SHOWING NEW CONCEPTS WITH THERMAL ACTIVATED PREFABRICATED FAÇADES FOR RETROFITTING RESIDENTIAL BUILDINGS

F. Hengel[1], T. Ramschak[1], M. Gumhalter[1] und D. Venus[1]
[1]AEE - Institut für Nachhaltige Technologien, Gleisdorf, Austria

ABSTRACT

Upgrading the existing building stock is one of the main leavers to reduce the heating energy demand. Therefore, prefabricated thermally activated curtain façades offer the possibility to upgrade insulation and the heating system in one step whilest reducing the disturbance of residents during the renovation process.

In this paper the performance of such systems with a validated model in IDA ICE for room heating is examined. To compare, a sensitivity study is carried out with different concepts and wall types, as well as a diagramm for designing such systems is established. All simulations are assessed with the defined key figures.

INTRODUCTION

To increase the energy efficiency and to reduce the energy demand of buildings, retrofitting of existing residential buildings is of utmost importance.

There is a huge potential for highly efficient thermal refurbishments of multi-family buildings that would result in significant reductions of CO_2-emissions. However, the renovation rate for existing buildings has been declining for the past few years. In the case of comprehensive thermal renovations in Austria, it´s lower 1% which is significantly lower than the goals set in the Austrian climate protection report (2% between 2020 – 2030). The current technical renovation standard as well as the renovation process have repeatedly proven to be insufficient in terms of providing the appropriate incentives. This applies not only to structural but also to HVAC refurbishments.

According to Fink et al. (2017) buildings constructed between the 1960s and 1980s account for the largest share of heating energy demand in Austria (cf. Figure 1 from IEE project TABULA from 2009 to 2012). The wall constructions are mainly based on concrete, vertical coring brick, or solid brick with either insufficient or no insulation installed.

Also, Höfler et al. (2006) shows in its investigations that in large-volume residential buildings from this era three different external wall construction are dominant:

- Concrete wall systems including wood wool panels with a total thickness of 25 - 30 cm
- Mantle block outer wall with a thickness of 25 cm or 30 cm, and
- Vertical coring brick wall with a thickness of 30 cm or 38 cm.

The u-values of these external wall constructions range between 0.7 W/(m² K) (30 cm concrete wall system) and 1.50 W/(m² K) (based on 25 cm vertical coring brick wall) according to Energieagentur Steiermark (2016). Top floor ceilings adjacent to an unheated attic typically exist of solid concrete and 3 cm of thermal insulation, resulting in a u-value of 1.00 W/m²K. Double-pane glazing with u-values between 2.5 W/m²K and 3.1 W/m²K is typical for Windows from this era. The heating of these buildings is often based on a fossil fuel fired boiler in combination with high-temperature radiators, and copper piping for energy distribution.

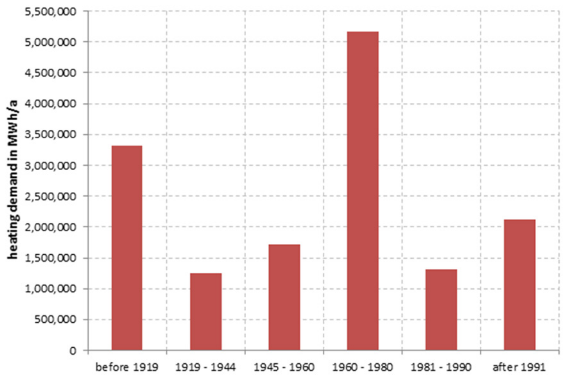

Figure 1: Total heating demand of all large-volume residential buildings per epoch according to IEE project TABULA, 2009 to 2012

Additionally to the necessary replacement of the heat source with more environmental friendly solutions the predicted lifespan of the copper piping is about to end after 50 years in operation. Replacing these heat distribution pipes can result in time-consuming construction works and high investment costs and also requires relocation measuers of the residents during the renovation phase, resulting in additional costs.

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As reported by STATcube (2020) there are 3.863.262 dwellings in 2.046.712 buildings and 86 % of these buildings are residential buildings in Austria. The authors show that the largest share of dwelling units is part of residential buildings with 3 or more dwelling units in total. Following this, the focus of this research is pointed at large volume residential buildings in Austria constructed in the epoch between 1960 and 1980.

