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Numerical and Experimental Validation of Low Exergy System for Heating and Cooling Of Residential Buildings

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Abstract*—This study presents the concept of a low-exergy thermal system with thermal barrier for indirect heating and cooling of a residential building. The main concept of this technology is based on the active layer with thermal barrier located inside of external wall that is reducing the transmission heat losses and gains through the building envelope by stabilizing the temperature in the thermal barrier at the level close to the indoor air temperature. With this approach the heat flux through the wall between the interior and the thermal barrier layer is reduced to a minimum value. The active layer technology is driven by the stored solar energy for heating in winter and cold soil for cooling of the building in summer. Application of the thermal barrier system with the soil heat storage has been studied numerically and experimentally on an existing residential building. On the basis of performed numerical simulations and the data obtained from the measurements the advantages and the effectiveness of the concept have been confirmed. This study provides valuable information on the application of the system and confirms its potential for zero-energy building requirements.

Index Terms*—Thermal barrier, Indirect heating and cooling, Renewable energy sources, Active layer.

I. INTRODUCTION

Buildings account for approx. 40 % of the total energy consumption in the European Union (EU), with the highest amount of the energy used for heating, cooling and ventilation. While the sector is still expanding, reduction of energy consumption and the use of renewable energy sources in the buildings sector seem to be the two most important measures to reduce the Union's energy dependency and greenhouse gas emissions. In order to allow the EU to comply with its own commitment to reduce overall greenhouse gas emissions and energy consumption by 20 %, and to increase the amount of renewable energy sources up to 20 % of total EU energy consumption by 2020, the Directive 2010/31/EU on the energy performance of buildings (EPBD) has been adopted [1].

The directive defines a 'nearly zero-energy building' which has a very high energy performance and the amount of energy required should be covered to a very significant extent by energy from renewable energy sources, including those produced on-site or nearby. According to the directive member states should ensure that by 31 December 2020 all new buildings will comply with this definition.

The directive is technically upgrading the well-known approach of passive buildings which is based on the method of reducing the heat losses in buildings by increasing the thermal resistance of building components, air tightness of the building envelope and a mechanical ventilation system with a waste heat recovery. However, as there are limitations in the further decrease of building heat losses only by the passive approach and considering that buildings still demand energy for heating, cooling and ventilation, the only effective way to overcome this problem is to utilize renewable energy.

Being the most attainable and renewable, solar energy seems to be the priority. However, there is one main issue that needs to be solved in exploiting this area, namely the availability of a solar energy supply and the heat demand of the building within every season. With other words, when there is a heat demand for a building, usually there is no or very little solar energy available and vice versa. For this reason most of the known approaches of the energy management in buildings are based on different technologies, using passive and active solar energy systems, including short-term and long-term heat storage systems, based on the large heat capacitance of building materials, ground and water, or on the latent heat of PCM materials. According to Chan et al. [2] both passive and active solar designs have several limitations, arising from system efficiency, architectural aesthetics and cost effectiveness. Although low-temperature heating systems are applied in these cases they have to be supported by heat pumps or additional heaters in order to increase operational temperature for a seasonal operation. According to different application studies seasonal heat storage systems were able to cover 40-50 % of the annual heat demand for domestic hot water and 10-20 % of the total yearly heat demand for space heating, as presented for a central solar heating plants of a low-temperature district heating system in Germany [3].

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At present, different research studies of the active heating and cooling techniques are mainly dealing with the problem of low efficiency due to seasonal temperature limitations and heat storage.

In this paper an active indirect heating and cooling system of a residential building is presented, which is based on the idea of the thermal barrier, located in the opaque external building elements, driven by solar energy stored in a low-temperature geothermal heat storage system, located below the building. The low-exergy concept of the system is based on maintaining the temperature in the semi-surface inside external walls and roof elements which is very close to the indoor air temperature. For this reason the system itself does not require any appliances to increase the temperature of the heat source, as already a very low temperature heat source (close to 20 °C) does efficiently reduce heat flow through the envelope. In this way the main problem presented above is to some extent avoided. The main objectives of the present study are to numerically and experimentally analyse the potential of the thermal barrier system with the soil heat storage applied on an existing residential building in Slovenia. On the basis of performed numerical simulations and the data obtained from the measurements the annual thermal performance of the system is presented in comparison to the reference situation without the implemented system.

