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Published in:
11th Nordic Symposium on Building Physics, NSB2017, 11-14 June 2017, Trondheim, Norway

DOI:
[10.1016/j.egypro.2017.09.628](https://doi.org/10.1016/j.egypro.2017.09.628)

Published: 01/01/2017

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Fadejev, J., Simson, R., Kurnitski, J., & Bomberg, M. (2017). Thermal mass and energy recovery utilization for peak load reduction. In S. Geving, & B. Time (Eds.), *11th Nordic Symposium on Building Physics, NSB2017, 11-14 June 2017, Trondheim, Norway* (pp. 39-44). (Energy procedia; Vol. 132). Elsevier.
<https://doi.org/10.1016/j.egypro.2017.09.628>

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11th Nordic Symposium on Building Physics, NSB2017, 11-14 June 2017, Trondheim, Norway

Thermal mass and energy recovery utilization for peak load reduction

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Abstract

Highly energy performing buildings need cost effective solutions which can deliver specified indoor climate and energy performance targets. In this study temperature variation of indoor climate category II according to EN 15251 standard is applied with the aim to allow free floating temperatures in this range to activate internal thermal mass of walls. Main hypotheses are that interior thermal mass of enough thick concrete layers can enable utilization of solar and internal gains resulting in significantly reduced peak loads for both heating and cooling, and reduced overall energy need. In this study, dynamic energy simulations are conducted to identify optimal solutions for a planned experimental building. Impact of energy recovery system on annual heating/cooling need and interior thermal mass on cooling design load are studied. Proposed energy recovery system consists of a piping layer installed into internal layer of a wall or floor structure and coupled with storage tank via piping and circulation pump. This system operates only when specified temperature differences exist that is expected to store excess room heat or cool within accepted indoor temperature range and to distribute it into other building zones. Modelling is performed in dynamic whole year simulation environment IDA-ICE, where a simplified two-zone model of a single-family house along with energy recovery system are modelled. Zones envelope and interior structures are modelled with finite difference wall/floor model accounting for thermal capacitances of structures material layers and exposure to solar radiation passing through detailed window model. Model of a piping layer connected to finite difference wall or floor structure computes heat transfer using logarithmic temperature difference. Rest of the energy utilization system is modelled using IDA-ICE standard model library components. Results reveal that interior thermal mass has significant impact on peak loads and energy need reductions. Modelled energy recovery system is capable of significantly reducing heating need as long as high system flow is maintained.

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Peer-review under responsibility of the organizing committee of the 11th Nordic Symposium on Building Physics.

Keywords: thermal mass; IDA-ICE; energy recovery; heating need reduction; cooling load reduction

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1. Introduction

As European Parliament directive 2010/31/EU [1] requires all new buildings built to comply with nearly zero energy building requirements (nZEB) by the end of 2020, cost effective solutions for reduction of heating and cooling need to maintain the indoor climate within EN 15251 standard [2] category II are needed. A known passive way to reduce building cooling demand and peak cooling load is to include additional thermal mass in the building structures [3]. The goal of this study was to assess the impact of conventional envelope structure thermal mass on annual cooling need and design cooling load of a single-family house in climate of Warsaw, Poland. Additionally, to utilize solar and internal gains and provide an excess heat/cold transport between zones of the building an energy recovery system can be applied [4]. Energy recovery system consists of a storage tank connected via piping and circulation pump to a piping layer installed into internal layer of a wall or floor structure. The second goal of this study was to model prior mentioned system and assess its performance.

Results of annual energy simulations applying two conventional wall structures with equivalent U-values and different thermal masses and their impact on annual cooling need and design load are presented. Performance of energy recovery system in heating and cooling need reduction are assessed with a parametric study and presented in graphical form, actual energy recovery system sizing is performed and proposals for system seasonal coefficient of performance (SCOP) improvements are conferred.

2. Methods

The modelling was performed in building climate and energy performance simulation environment IDA-ICE at advanced level interface, where user can manually edit connections between model components, edit and log model specific parameters, observe models code.

2.1. Numerical study description

To simplify the geometry of a single-family house, a two-zone model presented on Fig. 1 was generated based on principles of sizing the windows of the South façade to 60% of external wall that is facing South and North façade windows to 15% of North zone floor area. To comply with common design practices, an external shade with length of 1.8 m was added to South and applied in all simulated cases.

