, belong to the so called Low Temperature Systems (LTS); they can heat and cool buildings with a little temperature difference between the supply fluid and indoor air. As a consequence, an increasingly use of renewable energy sources and a considerable energy saving can be realized.

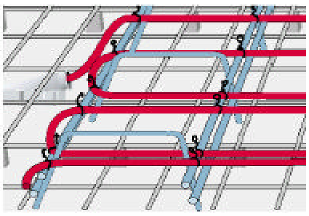
As far as the constructive aspects, active thermal slab systems have pipes embedded in the structure of a concrete slab. In this way the dimensions of the structures are reduced and the conditioning system takes advantage of the high thermal capacity to reduce peak loads and to transfer some of the heating/cooling requirements to night-time (peak-shaving) (Meierhans 1996), thus allowing several advantages like reduced size in the plant, possible low costs in night-time operation, and the use of high efficiency machines, e.g. ground coupled heat pumps (Currò Dossi et al.2003).

Although low installation and operation costs are possible, active thermal slabs need an accurate design with good thermal insulation and efficient solar shading devices, in order to reduce heating and cooling loads. As for the control of humidity level, natural ventilation or primary air systems can be used, depending on the climate.

The use of active thermal slab systems, however, has still some uncertainties. The requirement of careful controls strategies and the use of tools and guidelines, taking boundary conditions and dynamic system behaviour into account, are necessary to adopt such systems. In this regard new studies, simulations and measurements are required to optimize their use and to analyze their use in different climatic conditions.

2. ACTIVE THERMAL SLAB SYSTEMS

Radiant systems use an hydronic circuit of pipes embedded in the building structures. Depending on pipe position they can be divided into floor radiant systems, wall radiant systems and ceiling radiant systems. The most recent application of radiant systems is the active thermal slab system. This type of systems belongs to ceiling radiant systems, but its constructive and operating conditions are different from other types: the pipes are embedded in the structures, in order to get more mass and thermal capacity (Figure 1 A and B). Due to the construction technique, these systems are particularly suitable for multi-storey buildings.



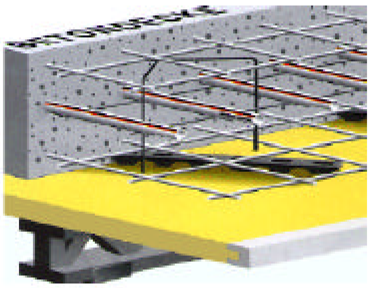


Fig. 1 - Typical disposition of pipes in thermo-active systems (Velta 2003)

As for the technological and constructive aspects, the design of active thermal slab systems is based on the characteristics of other radiant systems (i.e. distance and diameter of pipes, thickness of the concrete layer, position of the pipes inside the concrete, supply water temperature, water mass flow rate). Commonly the pipes are positioned in centre of the concrete layer, with a diameter of about 20 mm and a distance of 15 to 20 cm.

Two important aspects concerning these systems have to be taken into account for a correct design. The first one, related to heating period, is the risk of cold downdraft at windows, which may be solved by the design of windows with glazing U-factors less than 1.2 W/(m^2 K), or with an additional heating in the perimeter area. The second aspect, referred to cooling period, is the control of humidity which may limit the cooling capacity of the radiant system. As a matter of fact, surface temperature needs to be above the dew point, thus requiring a ventilation system (natural or mechanical) to provide air change or, depending on the climatic conditions, dehumidification.

The peak-shaving makes possible to work during the night to heat/cool the slab, which releases the day after the energy stored during the night. This aspect is very important as far as the comfort conditions are concerned. In the standards and guidelines on environmental reference to steady state conditions is made; this hypothesis is still valid for rates of change in operative temperature of less than ±5°C per hour (Knudsen et al. 1989). In the standards a comfort range of operative temperature for heating and cooling is given: for ISO EN 7730, ASHRAE 55-92, and CR 1752 the comfort range is 20°C-24°C in winter and 23°C-26°C in summer; in DIN 1946 the operative temperature has to be above 20°C in winter and less than 26°C in summer. The operating conditions may therefore vary slightly during the day, but still remaining into the comfort range, like during day-time operation with thermo-active systems, where a drift of operative temperature of about 3°C is possible (De Carli 2001).