II. THERMAL BARRIER SYSTEM AND REFERENCE BUILDING

The basic idea of the thermal barrier system is to use solar energy for heating and cold soil for cooling of the building. It is based on a technique of indirect heating and cooling which, instead of supplying energy into the internal air, supplies energy into the external building envelope by the circulating fluid. The main elements of the system are solar collectors, seasonal heat storage, which is located in the ground under the building, low-temperature soil heat exchanger for summer time cooling, hydraulic system with pumps and the thermal barrier (TB), composed of U-pipes. The TB is basically the active layer installed inside external walls, roof or attic, as shown in Fig. 1, forming a constant semi-surface temperature in the opaque elements of the building envelope. The fluid flowing inside the U-pipes supplies the energy into the TB during winter time and removes excessive heat during the summer time. In this way the heat flux normal to the outside wall and roof surface is stabilized and significantly reduced in magnitude throughout the year. A temperature of the TB semi-surface is controlled by the variable fluid mass flow rate and its supply temperature.

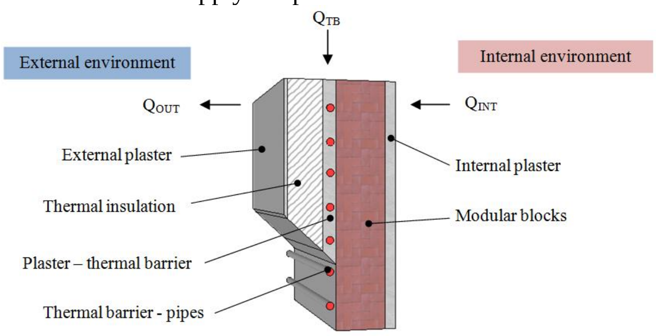

Fig 1. Concept of the thermal barrier located in external walls.

During the summer, solar energy from solar collectors is stored in the ground seasonal heat storage located underneath the building. The seasonal heat storage is divided into two zones, a medium temperature zone located near slab edges and a high temperature zone around the slab centre. Heat stored in the ground seasonal heat storage is then used in the thermal barrier for heating of the building in winter on the lowest needed temperature level. The ground floor of the building is well insulated in order to reduce heat gains from the storage through the ground floor, which may be problematic especially during the summer. In addition to this the ground under the facility is insulated also laterally, in order to reduce heat flux through the surrounding soil surface and to serve as an efficient storage for the supplied heat.

The performance of the TB is strongly dependent on its operating temperature, which is affected mainly by the circulating fluid temperature, flow rate, physical properties of pipes and active layer core structure material as well as the distance between the pipes. Ideally, the operating temperature of the TB during the heating period should be equal or very close to the indoor air temperature in order to reduce heat flux from the interior to the TB to zero. Temperature level of the seasonal heat storage is thus a crucial parameter for the efficient operation of the system and should be high enough during the entire heating season. By contrast, in the summer the operating temperature should be lower than the indoor air temperature in order to prevent heat gains through the building envelope and to compensate for the heat gains from the seasonal heat storage located underneath the building. The lowest recommended TB operating temperature of 16 °C is appropriate to prevent heat flux from the outside and even provides some reasonable cooling effect to the inside. The main source of the energy for the cooling is low-temperature soil heat exchanger located near the building. Apart from heating/cooling of walls, floors and ceilings, high efficiency pipe-in-pipe heat recovery system for mechanical ventilation of buildings is necessary to be used. The advantage of this system is that among the preheating effect produced in winter it works also as a cooling system in summer time. In principle, the technology should be covering all transmission heat losses through the external walls and roof if enough heat is produced by the solar collectors during the summer and stored into the seasonal heat storage. The transmission losses through the windows, ventilation and infiltration heat losses are covered with additional heat generator.

