HI-SMART: HIGHER EDUCATION PACKAGE FOR NEARLY ZERO ENERGY AND SMART BUILDING DESIGN

MODULE #3

CHAPTER 1: THERMALLY ACTIVE BUILDING SYSTEMS (TABS)

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3.1.1 REVISION OF HEAT TRANSFER PROCESSES

When there is a temperature difference, heat transfer occurs. In buildings, heat transfer occurs by three means between the occupants and their environment:

- Conduction
- Convection
- Radiation

Conduction is heat transfer through stationary matter by physical contact. Fourier formulated a law on heat conduction, that now bears his name (Fourier-law). By definition "heat flux, q (W/m2), resulting from thermal conduction is proportional to the magnitude of the temperature gradient and opposite to it in sign." [1] The proportionality factor is called k. The equation is as follows:

$$q = -k\frac{dT}{dx}$$

where,

k – thermal conductivity (W/mK, J/msK); (instead of k often λ is used

Heat flows from high temperature to low temperature, therefore dT/dx is negative because as 'x' increases the temperature will decrease, so the slope dT/dx, namely the temperature gradient will be negative (see Figure 3.1.1). In order to keep the heat flux positive, since heat always flows from high to low temperature, the negative sign is added in the Fourier equation.

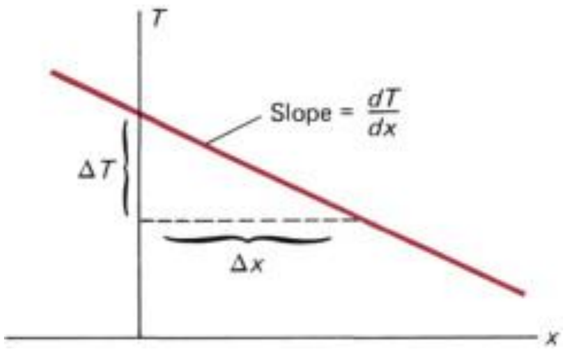

Figure 3.1.1. One dimensional heatflow – Slope of the temperature gradient [4]

In the case of one-dimensional heat conduction the direction of heat flow is known (q flows from high to low temperatures), therefore Fourier's law can be written in a simplified form:

$$q = k\frac{\Delta T}{L}$$

where,

k – thermal conductivity (W/mK, J/msK)

L – is the thickness in the direction of heat flow (m)

Convection is heat transfer through fluids (liquids, gases). “A fluid immediately adjacent to the body (or object e.g. wall) forms a thin slowed down region called the boundary layer. Heat is conducted into this layer, which sweeps it away, and farther downstream mixes it into the stream. We call such processes of carrying heat away by a moving fluid convection.” [1]

Newton considered the convective process (for cooling) and later the equation bearing his name was created for steady-state, namely:

$$q = \bar{h}\left(T_{body} - T_{\infty}\right)$$

where

h – heat transfer coefficient (average over the surface of the object or body) (W/m^2K, J/sm^2K)

Radiation is heat transfer via electromagnetic radiation. “The intensity of radiant energy flux depends on the temperature of the body and the nature of its surface. The perfect thermal radiation is a black body that can absorb all the energy and reflects nothing”. [1]

A non-black body can absorb (α), reflect(ρ) and transmit (τ) the incident energy.

$$1 = \alpha + \rho + \tau$$

In the case of a black body α=1 and ρ=τ=0

Stefan-Boltzmann law applies: “The total radiant heat power emitted from a surface is proportional to the fourth power of its absolute temperature…if E is the radiant heat energy emitted from a unit area in one second (that is, the power from a unit area) and T is the absolute temperature, then

$$E = \sigma T^4$$

where,

σ - representing the constant of proportionality, called the Stefan-Boltzmann constant. This constant has the value 5.670374419 × 10−8 W/m^2K^4. “ [1]

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The law applies only to black bodies, theoretical surfaces that absorb all incident heat radiation."

How does radiant heat exchange occur?