Due to the most relevant problems concerning dynamic effects, thermal storage capacity, and thermal comfort requirements, the support of design tools and guidelines are need. In this context, the adoption of suitable models, the study of different control strategies and the measurement of operative conditions are required.

3. A PILOT PROJECT FOR ACTIVE THERMAL SLAB SYSTEMS

3.1. DESCRIPTION OF THE ZUB

The pilot project here presented is the ZUB (Centre for Sustainable Building) at the University of Kassel (Germany) (Fig. 2), built in 2001 within collaboration between the Department of Building Physics and other Faculties. The ZUB is an innovative demonstrative building, in the frame of the IEA ECBCS Annex 37 "Low Exergy Systems for Heating and Cooling of Buildings", designed for an annual heating demand less than 20 kWh/m^2. It is based on the implementation of low energy heating/cooling systems, control strategies and new building materials, whose aim is to state the possibilities of active thermal slab systems to achieve comfort and energy saving. The building is close to the Faculty of Architecture, in an old urban neighbourhood.

Fig. 2 - The office building of the ZUB (Centre of Sustainable Buildings) (Meyer 2001)

As far as the construction is concerned, it is a 3-storey building with an atrium, used as a light gap, and a basement (Fig. 3). It consists mainly of three different parts: the first one for exhibitions, one part for offices and the last one for experiments and researches. The overall volume is 6882 m^3, with a net floor area of 1732 m^2 and a main floor space of 892 m^2. The height of each floor is 3.4 m, except for the basement (2.8 m) and the ground floor (3.7 m), and the main experimental room (6.7 m) (Table I). On the ground floor most of space is occupied by the lecture hall and the main experimental room that is situated also in the basement. Heating and cooling equipment and ventilation systems are installed in the basement.

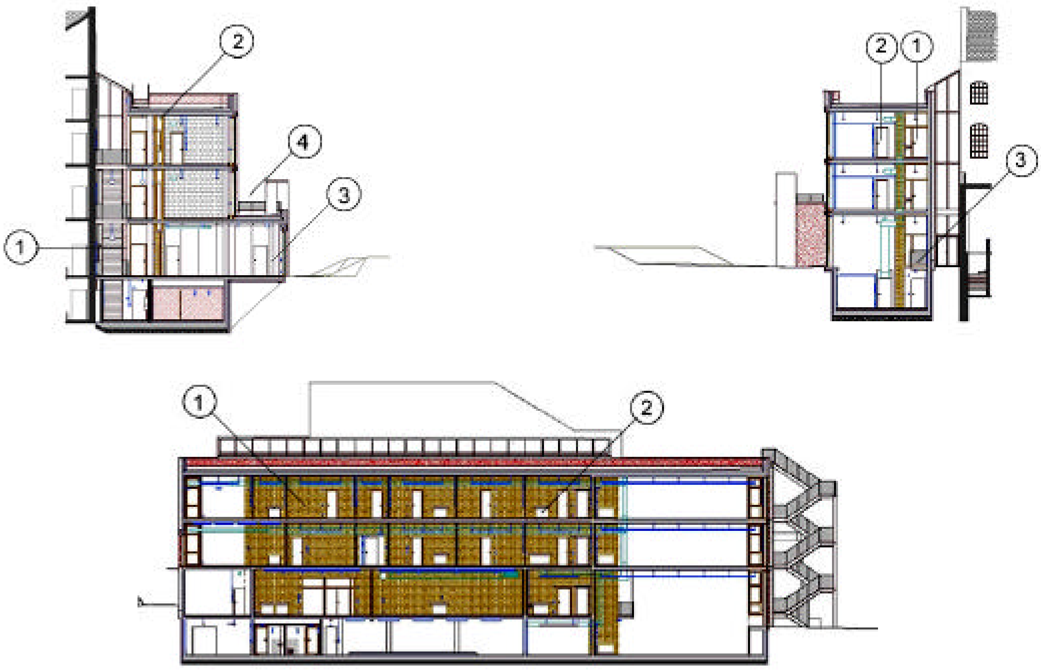


Fig. 3 - Sections of the ZUB building (Seddig 2001)

Tab. I - Features of the rooms in the ZUB

	Offices	**Lecture hall**	**Experimental room**	**Corridor**
Area [m^2]	24	174	94	60
Height [m]	3.4	3.7	6.7	3.4

External walls (500 mm thick) insulated with polystyrene and the large glazing surface is south oriented with a g-value of 0.42. To optimize solar gains the windows of the south façade and the atrium have been realised with the minimal frame-fraction of the construction and external rolling shutters have been installed outside. The U-values of all the external surfaces are reported in Tab. II.