During the heating season the direction of the overall heat flux through the wall is from the internal air to the ambient air. The external heat flux (Q_{ext}) is therefore the sum of heat fluxes from the internal environment (Q_{int}) and from the thermal barrier (Q_{TB}) which is supplied by the fluid:

$$Q_{ext} = Q_{TB} + Q_{\mathrm{int}} \tag{1}$$

The value of the outer heat flux depends also on the overall heat transmittance U of the wall:

$$U = \frac{1}{\dfrac{1}{\alpha_i} + \sum_{k=1}^{n} \left(\dfrac{\delta}{\lambda}\right)_k + \dfrac{1}{\alpha_o}} \tag{2}$$

where are:

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λ - thermal conductivity of materials which are built in the wall structure [W/mK],

α – internal and external convective / radiative heat transfer coefficient [W/m^{2}K],

δ – thickness of material layer [m].

The higher the thermal conductivity and the smaller the thickness of the material layer in the external wall is, the higher is the heat flux from internal to the external environment and more stored solar heat is needed to be supplied into the thermal barrier by the fluid. For this reason the active layer should be covered to the exterior by sufficiently thick layer of insulation as seen in Fig. 1. During the cooling season the direction of the overall heat flux through the wall is from both sides of the wall towards the thermal barrier, as the temperature of the active layer is lower than the internal and the ambient air temperatures. Thus, heat removed by the circulating fluid is therefore the sum of the external heat flux and the heat flux from the internal environment:

$$\dot{Q}_{TB} = \dot{Q}_{ext} + \dot{Q}_{\text{int}} \tag{3}$$

Application study of the presented thermal barrier technology was based on a reference building, designed as a residential detached house incorporating the thermal barrier system. The house constructed in 2010 is located at latitude 46.0° N and longitude 15.4° E approximately 70 km southeast from Ljubljana, Slovenia. It is made of prefabricated wooden elements and has no basement. A total living area of the house is 195 m^2, while the total volume of the house, which is generally occupied by four people, is 528 m^3. The thicknesses of the thermal insulation layers are 300 mm on the roof and ceiling, 250 mm in the external walls and 200 mm on the floor slab. The total window area is 29.3 m^2, of which 62 % are west and south facing, while the total area of external walls, roof and ceiling is 327.1 m^2, representing approx. 69 % of the total building envelope. Due to appropriate architecture design useful passive solar heat gains are expected in winter time. The plastic frame windows with low emissivity glazing with a g-value of 0.51 have an average heat transfer coefficient of 1.09 W/m^{2}K and the building average U value is 0.22 W/m^{2}K.

The building is designed with a thermal barrier system, incorporating solar collectors, seasonal heat storage, low-temperature soil heat exchanger, hydraulic system with pumps and the thermal barrier. Solar energy is collected throughout the year with solar collectors installed on the roof and stored in the seasonal heat storage located under the building. During the winter, the heat from the heat storage is used in the thermal barrier as a source of heat for heating of the building.