Assume that an object (object 1) radiates only to object 2 and both are considered thermally black bodies. In this case, the net heat transferred from object 1 to object 2 is the following:

$$Q = A_1 E(T_1) - A_2 E(T_2) = A_1 \sigma (T_1^4 - T_2^4)$$

If object 1 "sees" other objects than object 2, then a view or shape factor F1-2 must be included in the equation:

$$Q = A_1 F_{1-2} \sigma (T_1^4 - T_2^4)$$

3.1.2 HYDRONIC SYSTEMS IN BUILDINGS

In buildings with a hydronic radiant system, may it be surface heating or thermally activated building system, all three types of heat transfer occur.

Hydronic systems are considered radiant when more than 50% of heat exchange with the conditioned space is via radiation and are considered hydronic as water is the heat carrier or medium of heat distribution.

Radiant heating and cooling systems can be divided into three categories:

- Radiant heating or cooling panels
- Pipes isolated from the main building structure but embedded: radiant surface systems
- Pipes embedded in the main building structure (TABS)

How and where the three means of heat transfer occur in case of TABS?

Heat **conduction** occurs between the embedded distribution pipes and the building envelope (slabs or surfaces).

Heat **convection** occurs in the distribution pipes of systems. This is a *forced convection* as water is pumped and pressure difference is present. Convection also happens between the cold wall/window surface and the air indoors. This is *natural convection* that is caused by density difference.

Heat **radiation** occurs between the surfaces in the room if they have different temperatures.

3.1.3 WHAT ARE TABS EXACTLY?

TABS are usually installed during the building construction phase or installed in prefabricated building elements. Pipes are embedded in the concrete slabs (that has very good heat-conducting properties) of buildings, between storeys. It is also possible to attach prefabricated TABS systems to already existing building elements.

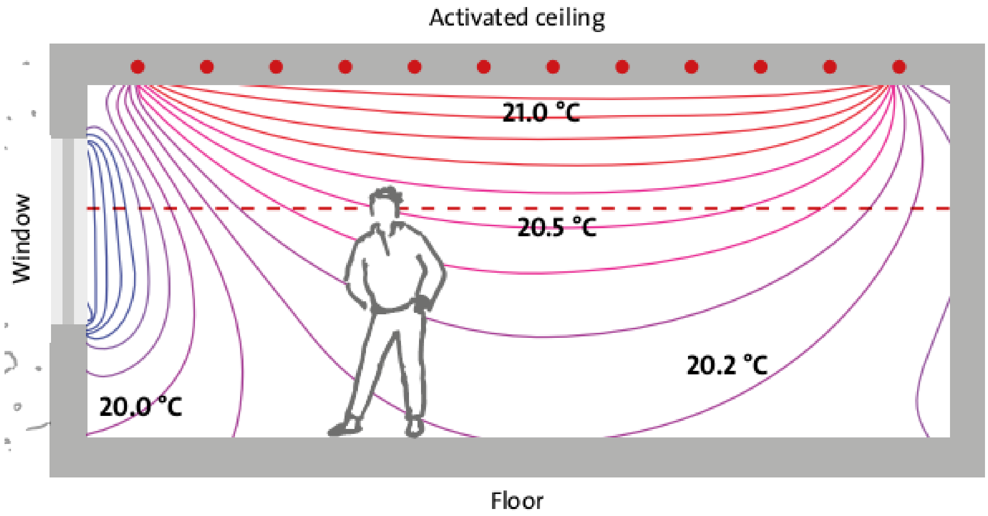

Figure 3.1.2. Uniform temperature distribution with TABS in winter [2]

This solution ensures a relatively high effective heat exchange surface that is why it is considered surface heating or cooling.

Concrete slabs have high thermal mass and thermal capacity, thus they have high thermal inertia (the degree of slowness with which the temperature of a body approaches that of its surroundings – Merriam Webster Dict.). E.g. in the case of heating, a large amount of heat from the pipes can be fed into the slab without increasing the supply temperature much.

Thanks to the storage capacity of concrete, heat can radiate to the room for a longer period and the supply temperatures need not be high. (Figure 3.1.2.)

In the case of cooling, the slab stores the heat that is generated during the day and later the circulated cold water that is in the embedded system can flush the gained heat from the slabs. This way the cooling demand is shifted to a different time compared to the thermal loads, that is most probably night time when cheaper night tariff electricity prices apply. (See Figure 3.1 3.)