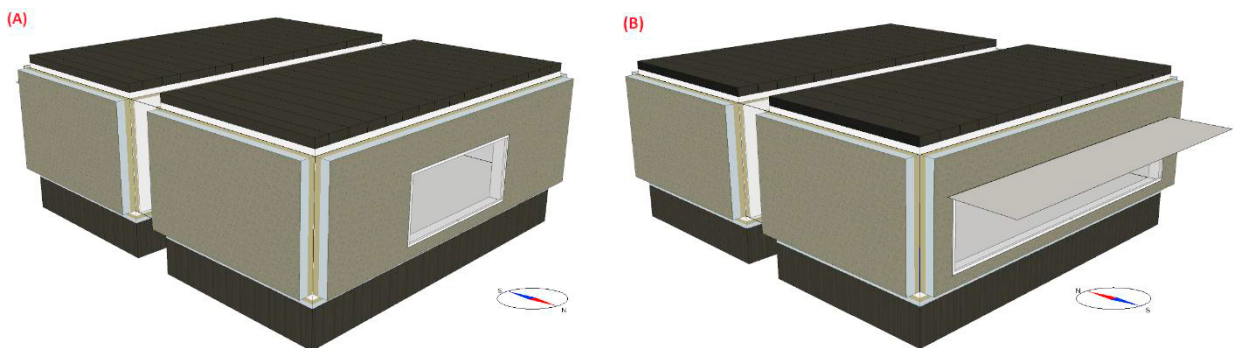


Fig. 1. (a) North-East façade of two-zone model; (b) South-West façade of two-zone model.

North and South zones lack connection between each other and interior wall in each zone is adiabatic. The reason for previous condition is to avoid the heat transfer between zones for more accurate reflectance of energy recovery system performance. Zone windows are oriented exactly facing North and South. The floor area of zones is equivalent and equal to 50 m² each. Ambient boundary conditions regarding local weather data were described in Warszawa-Okecie ASHRAE IWEC2 climate file [5] and applied in the simulation. Indoor air temperature setpoints correspond to indoor climate category II according to EN 15251 [2] standard i.e. heating setpoint 21 °C and cooling setpoint 25

°C. To ensure the prior mentioned setpoint values, ideal heater and ideal cooler were applied as room units in the modelled zones. More detailed description regarding two-zone model is presented in Table 1.

Table 1. Two-zone model descriptive parameters.

Descriptive parameter	Value
Location	Poland, Warsawa
Zones floor area, m ²	100 (50 each)
External walls area, m ²	97.1
Light wall structure, U = 0.15 W/(m ² K)	wooden frame with 270 mm mineral wool
Heavy wall structure, U = 0.15 W/(m ² K)	150 mm concrete with 230 mm of EPS foam
Roof area, insulated concrete U = 0.15 W/(m ² K), m ²	100
External floor area, insulated concrete U = 0.34 W/(m ² K) , m ²	100
Windows area, SHGC = 0.53, U = 1.127 W/(m ² K), m ²	22.9 (S=15.6, N=7.3)
Heating set point, °C	21
Cooling set point, °C	25
AHU operation schedule	24h/7d
Occupants, 1.2 met, 0.8 clo, no.	2
Equipment load, kW	0.24
AHU air flow, m ³ /s	0.242
AHU heat recovery, %	80
Supply air preheated to temperature, °C	18

Energy recovery system was modelled for floor and wall installation. The fundamental scheme of energy recovery system is presented on Fig. 2 (a) and detailed floor installation model on Fig. 2 (b). The soil, floor structure below piping layer and above piping layer are modelled with two-dimensional finite difference models. Initial temperature of floor slab and soil in finite difference models was set to 15 °C to imitate 3-4 year of building operation after construction.