In the external walls, roof and ceiling approximately 1700 meters of pipes (Pex-b/Al/Pex-b) with internal diameter of 18 mm and wall thickness of 1 mm are installed, forming a semi-surface temperature barrier. Pipes are installed with the distance of 200 mm between them and submerged into a 35 mm thick single-surface layer of plaster in order to enhance heat transfer and to achieve more uniform temperature distribution along the active layer. Two pumps for fluid circulation from the seasonal heat storage to the active layer and for domestic hot water heat storage are used. Fluid circulation is provided by a special pump E6. Heat is extracted from the seasonal heat storage with 800 meter long loop of pipes, while the same length of pipes is used to extract cold from the cold soil heat exchanger. The total fluid volume of the system is 860 litres and is filled by water – glycol (polypropilen) mixture. The size of underground heat storage for domestic hot water is approximately 50 m^3. The operating temperature of the active layer is controlled and set between +16 °C and +20 °C and is a function of internal gains and external air temperature. Mechanical ventilation of the building is provided by the high efficiency pipe-in-pipe heat recovery system with the energy efficiency over 80 %. Total length of the pipe for heat recovery is 100 meters. Internal and external pipe diameter is 180 and 250 mm, respctively. Total length of ventilation ducts in the house with diameter of 75 mm is 235 meters, Ventilation is provided by the supply and exhaust fans with maximum air flow rate of 450 m^3/h, while the seasonal average constant daily air flow rate was 160 m^3/h, corresponding to the air change rate of 0.3 h^{-1}. Additional heat required to compensate for ventilation and infiltration heat losses as well as for domestic hot water is covered by a ground source heat pump, using heat from the low-temperature soil heat exchanger.

III. MEASUREMENTS

Regulation, control and monitoring of the thermal barrier system of the reference building are performed by a control unit that allows continuous monitoring of the operation and optimization of the control processes. In addition to control functions a controller performs data logging of over 50 individual variables of system performance, such as temperatures of the circulating fluid, solar collectors, thermal barrier, seasonal heat storage, indoor air, ambient air, fresh supply air, low-temperature soil heat exchanger, solar irradiation, mass flow rate of the circulating fluid and others. In the present study only winter operation of the TB system was analysed and the main parameter considered and obtained from the measured data was the temperature of the seasonal heat storage, which directly represents the seasonal circulating fluid temperature. According to different studies [4,5] the problem of a temperature distribution in the ground is rather complex, and even more so when the heat is supplied seasonally to the ground. As there are obviously certain limitations of the accuracy of the simulation data on the distribution and heat losses of the ground seasonal heat storage, because the losses mainly depend on the structure and moisture of the soil, which is time-dependent, the performed simulations in this study were based on the measured temperature data of the ground. For this reason the available realistic data of the seasonal heat storage temperature were used to numerically analyse the seasonal performance of the TB system.

IV. NUMERICAL SIMULATIONS

A. TRNSYS model

The thermal performance of the TB system of the reference building was numerically investigated under the transient ambient climate and interior operating conditions, representing realistic behavior and response characteristics of the active layer and its influence on the overall heat balance of the building.

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In general, due to differences in composition, used materials and structures of the analyzed building elements, these elements may significantly differ in thermal characteristics and their dynamic thermal behavior. Taking into account also relatively higher complexity of multi-layer building elements with the active thermal layer inside and the influence of the realistic transient environmental conditions on both sides, such as solar irradiation, daily outside air temperature variations or internal heat gains, transient numerical simulation seems to be the most appropriate way to analyze the thermal performance of TB system. Light-weight building construction with relatively low heat capacity used in the present study was supplemented by the integrated fluid system which may be interpreted, while in operation, as a massive layer with an unlimited heat capacity. In this way the temperature stability was reached which strongly influenced the transmission losses and gains through the building envelope. Thermal barrier consisted of pipes with internal and external diameter of 18 and 20 mm, respectively, made from Pex-b/Al/Pex-b material with thermal conductivity of 0.43 W/mK. In simulations four different distances between the pipes were studied, namely 100, 150, 200 and 250 mm, while they were submerged into a 35 mm thick single-surface layer of plaster in order to enhance heat transfer and to achieve more uniform temperature distribution along the TB layer. A maximum length of a single pipe loop was limited to 100 m in order to achieve reasonable temperature drop of water-glycol mixture operating fluid. While in operation, volume flow rate in a single pipe loop was limited to 2 l/min, corresponding to the total mass flow rates from 1960 to 4900 kg/h at the pipe distances of 100 and 250 mm, respectively. In the present study the TB system was operating only during the heating season. Different constant seasonal inlet temperature of fluid mixture was studied in the range of 20°C to 17 °C and compared to the realistic measured seasonal temperature profile obtained from the reference building. In this way the direct comparison of the TB temperature significance was possible to be performed. The thermal performance of applied TB was numerically investigated by the transient TRNSYS [6] model, briefly presented below. In order to reach realistic results, the available climate data of Typical Meteorological Year (TMY2) for Ljubljana, SI, were chosen, containing the average hourly data. The performance of TB was assessed on the reference case of the same building without the TB system under the same conditions. In this way direct verification of the model and comparison of the required heating demand was performed. The developed numerical model consists of different TRNSYS generic modules for control of specific boundary and operating conditions to simulate the thermal behavior of a described building. As the main focus of the analysis was to determine the performance of the active TB system in comparison to the same building without TB, integrated model for thermo-active building elements was used and coupled with the building model. The present model was simplified as the annual inlet temperature of the TB operating fluid was simulated by the temperature forcing function, while the thermal response characteristics of the solar collectors and seasonal heat storage system were not considered.