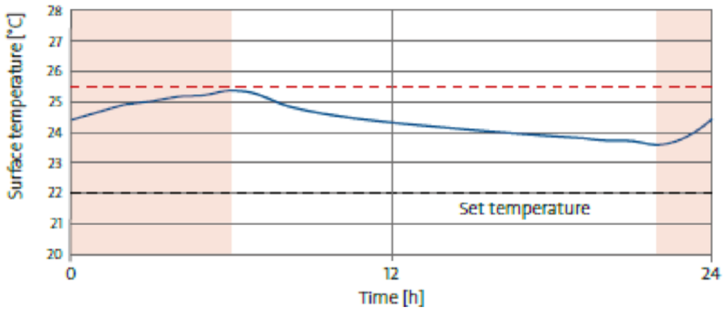

Figure 3.1.3. Surface temperatures of TABS for 24 h [2]

The graph shows a heating procedure: surface temperature is indicated for a TABS system over 24 hours. It can be seen that heating of the surface is shifted to the night time - off peak hours. The slab is "loaded" by the beginning of the day. At this point circulation is off and the slab will emit heat all day long until heating can start again in the evening.

When using TABS, the ventilation system is primarily used to provide the requested amount of fresh air. Ventilation may of course remove some of the heat loads as well, but primarily thermal loads are extracted from spaces by TABS.

In the case of steady-state cooling, TABS have capacities up to 30-80 W/m2. (limit is because of dew point). The heating power of TABS is approx. 25-40 W/m2.

3.1.4 ADVANTAGES OF TABS

The advantages of TABS are the following:

Due to the shift of loads, lower peak loads will be present, thus a smaller conditioning plant is sufficient.

Building height can be reduced (there is no need for suspended ceilings for air-conditioning systems), which results in savings of building materials.

They operate with low supply temperatures (24-32°C) in heating mode and high supply temperatures (16-20°C) in cooling mode. Environmentally friendly energy sources can be used economically.

For cooling purposes, night ventilation can be used as well – free cooling. In this case, the building is cooled by air during the night and TABS takes away excess (but not high) heat gains during the day. (Figure 3.1.4.)

The installation of the system is easy and cheap – no specific devices required. Operation costs and maintenance costs are low as well.

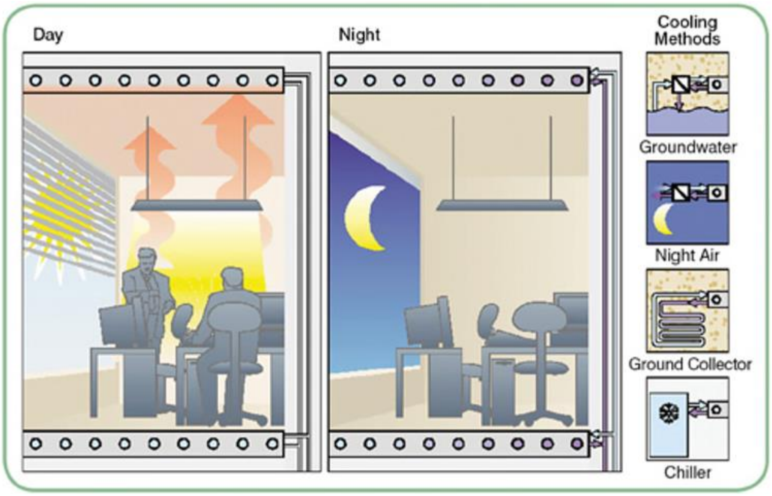

Figure 3.1.4. Cooling during the night time with TABS (Source: https://www.eco-structures.net/single-post/2018/05/19/How-To-Grow-Your-Concrete-Mindset)

Nevertheless, there are certain boundary conditions that have to be met so that TABS can be applied:

- TABS are best used in multi-storey buildings. They can be used in single-storey buildings, but then TABS is installed in the floor and ceiling, and then the ceiling, made of concrete, should be very well insulated from above.
- As no suspended ceilings are allowed, acoustical issues have to be solved in another way. Acoustic plasters should also be avoided.
- The design of the building envelope is very critical. The most important are:
  - good thermal insulation of the building envelope (lower U-values)
  - adequate solar radiation screens,
  - there shall be shading elements installed.
- It is also important decisions about the selection of component activation have to be made in the early planning phase of the building (cooperation with architecture)

3.1.5 THERMAL ACTIVATION OF CEILINGS (TAC)

There can be a prejudice against thermal activation of ceilings and the reason is that people know that warm air rises.