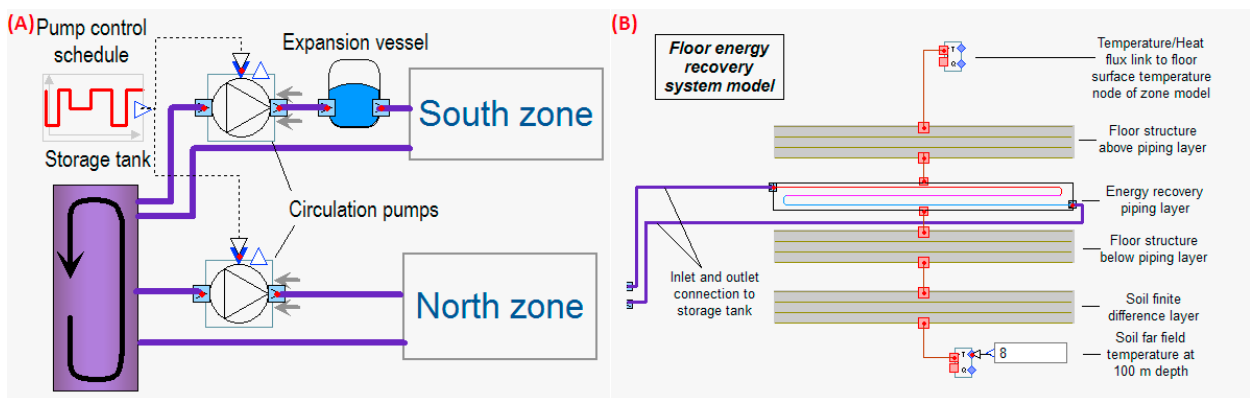


Fig. 2. (a) Energy recovery system model in IDA-ICE; (b) Floor connection of energy recovery system in IDA-ICE

Energy recovery system piping is modelled with a piping layer IDA-ICE model which performance is described with parameters – area and fluid-to-slab heat transfer coefficient that in this particular case was 20 W/m²K. Performance of the energy recovery system was assess based on the reduction or increase of ideal heater/cooler room units energy.

3. Results

According to results of two annual energy need simulations, application of an envelope structure with a heavier thermal mass resulted in a cooling need reduction of ca 16%, where in light structure envelope case cooling demand was 185 kWh/a and in heavy structure envelope case cooling demand was 156 kWh/a. Impact of envelope structure thermal mass on design cooling load is depicted on Fig. 3, where results of cooling design load simulations of two envelope structures having equivalent thermal conductivity $U=0.15 \text{ W/m}^2\text{K}$ and different thermal mass are presented.

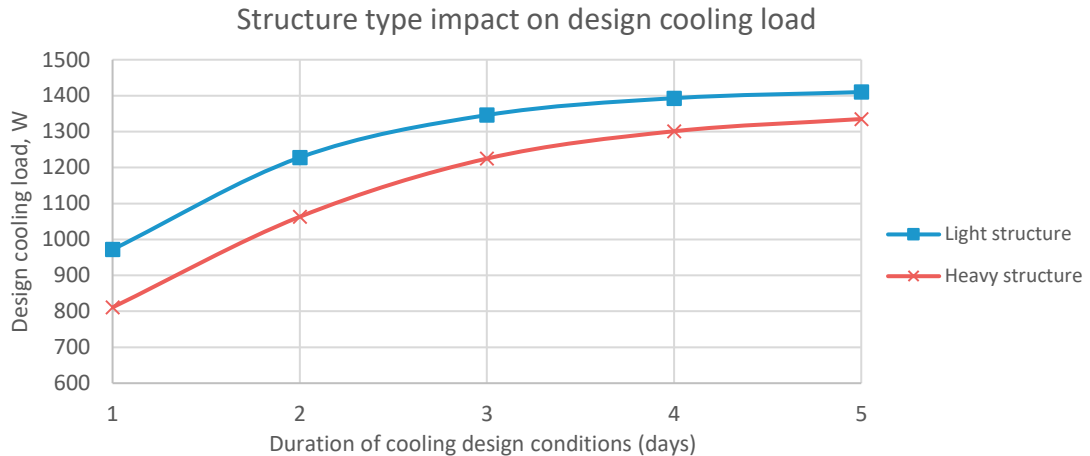


Fig. 3. Structure type impact on design cooling load

Heavy wall structure consisted of a concrete layer 150 mm thick with 230 mm of EPS foam insulation, light wall structure was a wooden frame wall insulated with 270 mm of mineral wool. When compared to light structure, thermal mass of heavy structure reduced the cooling load by ca 16% at first design day decreasing to ca 5% at fifth day in Warsaw cooling design conditions.