Tab. II - U-values of the building structures

Building part	**U-value [W/(m^2 K)]**
Exterior walls	0.11
Roof	0.16
Windows	0.80
Wall/floor against ground	0.26

As for as internal walls, the floors and the ceilings consist of concrete slabs whereas the dividing walls of offices consist of hollow bricks. A particular wall, however, has been realized to separate offices and other rooms from the atrium. It is a 635 mm thick clay wall, with an inner air cavity of 365 mm, made by massive unbaked clay bricks, that has a great heat retention capacity and the capability of dampening fluctuations of moisture.

3.2. RADIANT AND VENTILATION SYSTEMS AND REGULATION STRATEGIES

In the ZUB building radiant systems for heating and cooling have been installed. In order to investigate different solutions, some particular innovations have been introduced. The pipes are embedded in the upper concrete layer on the floor and in the centre of the slab, as it can be seen in Fig. 4, thus obtaining active thermal slab systems and floor heating and cooling system. Pipes are made in polyethylene with a diameter of 20 mm and a distance of 150 mm, except in the basement where the diameter is 25 mm. The distribution has a coil shape and an individual circuit for each room; in this way, each room has its own control system. Each circuit of the floor radiant system and the active thermal slab system is supplied by about 600 kg/h water mass flow rate, thus allowing to keep the difference between supply and return temperature lower than 4-5 °C.

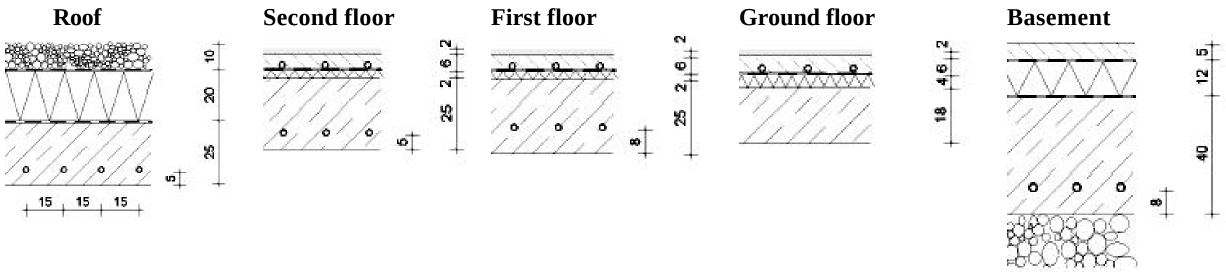


Fig. 4 - Position of different pipe layers in the concrete slabs of the ZUB building (SolarOpt 2003)

In the case of heating the radiant system is connected with the district heating supply system and it is divided in two different circuits to supply the traditional floor system and the thermo-active slabs systems.

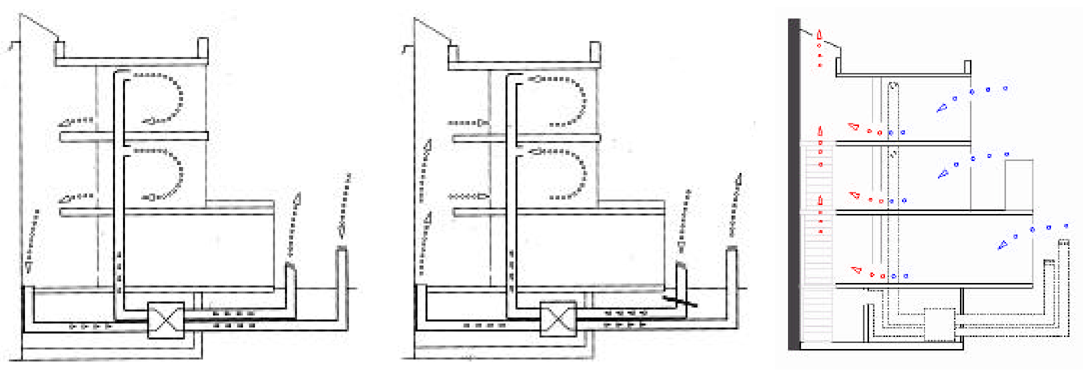
As for the cooling system, the hydronic pipes circuits employed are the same as the heating system, but, for investigating the possible use of renewable energy sources, an additional circuit of pipes in the slab construction of the basement has been installed to exploit ground coolness to cool the water. Thus, the ground heat exchanger replaces the installation of a mechanical cooling machine.