Derived from the challenges above, wall constructions using active heating layers between the structural part of the building and an outside insulation layer are quite promising. The typical appearance of those buildings with mostly flat surfaces encourages the installation of prefabricated curtain façades fitted with this active layer and holding the insulation. This technique also allows to retrofit a building without disturbing tenants on site with tedious construction work in and around the building over a long time period.

Challenging in this regard is the inconsistent contact situation between the active heating layer and the outside surface of the existing building. Also, the heat transfer rates are restricted as the thermal conductance of building materials like vertical coring bricks are quite low because of their air gaps in-between. However, to tackle this issue different concepts for active facades elements are investigated within this paper under consideration of comfort criteria. The paper also gives advices which concept can be used for which wall construction and discusses the flexibility potential.

To reach this aims a simulation model is established were a sample room is investigated. At the external wall a curtain façade with an active layer is implemented, and the heat transfer rates are determined for different concepts as well as for different construction of the external wall. To ensure proper simulation results a validation of the dynamic annual simulation model is done with a FEM based simulation model (higher spatial resolution). Additionally, the load shift potential is identified by applying a proper control strategy (using parametric runs for different setpoint temperatures of the observed rooms).

Based on the defined key figures the results are displayed in tables and diagrams and the compliance with comfort criteria is analyzed.

State of research

Regarding research work there are some publications concerning prefabricated façades. IEA ECBCS Annex 50 (2010) is a research project and dealt with renovation with prefabricated facade elements and integrated building services, such as solar thermal collectors, component heating of the outer walls and decentralized ventilation units. The façades also contained supply shafts for cable routing, heating, domestic hot water and ventilation. In contrast to this paper no detailed concepts were worked out to improve the heat transfer rate and additionally no standard façades were defined and used, e.g. vertical coring brick, plaster and insulation.

Further projects, Doenig-Meisinger et al. (2007), Höfler (2012), Giwog (2020a), Giwog (2020b) and Alingsas Schweden (2013) primarily deal with prefabricated facade elements for renovation towards passive house standard. Partially they integrated some HVAC systems in the façade but as beforehand they do not investigate heat transfer rates for different concepts and wall constructions. Sonneseite (2015) investigates innovative external wall heating elements with capillary tube mats which are connected to a concrete façade, but also here no other wall constructions are observed as well as no other dissipation system concepts.

SIMULATION & MODELLING

Within this chapter the concepts and basic constructions for the investigations are introduced and discussed. This includes the boundary conditions, the experimental building and the validation environment. Lastly, the matrix for the case studies is defined.

Concepts and construction

As discussed in the introduction the renovation of buildings from the 1960's to 1980's holds two main challenges. Installing additional insulation to the existing walls to safe energy and lower CO_2-emissions (cf. Figure 2) and replacing the outdated heating systems. As stated in the introduction a promising approach are pre-manufactured curtain façades including insulation and an active layer. The main task of such an active layer is to provide enough heat flux through the wall so that heating a room behind the wall is sufficiently possible. Therefore, four active layer design concepts from A to D (cf. Figure 3) are introduced and analyzed based on the performance. In concept C the active layer is exposed which means that the pipe is in-between the wall and the insulation and is surrounded by air in the gap. The other one, concept D, misses the air gap and the pipe is enclosed by insulation. In both of these concepts the PE-x pipes of the active layer are in direct contact to the existing wall. The other two concepts feature metal heat conduction plates (HCP) between the piping and the wall to increase the heat transfer rate to the room. In concept A the curtain façade is perfectly touching the existing wall, whereby concept B shows a small air gap in-between which is assumed to be 2 mm across the whole wall. This equidistant gap assumes a surface average of real existing construction with flatness and contract irregularities and therefore allows the use of 2D and