A heat transfer through the thermo-active TB system was assumed to be a 3D heat transfer problem, with a 2D temperature field developed in the plane of a cross-section of the element and the operating fluid temperature drop along the pipe loops. Therefore the transient heat transfer in the active layer was solved by the following equation:

$$c_p \rho \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \qquad (4)$$

where c_p is the specific heat [kJ/kgK], ρ the density of the wall layer [kg/m^3], T the temperature [°C] and t the time [s]. Eq. 8 was completed with boundary conditions on internal and external surfaces of active building elements, considering heat exchange by convection and radiation. While convective heat transfer coefficient for internal surfaces was considered to be a constant standard value, h_i = 7.7 W/m^{2}K, external convective heat coefficient h_e was influenced by the wind and therefore defined by empirical expression [7]:

$$h_e(t) = \max\left(5, \frac{8.6 v(t)^{0.6}}{l^{0.4}} \right) \qquad (5)$$

where $v(t)$ is the wind speed [m/s] and l the cubic root of the building volume [m]. Radiation heat exchange was on both sides considered by the short-wave radiation heat flux absorbed on the surface (solar gains) and the long-wave radiation heat transfer with all the surfaces in view. Solar absorptance of external wall and roof surfaces was set to 0.75.

Heat transfer between the operating fluid and the TB plaster material was defined by the process of convection from the fluid to the pipe shell and the process of thermal conductance through the pipe shell. For this purpose a fully developed flow of an incompressible fluid was considered, neglecting variations of fluid mixture mechanical properties with a temperature variation. In this way the energy equation for the fluid was simplified to:

$$\frac{\partial T}{\partial t} + u_x \frac{\partial T}{\partial x} + u_y \frac{\partial T}{\partial y} + u_z \frac{\partial T}{\partial z} = \frac{\lambda}{\rho c_p} \nabla^2 T \qquad (6)$$

Assuming the fluid flow to be 1D along the x-axis with velocity u, eq. (6) was numerically resolved for a single pipe loop considering the supply fluid temperature $T_{TB,in}$ and taking into account appropriate correlations for heat transfer coefficient in case of laminar and turbulent flows.

B. Numerical micro model of the thermal barrier

Due to some distinctive limitations of the presented TRNSYS model in terms of heat transfer and temperature distribution analysis over the cross-section of the active layer it was necessary to use more advanced numerical method in order to further investigate the thermal barrier. For this reason a commercial CFD package ANSYS Fluent v14.5 was used to generate the detailed 2D numerical model with the accurate representation of the wall TB layer pipes geometry. This model was developed and applied to simulate heat transfer characteristics over the wall layers and for the purpose of optimization of the distance between the pipes in the TB layer and for the comparison of the results obtained from the macro TRNSYS model. Using a finite volume method on the cross-section of the wall (Fig 2) a parametric study of the influence of various distances between the pipes for different TB fluid temperatures was made.