A particular type of ventilation system that allows fulfilling the requirements for air-change and air-quality has been installed. According to the standard DIN 1946 the air flow rate required is 7100 m^3/h. In the ZUB building, however, particular studies about the ventilation system have been carried out to reduce its size and heat losses. Thus, a mechanically balanced ventilation system using heat recovery with two cross flow heat exchangers in a series and a thermal efficiency of 0.8 has been installed. The designed air flow is 4000 m^3/h and the inlet temperature of the supply air flow is 17.7° C. Such system is not sufficient to supply the offices and the fully occupied lecture hall. For the lecture hall, therefore, a direct supply system from the air handling unit has been provided and, when required, offices can be ventilated by natural means.

The most important aspects related with these systems are, however, the adopted operating conditions and the control strategies. As for the heating system, the indoor temperature is set at the lower value of 19°C and the upper value of 21°C for the offices and approximately at 18° C in the experimental room. To achieve these conditions the inlet temperature of radiant systems depends on outside temperature, thus avoiding the heating system working continuously at the highest temperature. Then, after 8 p.m., the indoor air temperature is set at 19°C.

In the case of cooling, the temperature of rooms is set at an upper value of 26°C and the water mass flow rate is cooled by the ground heat exchanger. In this way the inlet temperature of the water depends on the ground temperature. Furthermore, the building structure can be cooled during the night by a flow of external air.

In the normal operation mode (Fig. 5A), fresh air is supplied directly to the office rooms and exhaust air is extracted from the atrium, and then transferred to the heat recovery unit, but, for research purposes the fresh air can be supplied to the central atrium and extracted from the offices (Fig. 5B). When the lecture hall is fully occupied, the mechanical ventilation system is employed only for the air-change of this room, while for the offices natural means are used. To allow natural ventilation in offices, fresh air is supplied through the open windows and the exhaust air leaves the rooms through particular air outlets, which are set in the clay wall near the doors. In this way the exhaust air is sent into the atrium and leaves the building through openings at its top (Fig. 5C), thus avoiding the installation of fan systems. The ventilation system works from 6 a.m. to 8 p.m., and at night and during the weekend it is turned off.



A **B** **C**

Fig. 5 - Operation modes of the ventilation system (Hausladen 2000)

Each office gets light from the windows of the south façade and the atrium from its glass walls, and the presence of light sensors allows using artificial lights only when a room is occupied and the value of natural light is too low. The presence of these large glazing areas is also used to exploit solar gains in reducing energy consumption. Solar radiation and internal sources reduce the requirements of the heating system and the presence of external rolling shutters allows to limit the incoming solar heat gain in the case of cooling. The choice of the artificial lights in the rooms (Tab. III) has been made by evaluating the thermal loads they may produce.

Tab. III - Lights installed in the ZUB building

	Offices	Corridor	Experimental room	Lecture hall	Atrium
Number of lights	4	6	24	36	22
Power [W]	39	55	55	55	20
Efficiency [lm/W]	85	91	91	91	25
Illuminance [lx]	553	500	1278	1036	63
Heat gain [W/m^2]	6.5	5.5	14.0	11.4	2.5

The energy consumption for the entire office building has been evaluated according to the German energy code WSchVO’95. The heating demand is 5.3 kWh/m^3 per year (16.5 kWh/m^2 per year), that is 27% of the limiting maximal value required by German standards, and an electrical consumption of approximately 10 kWh/m^2 per year.

During the year 2002 the measurements have shown a heating energy demand of about 23 kWh/m^2 and a total energy demand, including electrical consumption, lower than 40 kWh/m^2.