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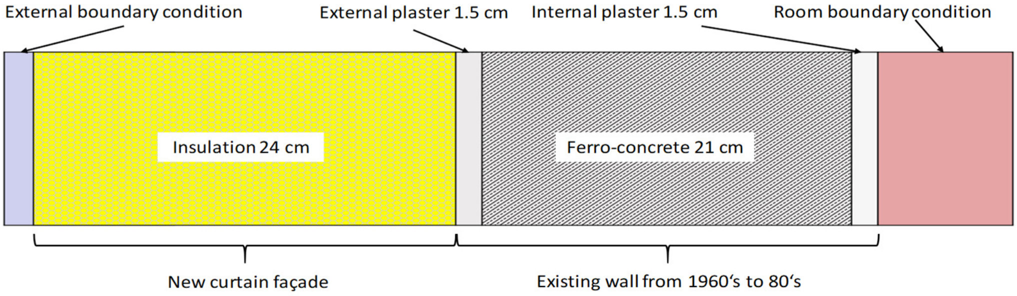

Figure 2: Basic wall construction with existing wall (e.g. ferro-concrete) and connected curtain façade without an active layer (active layers are displayed in Figure 3).

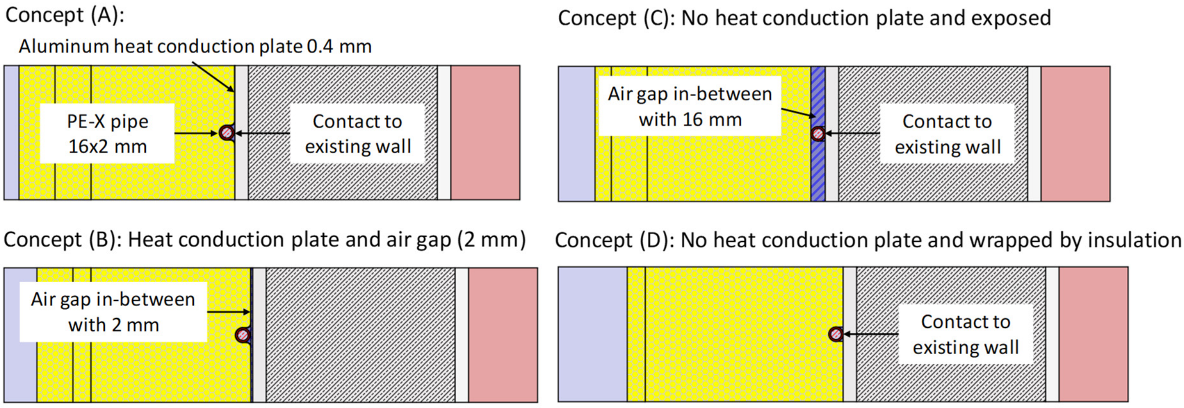

Figure 3: Four different design concepts for the active layer from A to D

1D model approaches. The thickness of the heat conduction plate is 0.4 mm (λ = 237 W/m.K). Table 1 shows the wall type variants (I to IV) and their material properties according to ÖNORM 8810-7 (2013) and Frei et al. (1994) which are used for the simulation. Furthermore, Table 2 shows the abovementioned total wall construction with the thicknesses of the different layers and their material properties. For the simulation the basic concept can be combined with different wall variants and dissipation system (concept A to D). The pipe is assumed as a PE-x pipe with an outer diameter of 16 mm and 2 mm wall thickness (16x2). The energy carrying fluid in all simulations is water.

Boundaries & Building

The modelled building/floor is derived from a real building in Graz, Austria. As there is no climate data available a climate data set of Graz-Thalerhof with latitude of 47.0° N and longitude of 15.43° E is chosen for the simulation.

Table 1: Wall type variants and their material properties

Wall type variant	Thickness in m	Thermal conductivity in W/(m.K)	Spec. heat capacity in J/(kg.K)	Density in kg/m³
Ferro-concrete (I)	0.21	2.3	1000	2300
Vertial coring brick (II)	0.3	0.55	1000	1200
Solid brick (III)	0.34	0.8	936	1700
Concrete (IV)	0.25	0.4	1116	500

This can be justified as both locations are nearby. The elevation of the location is 340 m with a minimal dry-bulb temperature of -12.5 °C, and $HDD_{20/12}$ of about 3100 K.d/a according to ASHRAE Fundamentals (2013).

Figure 4 shows the area where the building is located with the surrounding shades (left), and the floor consisting of three rooms, a corridor and a combined bathroom with WC (right).