Energy recovery system installed at 50 mm depth of insulated concrete floor slab with constant annual flow of 1 kg/s (Case no 2 in Table 2) produced a reduction of annual heating need by ca 10% and increase of annual cooling need by ca 29% compared to the case without energy recovery system (Case no 1 in Table 2). Increase of cooling need can be explained by the constant operation of the system i.e. operation during both heating and cooling season. During the heating season energy recovery system benefits from the distribution of solar gains to zones with additional heating need, but during cooling period solar gains produce opposite effect. Increase in annual cooling need was further avoided by modifying operation schedule of energy recovery system to heating period only (Case no 3 in Table 2) that corresponds to September – May for two-zone model in Warsaw climate conditions. Heating period duration was obtained by observing monthly cooling energy demand of Case no 2. Circulation pumps energy and heat generation was not taken into an account in cases no 2 and 3 (Table 2).

Table 2. Operation schedule impact on performance of energy recovery system (floor installation, heavy structure)

Case no	Flow, kg/s	Heating need, kWh/a	Cooling need, kWh/a	Pumps energy, kWh/a	Operation schedule
1	0.0	3317	264	0	OFF
2	1.0	3006	340	Not accounted for	Always ON
3	1.0	3010	263	Not accounted for	Heating period (Sept-May)
4	2.1	2199	263	700	Heating period (Sept-May)

Impact of energy recovery system installed in floor slab with constant 1 kg/s flow on zones indoor air temperature is depicted on Fig. 4, where indoor air temperatures in North and South zones equipped with energy recovery systems

are compared to indoor air temperatures without the installation. Noticeable increase of indoor air temperature is well displayed in North zone on Fig. 4 (b), where South zone’s excess heat from solar gains is being efficiently utilized. Also, a cooling effect due to the temperature difference between South and North zones can be observed on Fig. 4 (a) in September - October period, where energy recovery system is reducing indoor air temperature in South zone and increasing it in North zone.

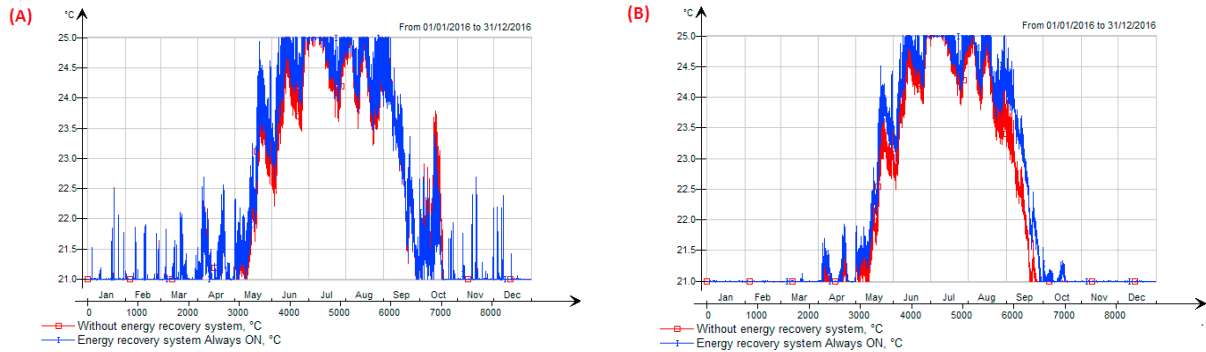


Fig. 4. (a) Indoor air temperature in South zone; (b) Indoor air temperature in North zone.

Performance of energy recovery system in reduction of heating need depending on the system flow are presented on Fig. 5 prepared based on the results of parametric study where variables were system flow 0...4 kg/s, installation type – floor installation 50 m² or external windowless wall installation 15 m², envelope structure type – light or heavy.