3.3. MEASUREMENT EQUIPMENT

In the ZUB building, one of the main issues is the monitoring of all the data that allow verifying and controlling concepts and researches. For this reason an intensive project for "Solar Optimised Buildings" (a national research program promoted by the German Ministry of Economy and Technology) is currently being run. According to this program the planning and construction processes are being followed up over a period of four years and for at least two years measurements of main parameters are being drawn out. To collect data such as heat exchanges, temperature, thermal comfort and air quality, however, a complex measurement system and detailed programs are required. In the office building of the ZUB the survey of these parameters has been planned to supervise all the building and to investigate in depth the behaviour of control strategies and systems (Tab. IV).

Tab. IV - Monitoring plan of the ZUB

MONITORING

BUILDING	SINGLE ROOM	EQUIPMENT
- Energy Consumption	- Thermal Comfort	- Ventilation System
- Daily Employment	- Visual Comfort	- Natural Ventilation
- Lighting	- Air Quality	- Heating System
- Sensitivity	- Shading	- Cooling System
- Service Management		
- Systems Interaction		

The adopted measurement system consists of 448 sensors, located in different positions of the building that allows collecting 1172 data every minute. At first, some weather instruments have been set outside the building to collect outside parameters, such as air temperature, solar radiation, air moisture, speed and wind direction. To control all the equipment, then, thermocouples, hygrometers and water mass flow meters have been installed in the ventilation system and in the heating/cooling radiant systems. In this way the working parameters and the efficiency can be analyzed and improved and the energy consumption can be assessed. In all rooms, finally, several sensors have been placed to gather information about internal conditions of thermal comfort, air quality and heat loads. In particular indoor air quality sensors are used to manage the ventilation system through the evaluation of CO_2 concentration. Instruments, able to assess the intensity of lighting, both natural and artificial, analyse the possible produced heat gains. Furthermore, a set of temperature and air humidity probes in the rooms allows calculating the operative temperatures.
The most relevant aspect of this measurement system, however, is the installation of thermocouples inside the concrete slabs. As a matter of fact, some researches deal with the behaviour of active thermal slab systems related to peak-shaving. In order to monitor the temperature of active layers, during the construction of the building sensors have been set in the concrete slabs (Fig. 6). Through these instruments data concerning the temperature and the performance of the active thermal slab system can be collected both upright and horizontally and a detailed map of heat exchange can be drawn up. It is also possible to know the direction of heat exchanges and the behaviour of the used building materials.

Nevertheless, the installation of these sensors is not sufficient to manage and analyse all the data collected. Because of the large number of parameters to be processed every day (about 846000) a careful method avoiding hitches is required. The sensors used are connected, at first, to three computer centres that survey the measurements coming from the building, the rooms and the equipment. In these centres they are recorded as ASCII data including the information about control strategies. Then, through a bus system, they are sent to the management system where they are processed and recorded in a database that is also connected to a display station. Through this system, therefore, the collected information is displayed every minute, thus allowing to understand the efficiency of the installed systems, the thermal conditions in rooms, and to optimise the chosen control strategies.