Table 2: Total wall construction based on Figure 2

Layer external to internal	Thickness in m	Thermal conductivity in W/(m.K)	Spec. heat capacity in J/(kg.K)	Density in kg/m³
Insulation	0.24	0.038	1030	90
Active layer	Concept A to D			
External plaster	0.15	0.87	1100	1800
Wall type	Variant I to IV			
Internal plaster	0.15	0.7	1000	1400

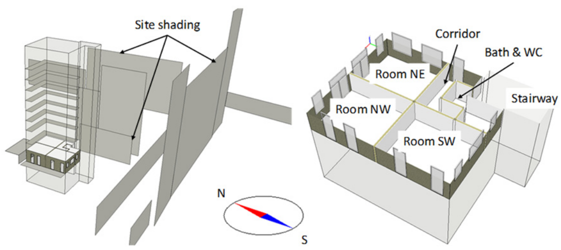

Figure 4: Whole area of the building (left) and the considered floor (right)

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The rooms NE, NW, SW are utilized for two bedrooms each e.g. as student hostel as in the real building. Due to simplification the two bedrooms are merged to one thermal zone. Further details concerning net heating area, conditioned walls and windows are listed in Table 3.

The room height is 3.66 m based on the real building. The windows within the building are modeled based on the type UNITOP 0.7 filled with argon in-between. The g-value is set to 0.52 according to DIN EN 410 (2011) and the visible transmittance is 0.7. The total u-value of the window is calculated to be 0.74 W/(m².K).

For the ventilation a decentralized unit is implemented in each room with volume flow rates of 45 m³/h for the rooms and 75 m³/h for the bathroom and WC, respectively. The efficiency of the heat recovery is set to 90 % e.g. according to Meltem systems. The infiltration rate is assumed as 1 ACH (air change per hour) at 50 Pa pressure difference and depends on pressure coefficients for different wind directions. The latter are assumed as "semi-exposed" which means that the building is partially covered from the surrounding area (cf. *Figure 4*)

The boundary condition to the stairway is defined as Dirichlet boundary condition with 15 °C and to the other floors the Neumann boundary condition (zero gradient) is chosen.

The heating setpoint for the rooms as well as for the corridor is 22 °C, for bathroom & WC it is set to be 24 °C. The heating system is controlled with a PI controller. Concerning control strategy of the integrated shadings, they are drawn if solar radiations of 100 W/m² at the inside of the windows are reached and can be activated individually. Another requirement is that a window is opened – by the user – if the room temperature exceeds 26 °C to avoid miscalculation of the heating energy demand.

Table 3: Geometric details of the room and windows and heat load calculation (for wall type variant I, cf. Figure 2)

Name	Net heating area in m²	Conditioned wall area in ²	Area external window in m²	Heating load in W
Room_NW	31.1	28.0	13.0	680
Room_NE	31.1	26.1	14.9	719
Room_SW	31	31.1	9.8	605
Bath & WC	10.2	8.1	1.4	523
Corridor	11.7	8.2	2.8	187

The remaining internal loads are around 200 kWh to 250 kWh, occupants excepted. Using the active layer for cooling purposes is thinkable but not object of this research. The simulation time is therefore set from 1st of Oct. to the 30th of April (heating only) and the time resolution is maximum 1 h, whereby the solver of IDA ICE can shorten these time steps whether vital for mathematical convergency or not.

The heat load calculation is done with the setpoints defined beforehand and the associated results are shown in the last column of Table 3. For the internal loads of the energy simulations the SIA 2024 (2015) standard is chosen. This standard defines the presence of the occupancies, the schedules, the devices and lights for different zones which is shown in *Table 4*. The highest energy consumption is allocated to lighting in the three thermal zones, respective to the three bedrooms with 4260 kWh.