It is a very important characteristic of large-area heat output systems that, due to the relatively low surface temperatures of the heated areas, the convective share of the heat transfer is low. Therefore, TABS can be considered as a radiant heating system. Heat radiation is massless; therefore, it is independent of gravity – it will radiate heat from the ceiling.

3.1.6 SELF-REGULATING EFFECT OF TABS

An important feature of TABS is the self-regulating effect. As discussed earlier the supply temperature of TABS is quite low for heating and quite high for cooling. This means that surface temperatures of the heated parts of the slab is only a bit above (or below) the temperature of the room. When the temperature difference becomes smaller and smaller between surface and room, the lower the heat output of the TABS will be, or in the case of cooling, lower the heat absorption of the component will be.

For heating:

Room air temperature	Heat output of TABS
If Increases	Then Decreases
Equals to surface temperature	No output

For cooling:

Room air temperature	Heat extraction of TABS
If Decreases	Then Decreases
Equals to surface temperature	Does not extract more heat

In the case of heating, the surface temperature of the heated slab must not be more than 4 K above the set room temperature. If this is true, the self-regulating effect of TABS can be utilized. This "self-regulating effect" occurs with heating systems that operate with relatively low temperatures and with cooling systems that work with relatively high temperatures of the cooling medium. As a result of self-regulation, if the surface temperature of a thermally-activated ceiling is 24 °C, the ceiling does not output any more heat at 24 °C, regardless of the flow speed of the heating medium in the pipe register. This self-regulation is a great simplification concerning the building service system and technology.

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3.1.7 QUESTION OF CONDENSATION

A limitation of cooling with TABS is that condensation on the surfaces must be avoided. The danger of condensation can be ruled out at relatively high cooling surface temperatures (>19°C) with a very well insulated building, or by installing a ventilation system preferably with heat recovery.

If there is a ventilation system in the building, then condensation can be avoided by dehumidifying the ventilation air to a certain level and keeping the surface temperature of the slab above the dew-point temperature of the room air for all operational conditions.

3.1.8 SYSTEM TYPES – SUPPLY SOURCES

Overall with TABS high thermal comfort can be provided even under extreme outside weather conditions. TABS can be operated in an energy efficient way by applying mainly renewable energy sources - low temperature heating, high temperature cooling.

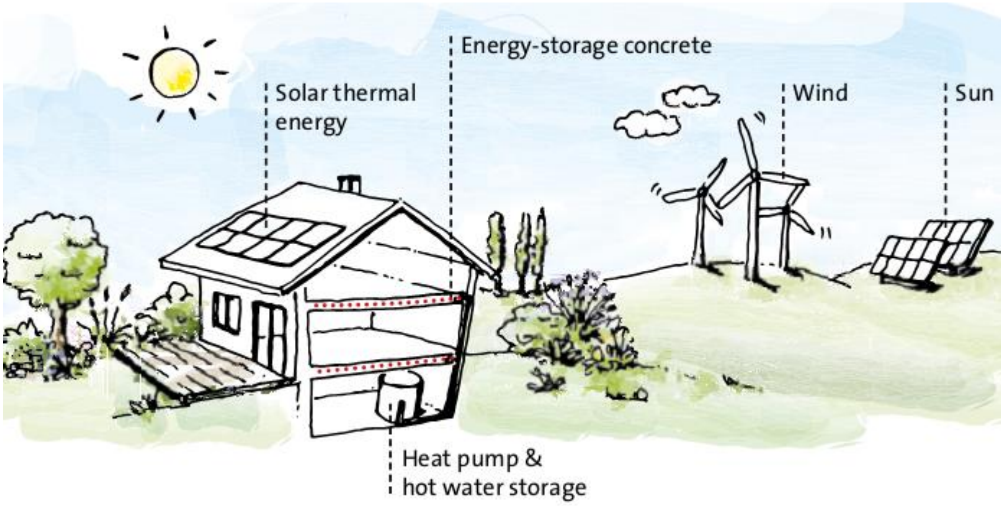

Figure 3.1.5. Supply sources of TABS from renewables [2]

As stated earlier TABS operate with low supply temperatures in heating mode and high supply temperatures in cooling mode. This makes the use of renewable energy a viable solution (Figure 3.1.5.).