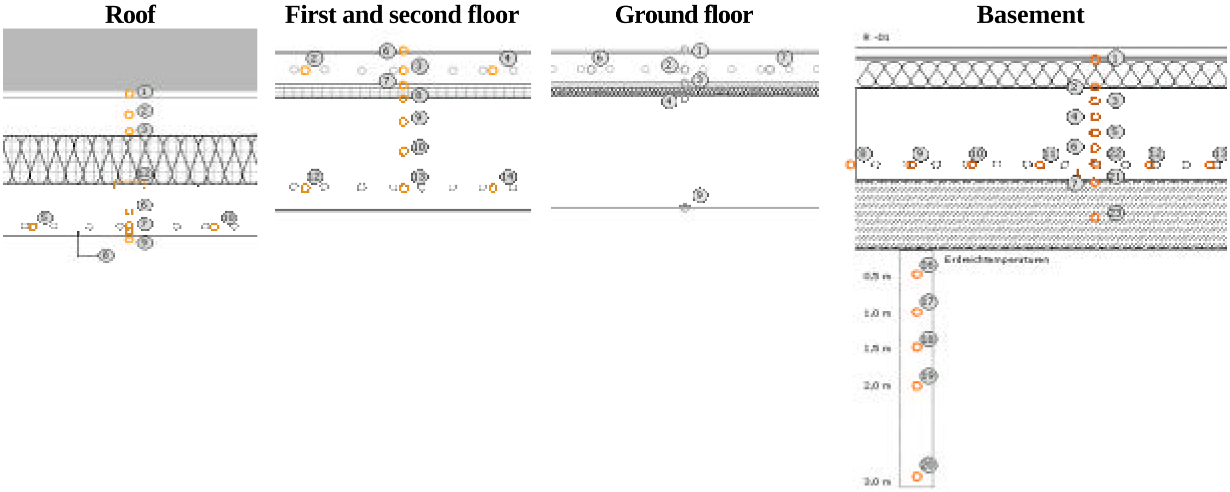


Fig. 6 – Sample of disposition of the thermocouples in the slabs (SolarOpt 2003)

3.4. MODELLING THE BUILDING

To evaluate the thermal conditions and the energy performance of an HVAC system, the knowledge of air indoor temperature is not sufficient. To predict the efficiency of a control strategy, moreover, a design tool that allows to take into account building envelope, solar shadings, boundary conditions and gathering information about thermal loads, energy consumption and thermal comfort is required.

In this paper the first step of modelling the building is shown. For this purpose, the widely used commercial software TRNSYS 15 (Klein et al. 1992) has been chosen to look at the possibilities of the active thermal slab system adopted in the building and to start studying its behaviour with particular reference to the control strategy. The assumed basic model is an office room of the first floor, with the same structures above described, whose dimensions are 5.2 m (South side) by 4.7 m, and 3.4 m height.

During the occupancy of the room from 8 a.m. to 6 p.m., the presence of one person (75 W sensible heat and 75 W latent heat) and one PC with monitor (140 W) and artificial lighting (5 W/m^2) is assumed. As for the parameters affecting comfort, a metabolic rate of 1.2 met has been assumed according to EN ISO 7730, while the clothing factor depends on the outdoor air temperature at 8 a.m. as shown in Tab. V, as proposed in (Brunello et al. 2002).

As far as the control strategy is concerned, it has been tested the possibility of controlling the supply water temperature of the thermally activated slab circuit, according to a linear correlation between outdoor and supply temperature.

Two different shading coefficients have been chosen as protection from solar radiation in heating (C_s=0.6) and in cooling (C_s=0.5) conditions. As for the ventilation system, the heat exchanger with efficiency of 0.8 has been assumed to supply an air change of 0.5 h^{-1} during the occupancy time (no post-heating is present in winter and no cooling/dehumidification is assumed in summer). The water mass flow rate supplying the hydronic system has been fixed at 515 kg/h if the indoor air temperature is lower than 21.5° C (±0.2°C), in the case of heating, or higher than 23° C (±0.2°C), in the case of cooling.

Tab V – Values of the clothing factor in dependence of outdoor temperature

Outside temperature at 8:00 [°C]	Clothing factor [clo]
T_{out}<5° C	1
5° C<T_{out}<12° C	0.8
12° C<T_{out}<15° C	0.7
12° C<T_{out}<15° C	0.6
T_{out}>20° C	0.5

To evaluate the efficiency of this control strategy, the values of some parameters have to be calculated, e.g. comfort parameters PMV and PPD, the values of supply air temperature and relative humidity, supply and return temperature of the water circuits, the radiant surface temperature, heat flows from ceiling and floor, etc.

4. SIMULATIONS OF THE ROOM

Simulations have been performed with three types of Test Reference Year. The results here presented have been performed in order to gather information about the possibility to adopt a similar building with similar plants in different climatic conditions, briefly summarised in Tab. VI.

Tab VI – Relevant parameters of the weather in the different investigated cases

	Latitude [°]	Design temp. (winter) [°C]	Degree day [Kd]	Design temp. (summer) [°C]	Daily range [°C]
Kassel	52	-12	3317	32	15
Venice	45	-5	2345	31	9
Palermo	38	5	751	32	6.5

4.1. KASSEL (GERMANY)

This case deals with a typical climatic condition of Germany and in particular the city of Kassel. In Figure 7 the distribution of the energy demand is reported, while in Figure 8 the distribution of PMV can be seen. The control strategy is acceptable, since the comfort conditions are only 5% of the time below the comfort requirements. The overall amount of operation hours of the pump of the radiant system is 4960 in heating conditions and 700 in cooling conditions. The maximum heating load is 2220 W and for cooling is 1130 W. The overall demand of energy in winter is 2270 kWh and the recovery heat coils allow a saving of 440 kWh energy. The overall demand of energy in summer is 580 kWh.