Table 4: Internal loads for the rooms

Name	Number	Activiy level	Mean power in W	Yearly total in kWh
Occupancy	6	1.2		
Devices	9.3		81	229
Lights	9.3		486	4260
Lights_Bath	1		29	255
Lights_Corr.	1.2		21	182

Model calibration & validation

The simulation tool which is used within this study is IDA ICE from EQUA Simulation AB. To calculate the heat transfer rate from the active layer to the room a 1-dimensional approach within the simulation tool is used whereby the heat transfer coefficient (HTC) has to be set. This value includes the heat transfer coefficient from the fluid to the slab/wall with respect to the total heated wall area (cf. equation (1)) and uses the nomenclature of the EN15377-1 (2009) standard.

$$\frac{1}{HTC} = R_w + R_r + R_x = R_t - R_z \qquad (1)$$

Contrary to a floor heating system where the HTC value is nearly constant for all systems, the HTC value varies widely for the four active layer concepts described in Simulation & Modelling. The HTC is determined for all concepts and varying pipe distancing with an external software which is more related to heat transfer problems. HTflux – a 2-dimensional simulation tool based on FEM approach – is used to calculate the heat transfer rates for all active layer variants. A crosscheck procedure with heat flow results in IDA ICE leads to the identification of the needed HTC values.

The general suitability of IDA ICE for this class of simulation tasks is validated by comparing results for 1-dimensional heat flux in walls with results of identical HTflux simulations. This direct comparison which was conducted for static and dynamic cases is exemplary shown in Figure 5. In this Figure the used case is concept A with wall variant I (ferro-concrete) implemented as defined in Table 2. The validation uses a sequence of heating with an average fluid temperature of 35 °C followed by a cool down phase for which the mass flow rate is set to zero. The HTflux simulation uses about 5 million cells and 2D spatial resolution whereas the IDA ICE simulation utilizes a 1D 50-layer model.

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Both use a time step of 10 min. The results show good agreement for the heating-up phase and slight deviation at the end of cool-down phase. This can probably be justified with the difference in the spatial resolution – 1D vs. 2D – which has a higher deviation as the wall temperature reaches towards room temperature, which is 22 °C in this case. Further steps of the validation show similar results which are not shown here.

As mentioned before, individual HTC values are calculated for the different concepts (A – D) and varying pipe distances. Latter ones have an impact on the heat transfer rate to the room and can only be represented by a higher or lower HTC value in IDA ICE because of the 1D spatial resolution. Table 5 shows these determined HTCs.

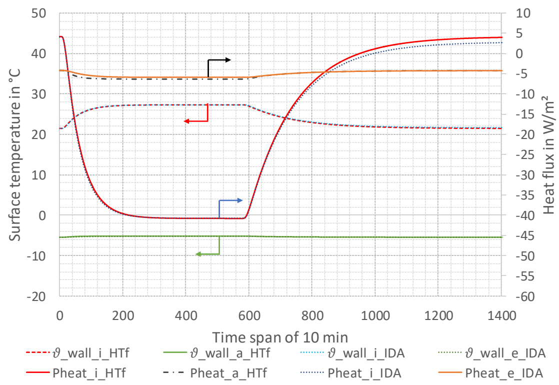

Figure 5: Validation of IDA ICE with HTflux for wall type variant I and concept A with a mean fluid temperature of 35 °C for heating purposes

With the applied HTC values in IDA ICE the heat flow or heat transfer rates shown in Table 6. The values are calculated with fixed room temperatures of 22 °C and ambient temperatures of -6 °C. This lower ambient temperature boundary was chosen as it is only rarely fallen short of over the whole heating period. Also, the design of the active layer in the façade and static simulations are based on this temperature difference.

Table 5: Calculated HTC values in W/(m².K) for the different concepts and pipe distances

System/concept	Pipe distance in cm				
	10	15	20	25	50
HCP_dir (A)	31.6	19.8	13.5	10.4	4.3
HCP_air (B)	11.5	9.4	8.0	6.6	3.1
AL_exposed (C)	8.1	5.0	3.6	2.8	1.2
AL_wrapped (D)	7.0	4.4	3.2	2.5	1.1

Parametric runs

Table 7 shows the matrix for the parameter runs which are carried out. Herein the wall type variants, the insulation, the supply temperature to the active layer and HTC values are varied. For the latter the concept and pipe distances are combined to the HTC value which are varied from 1 to 30 and can be compared with *Table* 5 which shows the representative concepts.