Solar collectors may produce heat for TABS, however, climatic conditions have to be considered (it maybe only a supplementary solution for transitional seasons – spring, autumn)

Heat pumps are suitable solutions for TABS as they provide energy both for heating and cooling. They are operated with electricity that can be supplied from renewable energy (wind, PV) or with a green tariff from the grid.

System solution examples for the supply of TABS

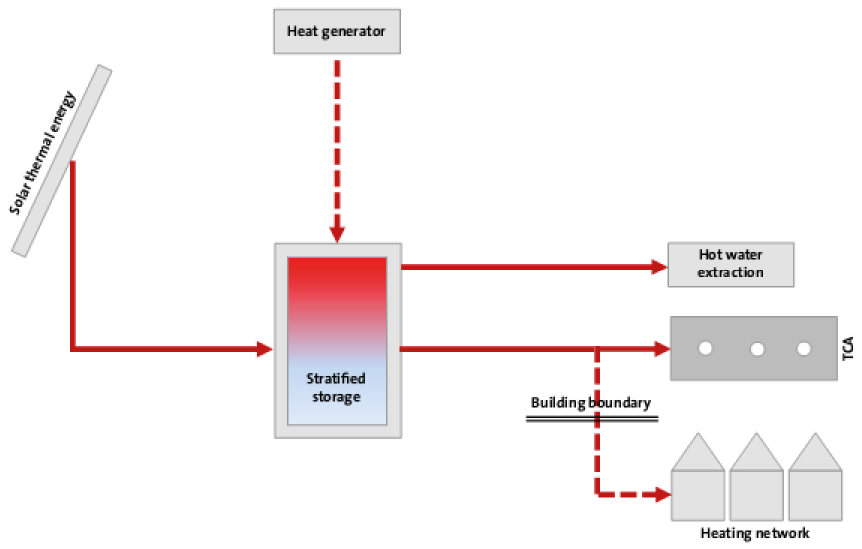

Figure 3.1.6. Supply of the system with solar collectors and a heat generator [2]

In the heating season heat is generated whenever possible with solar collectors and the thermal energy obtained from there is 100% used for heating purposes. It is possible that due to weather condition solar collectors cannot fulfil the demand, thus a heat generator is needed that is not dependent on weather (biomass boiler, heat pump, district heating or more traditional type solutions). In summer the collectors may produce too much energy as in this case only domestic hot-water production is needed. It would make sense, in this case, to be able to supply the local heating grid if possible (in Hungary this is not possible yet) or supply consumers/other buildings nearby, or supply pool heating with the excess heat).

Advantages: use of renewable energy on-the-spot, high coverage despite of costs, simple technology, can be independent from the energy provider, low CO2 emission

Disadvantages: coverage rate is highly influenced by meteorology and topology, energy gain cannot be utilized in summer, active or passive cooling is not possible without another system (only warm energy is produced)

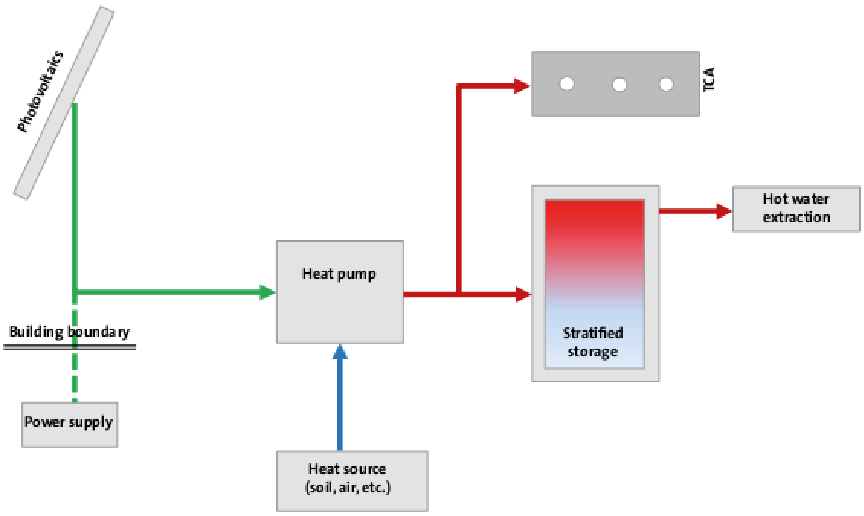

Figure 3.1.7: Supply of the system with heat pump and PV panels [2]

In this case, PV panels provide the electricity on-site for the heat pump whenever possible. Often in winter PV cannot cover the entire electricity need of the heat pump that is used for heating and hot water production, thus other heat sources are needed (Figure 3.1.7.).