4.2. VENICE (ITALY)

In the case of Venice TRY, the results are reported in Figures 9 and 10. The control strategy is good, since the comfort conditions are almost always in the comfort range. It may be seen that the comfort conditions are fulfilled without an air treatment. It has been verified that no problem of condensation occurs. The overall amount of operation hours of the pump of the radiant system is 3955 in heating conditions and 2120 in cooling conditions. The maximum heating load is 1645 W and for cooling is 1365 W. The overall demand of energy in winter is 1855 kWh and the recovery heat coils allow a saving of 305 kWh energy. The overall demand of energy in summer is 1560 kWh.

4.3. PALERMO (ITALY)

In the case of Palermo TRY, the results are reported in Figures 11 and 12. The control strategy is also good in this case, since the comfort conditions are almost always in the comfort range. Even in this case the comfort conditions are fulfilled without any air treatment and no problems of condensation occur. The overall amount of operation hours of the pump of the radiant system is 1990 in heating conditions and 3075 in cooling conditions. The maximum heating load is 1230 W and for cooling is 1390 W. The overall demand of energy in winter is 775 kWh and the recovery heat coils allow a saving of 145 kWh energy. The overall demand of energy in summer is 2110 kWh.

5. DISCUSSION

The results of the simulations show that the comfort conditions are fulfilled in all the examined cases. Also the indoor temperature variation during the whole day is below 3°C most of the time.

As for the hydronic circuit, the temperature variation between the supply and return temperature of the hydronic circuit is lower than 3°C. It has to be underlined that the active thermal slab system works basically on the ceiling, due to the relevant insulation under the upper concrete layer of the floor. Also the solar radiation that comes through the window and strikes the floor surface has its effect.

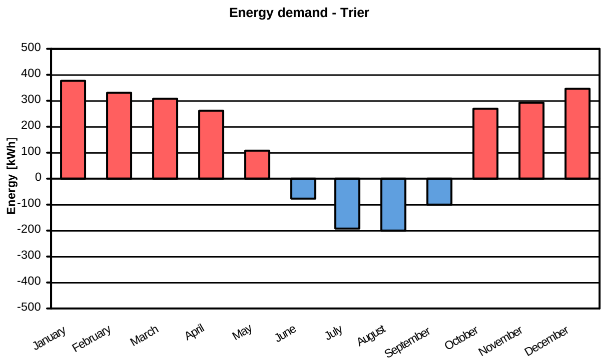
In all cases the use of thermally activated slabs allows achieving thermal comfort, but to realize also energy saving some details about external conditions have to be taken into account. In a cold region, such as the climatic condition of Kassel, the relevant parameters concern the operating conditions for heating; an improvement for these systems, therefore, can require the reduction of cooling loads during heating condition and the optimization of solar gains. In regions where the outdoor temperature is higher and relevant operating condition is cooling, such as Palermo, the optimization of the thermo-active slabs systems can concern a good insulation from solar radiation and the use of night ventilation to cool buildings structures. In the case of Venice, finally, the variability of external conditions requires an appropriated control that can optimize both aspects.

Anyway the simulations here performed refer to an office with only one person, and in the case of warmer climates the presence of other people should give different results, but better shading devices can avoid the overall cooling load to be removed during night-time operation of the slab.

6. CONCLUSIONS

The mathematical model shows that the office building of the ZUB can achieve good comfort conditions. This indicates that in buildings with energy conscious design the implementation of active thermal slabs systems is possible. The computer simulations, furthermore, show that the correct use of active thermal slab systems needs an appropriate control strategy. A deep knowledge of inside and outdoor conditions is essential to correctly predict their behaviour and their related thermal loads, thus also allowing the achievement of an optimum solution for every case. Measurements will investigate other aspects and different solutions for the control strategy may be studied. The control strategy here presented seems to be very interesting to be applied in the pilot building.

The simulations here performed represent only the first step of an investigation program which should include other rooms (first and second floor) and the overall heating/cooling system, with particular reference to the possibility of cooling the room by means of the direct coupling with the circuits embedded in the groundwork of the building. Further investigations based on different controls are finally necessary to analyse the potential coupling with renewable and recovery energy source and minimize energy requirements.