Table 6: Calculated heat flow to the room with the according HTC values in W/m²

System	Pipe distance in cm				
	10	15	20	25	50
HCP_dir (A)	61	57	52	49	34
HCP_air (B)	50	47	45	41	28
AL_exposed (C)	45	37	31	26	13
AL_wrapped (D)	43	34	28	24	12

To investigate the flexibility potential, additionally the heating setpoint is increased from 22 °C to 26 °C to show if a proper control strategy can meet the comfort criteria by utilizing the thermal masses. For the mass flow rate a specific heating capacity of 38 W/m² and a fluid temperature drop between inlet and outlet of 5 K is assumed for the active layer.

Table 7: Matrix for the parameter runs which are investigated in the result chapter

Wall type variant	Insulation thickness in cm	Concept	Pipe distance in cm	Supply temp. active layer in °C
Ferro-concrete (I)	10	HCP_dir (A)	10	30
Vertical coring brick (II)	15	HCP_air (B)	15	35
Solid brick (III)	20	AL_exposed (C)	20	40
Concrete (IV)	24	AL_wrapped (D)	25	45

ANALYSIS AND DISCUSSION OF THE RESULTS

This chapter tries to draw a consensus between the results of two different analytical approaches. First and foremost, the dynamic simulations of the defined sample rooms during a complete heating season from Oct. to April, and secondly a static heat flux analyses of isolated wall segments.

Dynamic seasonal simulations

All seasonal parameter runs are carried out based on the assumptions made in the abovementioned chapter. To investigate the systems behavior two KPI's are defined in advance.
The following conclusions and figures are based on these indicators.

- The minimal room temperature of all rooms, which must not undercut 20 °C

$$\vartheta_{min,tot} = \min(\vartheta_{NE}, \vartheta_{NW}, \vartheta_{SW}, \vartheta_{bath\&WC}, \vartheta_{Corr})$$

- Heating energy demand (HED) of all rooms

$$HED = \sum_{i=1}^{n} Q_{room,i}$$

Figure 6 to the left shows on the ordinate the minimal room temperature of all rooms $\vartheta_{min,tot}$ during the parameter run, whereby on the abscissa the HTC value implemented in IDA ICE is shown. The datapoints represent different wall type variants and different supply temperatures as well as the

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insulation thickness as the latter one has a high affect to the heat losses of the rooms. As the bathroom & WC cannot be heated properly a small radiator with 300 W is assumed parallel to the wall heating element. The right-hand side of Figure 6 shows the total heating energy demand of all rooms. For this first set of simulations a heating setpoint temperature of 22 °C was chosen for the PI-controller. The red horizontal line represents the comfort threshold for $\vartheta_{min,tot}$ at 20 °C. Obviously $\vartheta_{min,tot}$ is undercut often for the lower HTC values (e.g. HTC = 1 to HTC = 5), especially in combination with low insulation thicknesses (0.1 m to 0.15 m). However, using HTC of about 10 or higher leads to lower spreads amongst the data points for varying insulation thicknesses and wall type variants. Still, the lowest $\vartheta_{min,tot}$ is close to the threshold of 20 °C for the lower insulation thicknesses. The highest reached values for the room temperature are at about 21.5 °C even though the setpoint temperature is at 22 °C.

To answer whether these inconsistency origins from a lack of heating power or control deviation comes from, the same simulation runs are conducted with a setpoint of 26 °C. This can also show if there is some flexibility potential by using the high thermal mass of the wall. The results of these runs are demonstrated in igure 7. On the left-hand side $\vartheta_{min,tot}$ is shown and to the right the HED. Compared to Figure 6 it can be said that by increasing the heating setpoint temperature of the room the number of times $\vartheta_{min,tot}$ is undercut can be reduced for HTC values of 1 and 5 and can be eliminated for higher HTC values.

Three main conclusions can be drawn out of this comparison.

- A simple PI controller is not able to properly control a system of this type due to the high thermal masses involved and the resulting long latencies. Using a proper control strategy and utilizing the thermal masses can handle low heat transfer coefficients of the active layer in a certain range.
- Façade integrated heating systems with HTCs lower than 5 might not provide enough heat flow to meet comfort criteria during heating season. This however, is highly dependent on the underlaying setup.
- Higher achievable wall and room temperatures for well insulated, high HTC setups allow for more flexibility in operation as the thermal mass of the wall can be deployed as storage.