On the other hand, in summer, PV panels can supply entirely the heat pump that cools the cooling media and cools the building.

Advantages: Solar energy is used on-site, energy costs are low, cooling is possible with low additional investments, one energy source to supply the building

Disadvantages: Solar yield is limited in the time of greatest need (winter), system performance is highly influenced by meteorology and topology.

3.1.9 CONTROL OF TABS

For TABS individual room control is not reasonable, but the use of zone control (south, north etc.) can be an option. (zoning should consider external and internal heat loads)

The following parameters may differ from zone to zone:

- supply water temperature
- average water temperature
- flow rate

What parameters are monitored for the proper control of TABS?

- zone temperature

- the temperature of the concrete core

Zone temperatures are measured by room thermostats that are connected to the control system [3].

The core temperature is measured by a sensor installed in the concrete during the construction phase and is passed to the building control system (Figure 3.1.8.).

Figure 3.1.8: Sensor installed during the construction phase [2]

Operation of system control (short explanation for winter and summer)

Please consider the description below in a way that this control cycle lasts for e.g. a day. Tabs are reacting slowly and as it was shown earlier the aim is to shift loads to off peak periods.

In winter, if room temperature approaches the lower limit of the set temperature band, the circulation pump is put into operation due to the thermostat report and heat is supplied to the activated ceiling. If the core temperature exceeds an upper limit in winter, the heat supply is interrupted by switching off the circulation pump. (temperatures 25°C to 26°C). When the thermostat reaches the set lower limit the circulating pump is switched on again.

In summer, the room thermostat switches the circulation pump on if the room temperature approaches the set upper limit (26°C).

Cooling must be restricted for reasons of comfort and to prevent condensation. If the temperature registered by the core temperature sensor falls below a set minimum value – in the range of 20°C –, the circulation pump is switched off, thereby ending heat extraction (and avoiding possible condensation). The lower limit for the supply water temperature has to be set to equal the dew point temperature. If a ventilation system is available that can dehumidify the air, then the capacity of the radiant cooling system can be increased.

Peak shaving

As stated earlier one of the advantages of TABS is that demand peaks can be shifted or shaved. With the intelligent operation of TABS, peak power demands may be reduced. The energy heat gains during the time of occupancy are accumulated in the active structure component and later on during the night extracted by a water circulating system or by free night cooling. Hence significant peak shaving can be achieved by shifting partial loads to night time and the heat source/sink can be scaled down to 60% (depending on application).

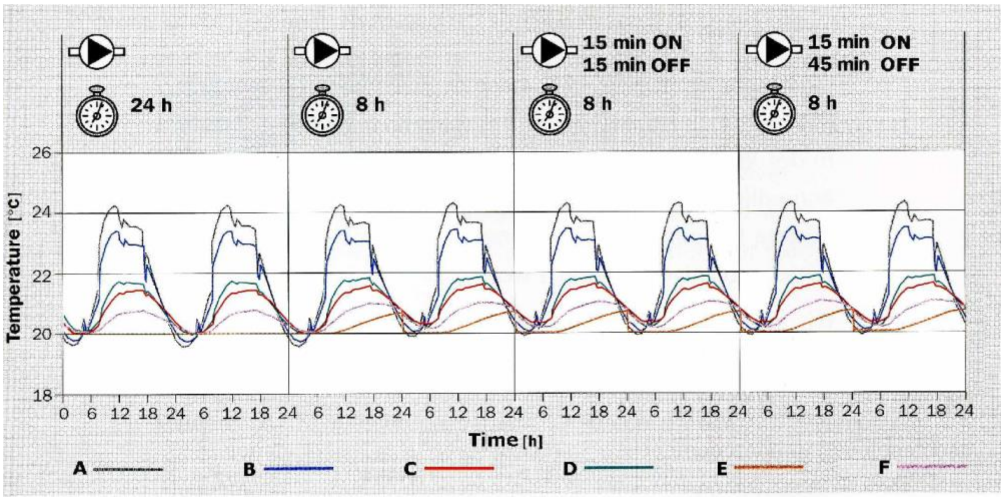

Figure 3.1.9: Study about the effect of circulation pump usage in TABS
(A – air, B – operative, C – floor, D – ceiling, E – mean slab core, F – slab) [3]