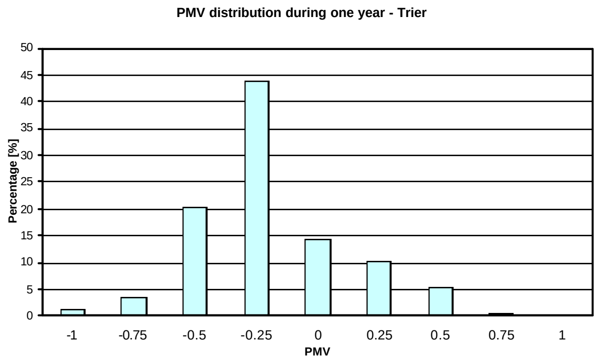
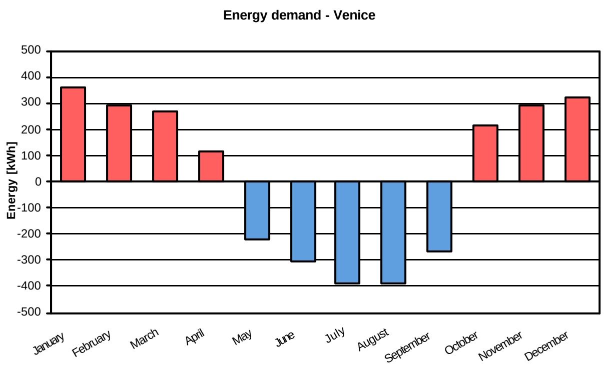


Fig. 7 – Monthly distribution of the energy demand of the room during one year in Kassel

Fig. 8 – PMV distribution of the PMV in the room during one year in Kassel



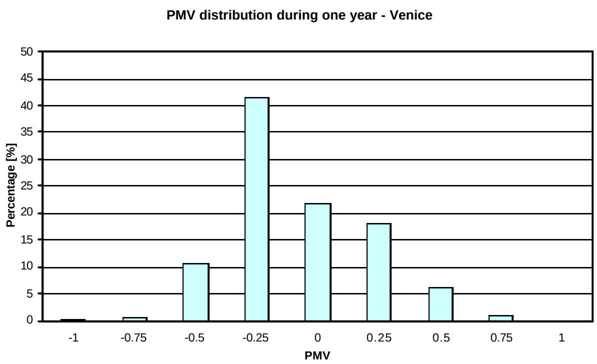
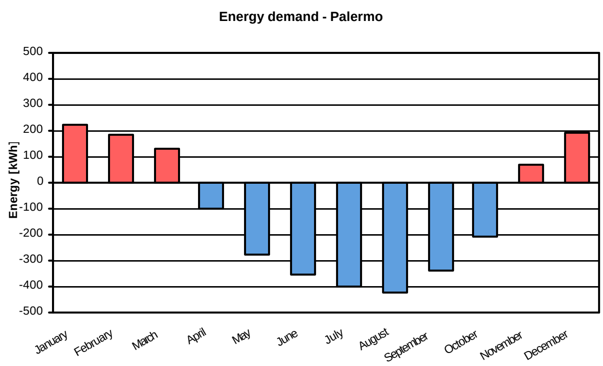


Fig. 9 – Monthly distribution of the energy demand of the room during one year in Venice

Fig. 10 – PMV distribution of the PMV in the room during one year in Venice



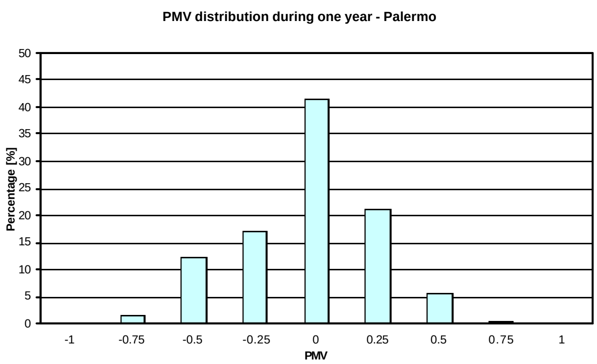


Fig. 11 – Monthly distribution of the energy demand of the room during one year in Palermo

Fig. 12 – PMV distribution of the PMV in the room during one year in Palermo

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