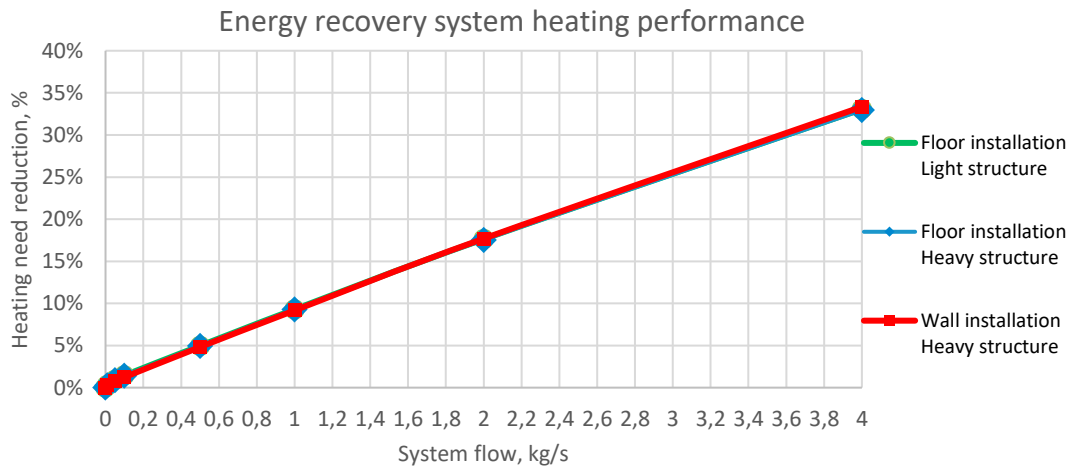


Fig. 5. Energy recovery system heating performance

As it can be observed on Fig. 5 heating need reduction potential is in linear correlation with system flow where a 33% reduction in heating need can be achieved for two-zone model with a system flow of 4 kg/s regardless the installation and envelope structure type. Last two mentioned parameters produced a minor impact on heating need reduction performance of the energy recovery system. Difference between floor and wall energy recovery system installations appeared in circulation fluid temperature where wall installation fluid temperature was slightly higher due to smaller installation area 15 m² compared to floor installation 50 m². Adding a 100 mm concrete layer above floor slab with the initial energy recovery system decreased the heating need reduction performance by ca 0.5% and reduced annual cooling demand by ca 2% due to thermal mass. Despite the high heating need reduction potential,

realization of system with flow above 1 kg/s in practice may become problematic due to high pressure drop of conventional distribution systems resulting in high pumping cost.

Sizing of the actual energy recovery system (Case no 4 in Table 2) installed in floor slabs of two-zone model to pressure drop of 15 kPa per zone using conventional distribution system such as PEX-a DN20 pipe resulted in 2,1 kg/s flow when piping is spaced at 300 mm with overall length of 150 m divided into ten separate loops connected in parallel via manifold. Circulation pump sized to 15 kPa with 2,1 kg/s flow would consume ca 60 W/h of electricity. Each zone should be equipped with a circulation pump resulting in pumps power of 120 W and expected annual energy consumption according to heating period schedule of 700 kWh/a, that is transferred to fluid as a heat during pumps operation. Annual heating need in simulated case with heat generation of circulation pumps was 2199 kWh/a which results in decrease of heating need by 1118 kWh/a i.e. ca 34% compared to case without energy recovery system. On the other hand, electricity consumption in case with heat generation of circulation pumps increased by 700 kWh/a due to pumps energy consumption. Final seasonal coefficient of performance (SCOP) equals to 1.6. Implementation of circulation pumps control strategies and reduction of system pressure drop may significantly reduce pumps energy consumption and increase SCOP.

4. Conclusion

Numerical study revealed that thermal mass can have significant impact on both annual cooling need and design cooling load reducing prior mentioned with addition of thermal mass to building structure. Comparison of two conventional envelope structure solutions showed that cooling need reduction of 16% and design cooling load reduction of 5% can be expected when switching from insulated wooden frame wall to insulated concrete wall structure with equivalent U-value of 0.15 W/m²K in climate of Warsaw, Poland.

According to results of energy recovery system parametric study both floor and wall installations in light or heavy structures can reduce heating need significantly by utilizing solar and internal gains and distributing them between zones as long as high system flow is maintained. Important finding was an increase in annual cooling need due to constant system operation where issue was solved by modifying system operation schedule to heating period only - September – May. Energy recovery system might also have cooling need reduction potential in case the right conditions exist – temperature difference between zones, which was only the case in period of September – October for this study.

Actually sized energy recovery system using conventional distribution components applied in radiant floor heating industry resulted in SCOP of 1.6 and demonstrated the need to reduce system pressure drop and implement pump demand-oriented control strategies to reduce circulation pumps energy consumption and improve overall system SCOP. This study will be continued with research of available low pressure drop distribution equipment solutions and implementation of different pump control strategies.

Acknowledgements

The research was supported by the Estonian Centre of Excellence in Zero Energy and Resource Efficient Smart Buildings and Districts, ZEBE, grant 2014-2020.4.01.15-0016 funded by the European Regional Development Fund and by the Estonian Research Council with Institutional research funding grant IUT1–15.

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