On the graph, the result of a study can be seen done by Meierhans and Olesen. They studied how the operation of circulation pump affects certain temperatures (slab surface operative). It can be seen that when the pump is operated periodically for 8 hours during the night it will result in the same operative temperature -but energy consumption will be much different compared to continuous operation.

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3.1.10 HEAT LOAD CALCULATION OF TABS

Currently valid standards that contain regular heat load calculation methods result in oversizing in the case of low energy and passive houses that are necessary and suitable buildings for TABS.

The reason is that low energy or passive houses are highly insulated buildings therefore they only react very slowly to extreme outdoor climatic conditions. The safety factor that is included in other current standards is not necessary for such buildings. Also, the effect of internal gains is neglected in the standards – but is a significant input in the case of e.g. passive houses.

For this reason, it is advised to use the Passive House Planning Package (PHPP) as a tool for the calculation of heat loads in the case of such buildings.

ISO 11855 is another possibility for the dimensioning of radiant systems. Specifically, ISO 11855-4 pertains to dimensioning of TABS. (ISO 11855-4:2012: Building environment design — Design, dimensioning, installation and control of embedded radiant heating and cooling systems — Part 4: Dimensioning and calculation of the dynamic heating and cooling capacity of Thermo Active Building Systems (TABS))

In this material, the PHPP method is used to introduce the sizing of TABS in a building.

If the results of heat load calculation are available a preliminary calculation can be made to see whether the thermally activated building component (floor, ceiling) can cover the heat load on its own. The heat output by the treated area of the TABS, should not exceed 25 W/m^2. This 25 W/m^2 comes from the following: if the 4K temperature difference is to be maintained between the TABS surface and room (for self-regulating effect); and considering a surface heat transfer coefficient of 6.5 W/m^{2}K, then the maximum q heat output will not be greater than 26W/m^{2}K.

Thus, the minimum required effective heat exchanger surface is calculated by dividing the calculated heat load of the considered space by 25.

$$A_{R,min} \approx \frac{\Phi_{HL}}{25}$$

3.1.11 SIZING OF TABS [2]

As mentioned earlier it is advised to carry out heat load calculations according to PHPP if possible because it:

- sets higher outside air temperatures (highly insulated houses react slowly)

- takes into account the effect of heat sources in building interiors (significant sources in highly insulated buildings)
- does not set thermal bridge correction factors (passive houses are thermal bridge-free)
- expects small air change rates through the envelope (fresh air supply, on the other hand, is derived from use)

/Note: PHPP is only available for purchase, however, Demo version is available to get acquainted with the program and a version can be obtained at a lower price if used for educational purposes/

The steps of heat load calculations are as follows:

- Collect building figures: built area, gross area, perimeter, envelope surface, heights (headroom, storey) etc.
- Collect building envelope materials, layer structures, calculate U-values for building envelope materials (outside components: exterior wall, windows, doors etc.).
- Surface calculation for the outside components
- Areas are calculated for outside dimensions; when calculating the wall areas of a room, half the thickness of the partition wall has to be included.
- Doors and windows are collected according to orientation (S, E, N, W etc.)
- Climate data for the calculation for heat load from PHPP - standard outside temperature for the site (for edu version limited locations available)
- Calculation of the thermal transmission conductance:

Building components exposed to air and to soil are distinguished/calculated separately

L_e - Thermal conductance of the components exposed to air

L_b - Thermal conductance of the components exposed to soil

$$\text{Thermal conductance [W/K]} = \text{Area [m}^2\text{]} \cdot \text{U-value [W/m}^2\text{K]}$$

The effect of thermal bridges on the total thermal conductance must be small in the case of buildings where TABS are to be installed. No thermal bridge correction is needed as it is after the careful and detailed planning of highly insulated buildings heat losses near the thermal bridges are decreased. Thermal conductance of wall openings is higher than that of the outer wall!