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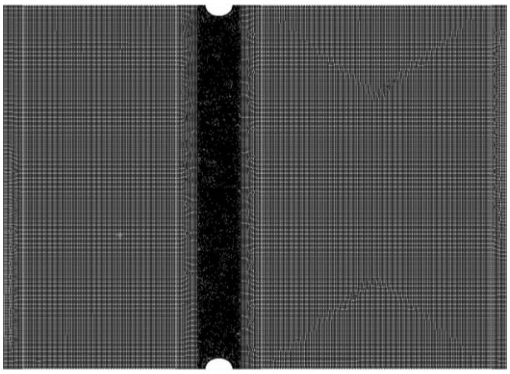

Fig 2. Numerical mesh of the micro model.

V. RESULTS AND DISCUSSION

A. Heat storage

The thermal behaviour of the reference building seasonal heat storage was characterised by the measured temperature data throughout the year 2012. According to the data the TB system was operating throughout the whole year and was in the heating mode operation during 183 days, from Jan 1st to Apr 27th and from Oct 28th to Dec 31st, serving as a representative pattern of heat demand. The annual variation of the measured seasonal heat storage temperature is given in Fig. 3, together with the annual variation of the ambient temperature. The highest seasonal heat storage temperature of 31.2 °C was measured on the Aug 25th, while the lowest temperature of 12.8 °C occurred on the Feb 10th. Average temperature during the heating mode operation was 18.4 °C. According to the available data the seasonal regeneration rate of the heat storage was positive as the temperature at the end of the year was 1.5 °C higher than at the beginning of the year. Obtained seasonal temperature profile was used as a one of the main input parameters for the numerical simulation of TB system performance.

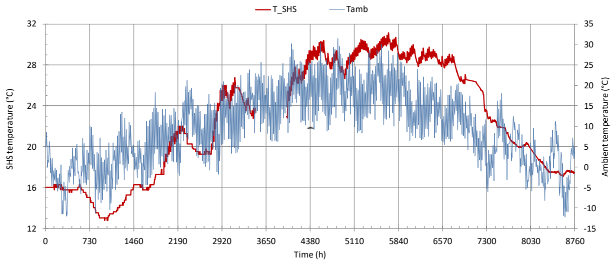

Fig 3. The annual variation of the measured seasonal heat storage temperature and the ambient temperature.

B. Numerical results of TB performance

The main objective of performed numerical simulations on the thermal behavior of the residential building was to determine the annual thermal performance and temperature stability of the TB system, implemented on a reference building. Additionally, effects of the inlet temperature and the distance between the pipes were investigated at the same maximum pipe loop fluid flow rate of 2 l/s. In all analyzed cases the TB system was set to the heating mode operation between the Sep 15th and Apr 21st, however heat from the operating fluid has not been supplied constantly to the external building elements but only when this was necessary. Therefore the actual operation time of the TB was different in analyzed cases, but the differences were not substantial as seen from Table 1.

Table 1. The annual simulation results of TB system operation.

Case	*Pipe distance [mm]*	*$T_{TB,in}$ [°C]*	*T_{TB} [°C]*	**TB operation [h]**	$\dot{m}_{tot}$ **[kg/h]**	*Q_{TB}* **[kWh/a]**	*Q_h* **[kWh/a]**	*q_h* **[kWh/m²a]**	*Difference* **[%]**
Ref.	-	-	-	-	-	-	4147	21.2	0.0
Ref. TB	200	18.4	18.1	3854	2450	2865	2030	10.4	-51.1
1	100	20.0	19.9	4266	4900	4707	821	4.2	-80.2
2	150	20.0	19.7	4346	3267	4469	903	4.6	-78.2
3	200	20.0	19.5	4376	2450	4265	979	5.0	-76.4
4	250	20.0	19.3	4384	1960	4048	1063	5.4	-75.0
5	100	19.0	18.9	4118	4900	3942	1180	6.0	-71.5
6	100	18.0	17.9	3920	4900	3175	1596	8.2	-61.5
7	100	17.0	16.9	3645	4900	2425	2057	10.5	-50.4

Verification of the TRNSYS model was performed for the studied residential building with the inactive TB system by the results of the heat load calculations made with a Passive House Planning Package (PHPP software) [8]. According to the benchmark heat load calculations specific energy required for heating was 20.5 kWh/m²a, while the applied hourly simulation method performed by TRNSYS resulted in 21.2 kWh/m²a. Based on this comparison the simulation approach was confirmed to be appropriate.