Comparing the HED in Figure 6 and Figure 7 reveals an increase for the 26 °C cases which is obvious as the room temperature is also higher compared to the standard case. More informative is a comparison of scenarios within the diagrams. As expected, the highest HED is obtained with the lowest insulation thickness of 0.1 m. Good improvements can be seen by using thicker insulation (0.15 m and 0.2 m) but

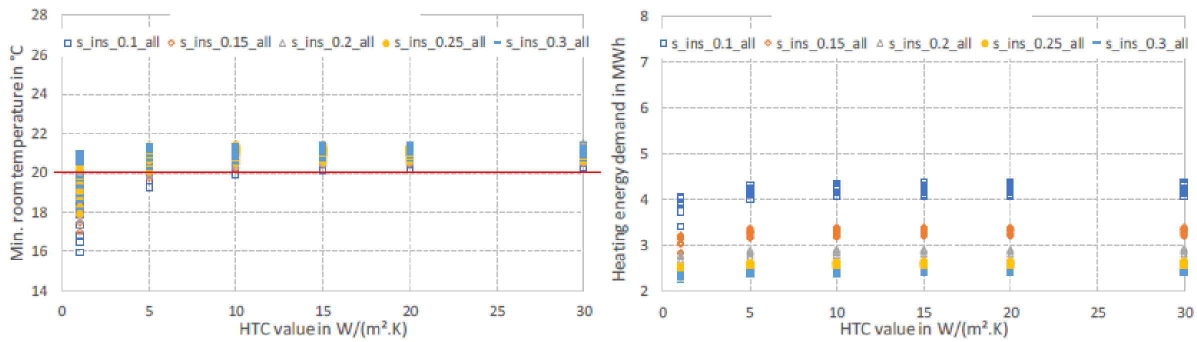

Figure 6: Analysis of the minimal room temperatures (left) and the heating energy demand of the floor (right) for all defined variants with a heating setpoint of 22 C

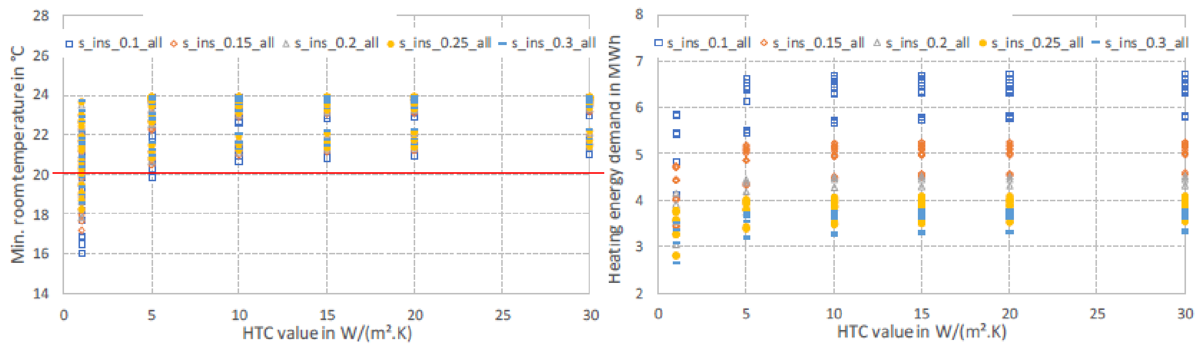

Figure 7: Analysis of the minimal room temperatures (left) and the heating energy demand of the floor (right) for all defined variants with a heating setpoint of 26 C

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with decreasing gains for more than 0.25 m. Most interestingly the HTC value has just minor impacts on energy demand except for values lower than HTC = 5. In these cases, the HED is restricted by the inability of the active layer to emit more heat and not by the actual heat demand of the rooms. These limits on heat transfer rate are quantified in the following static heat flow considerations.