Calculation of transmission heat losses

Through the foundation plate:

$$\Phi_b = L_b \text{ components exposed to soil} \cdot \text{(set temperature – soil temperature)}$$

Through the components exposed to air:

$$\Phi_e = L_e \text{ components exposed to air} \cdot \text{(set temperature – outside temperature)}$$

Total transmission heat loss:

$$\Phi_T = \Phi_b + \Phi_e$$

Calculation of ventilation heat loss: In the case of heat recovery use, the heat losses due to required hygienic ventilation are covered, but heat losses due to infiltration are 100% present.

$$\Phi_V = L_V \cdot (\Theta_i - \Theta_e)$$

Θ_i – set temperature of the room, Θ_e – outside air temperature

L_V – thermal ventilation conductance

$$L_V = 0.34 \cdot V \cdot [(n_L \cdot (1 - \eta_{WRG}) + n_X)]$$

Where,

V – room volume, m^3 (living area · headroom height)

n_L – air change rate (minimum fresh air for hygiene: 0.3 1/h)

η_{WRG} – heat supply efficiency (e.g. heat recovery unit, indicated on the energy certificate)

n_x – air change rate for infiltration (0.12 1/h, if n50=0.6 1/h with blower door test)

Total heat loss: Sum of Transmission heat loss and Ventilation heat loss

$$\Phi_l = \Phi_T + \Phi_V$$

Heat input/gain calculations:

Φ_g – total heat gains consist of the following:

Occupancy sensible gain: A heat output by living area of 1.9 W/m^2 is set. Includes all heat outputs caused by occupancy, lighting and the operation of devices.

$$\Phi_i = 1.9 \cdot \text{living space}$$

Heat gain due to sun radiation (through the transparent parts of the building envelope)

$$\Phi_S = A_W \cdot g \cdot r \cdot I$$

A_w - Area of the windows and glazed doors (including frame)

g - Solar heat gain coefficient ("g value") of the glass - production value; (how many percent of the sun radiation that hits the glass becomes a heat output after passing through the glass into the interior).

r - Reduction factor: value is between 0 and 1 and reduces the g-value of the glass. Reasons for reduction: shading effects, contamination of glass upon installation, sun radiation hits the glass in angle etc.

I - Solar irradiation intensity

Total heat input :

$$\Phi_g = \Phi_i + \Phi_S$$

Total heat load: (difference of the heat loss and heat input rate)

$$\Phi_{HL}(\text{heat load}) = \Phi_l \text{ (heat loss)} - \Phi_g \text{ (heat input)}$$

<u>Heat output:</u>

q= Φ_{HL}/living space area

Heat output should be below 25 W/m2 in order TABS can ensure comfort under design conditions.

3.1.12 STEPS OF SYSTEM CONSTRUCTION

During the building phase of the concrete slab of the building envelope the TABS pipe system is laid on the slab according to the design plans.

Figure 3.1.10. Laying of the pipe system [2]

Core sensors that are used for the control and monitoring of TABS are installed in this phase too.

Figure 3.1.11. Installation of the core temperature sensors [2]

The applied polymer pipes (usually PEX - oxygen diffusion protected) are connected to the fittings via company dependent press tool kits.

After installation of the pipe system, a pressure test is carried out in order to see if all pipe connections are secured and that there are no construction errors, material flaws in the system. If pressurised air is used, a test pressure of 2.5 to 3 bar is recommended. If water is used as the testing medium, the pressure should be increased from 4 to 6 bar. The test duration is 12 hours.

If the system passes the pressure test, it can be covered up. Concrete is laid on the pipe system and core sensors.

Figure 3.1.12. Laying of concrete on the pipe system and core sensors [2]

After this the collector and distribution fittings are also installed so that TABS pipe registers can be connected to the central heat supply in the building. The supply can be e.g. heat pumps, solar collectors+additional traditional sources as introduced earlier.

Figure 3.1.13. Installation of collector and distribution fittings [2]

This concludes the system construction of TABS.

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