Static heat transfer and design guidelines

In addition to the previously introduced dynamic simulations a static assessment of heat transfer rates is conducted. Static heat fluxes were calculated with IDA ICE to find corresponding maximum heat transfer rates (HTR) to all cases from the matrix for parameter runs in Table 7. Founded on this data a design diagram for multifunctional façades with active layer (similar to the existing design diagrams for floor heating) was created. Exemplary for the wall type variant (I) ferro-concrete such a novelty diagram is pictured in Figure . The aim of this diagram is to provide easy to use design guidelines for planers and architects. A sample application is marked in orange color in the diagram and contains of the following steps:

1. Select the desired heat transfer rate per m^2 of wall area draw a horizontal line from there.
2. Choose a design over-temperature for your heating system and find the intersection of this temperature curve with the horizontal line from before. From there draw a vertical line reaching to the lower part of the diagram crossing the horizontal axis. Physically a u-value for the inner part of the wall including the HTC of the active layer and the boundary layer is set here.
3. Find the intersection of the vertical line with the curve related to your planed insulation standard (choice between passive house (PH) standard demanding for a total wall u-value of 0.15 W/(m^2.K) or the OIB standard demanding for a total wall u-value of 0.35 W/(m^2.K)). From there draw a horizontal line to the left.
4. The intersection of the horizontal line with the lower vertical axis points to the HTC value which is the minimum required value for the system to work as intended. Based on this minimum value a suited system can be chosen e.g. from Table 5.

Discussion and conclusion

The dynamic as well as the static analysis show that the achievable heat transfer rates from the active layer to rooms on the inner side of the wall are sufficient for common heat loads. When using state-of-the-art thermal insulation (about 0.2 m) there are usually several system concepts available to meet comfort criteria. High insulation thicknesses over 0.10 m, while still having impact on the rooms heat load, do hardly have any effect on the possible heat transfer to the inside of the room (see the really close curves in the lower part of Figure).

Depending on the wall type variant, the use of very high HTC systems could be redundant as the thermal resistance of the wall might be the prevailing term of the equation. A very effective way in reducing the needed HTC value is choosing a higher fluid temperature which of course opposes the trend towards lower inlet temperatures. Once more this highlights the importance of fitting the facades to the heat generation systems and vice versa. Feeding the system with a low temperature producer e.g. a heat pump in combination with PV will call for a different active layer design as e.g. a solar thermal based concept.

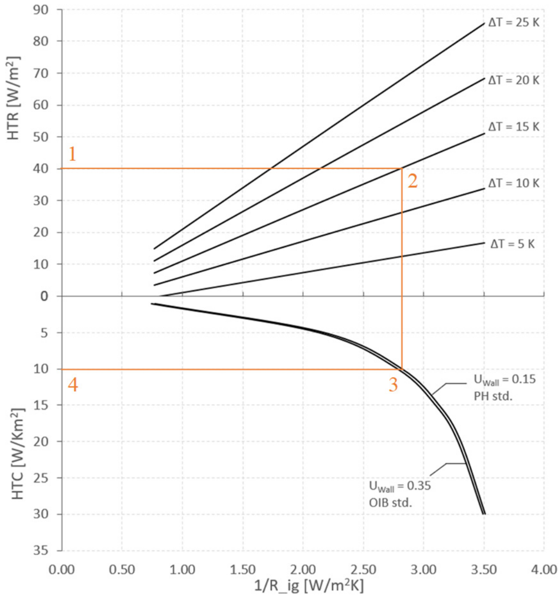

Figure 8 Design diagram for active layer façades on type variant (I) ferro-concrete walls

Based on the results of this research curtain façades with integrated active heating layers are a technology to be considered when retrofitting a building. With foresight to more and more volatile energy systems and a trend on using and storing energy on site, thermal energy storages will get more popular as well. Façade concepts like the ones discussed in this paper enable building structures to serve a double purpose as storages whilst having multiple advantages to standard building renovation.

Follow up research projects will be done on the topics of cooling with active layers and predictive controllers for this high latency application.

SUMMARY

This paper views active layer concepts in prefabricated façade elements which can be connected to standard existing buildings from the period 1960's to 1980's. The simulation software IDA ICE was verified to be a suited tool for system

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simulations of this type by crosschecking results with the high-resolution FEM software HTflux. With the exception of some scenarios (very low HTC, thin Insulation) the achieved heat transfer rates are suitable for common room heating demands. Depending on the possible control strategies these façade systems can also utilize the thermal mass of the wall for operational flexibility.

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