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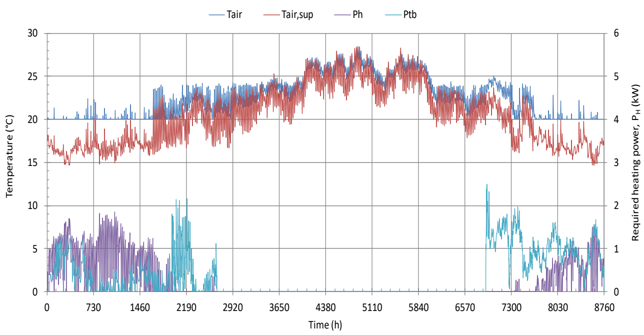

Fig 4. The annual variation of interior and supply air temperatures, the additional heating demand P_h and the total TB heating power output P_{TB} for the reference building.

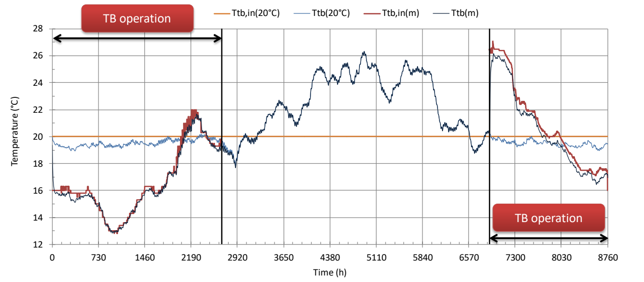

Fig 5: The annual variation of TB temperature stability comparison.

The annual simulation results, incorporating realistic temperature profile of the seasonal heat storage, have shown that the TB system installed in a reference building was able to decrease the total energy required for heating by as much as 51.1% to 2029.7 kWh/a, or 10.4 kWh/m^{2}a (Case Ref. TB, Table 1), which is in terms of energy use lower than the passive house requirement (15 kWh/m^{2}a). This means more than half of the total energy for heating was provided by solar energy and the rest by the heat pump. Average seasonal TB temperature was in this case 18.1 °C. Obviously, temperature stability of heat storage is crucial in terms of improving efficiency of the system. This can be seen when comparing present results with the simulated conditions of the assumed ideal constant inlet temperature $T_{TB,in}$ = 20.0 °C (Case 3, Table 1) throughout the heating period, where due to temperature stability average seasonal TB temperature was as high as 19.5 °C and the total energy required for heating decreased by as much as 76.4% to 979.0 kWh/a, or 5.0 kWh/m^{2}a. However, as seen from the seasonal temperature profiles in Fig. 5 TB under the measured conditions operated with the highest efficiency in autumn, while afterwards it was progressively falling with the seasonal heat storage temperature decreasing.

According to the results of different inlet temperatures of the TB circulating fluid, TB temperature plays a significant role in terms of reducing the required energy for heating and the amount of energy provided by the TB (Fig. 6). Thus, in case of inlet temperature of 17 °C the heat provided by TB was on the same level as the reference TB case, able to cover approx 50 % of the total required heat, while at 20 °C the heat provided by TB was almost two times higher and was covering approx. 80% of the required heat.

Another important finding of the present study is also the influence of the pipe distance on the overall performance. In terms of TB temperature deviation, defined as the maximum temperature difference between the inlet $T_{TB,in}$ and instantaneous temperature T_{TB}, annual average data are confirming the significance of the pipe distance. While the average annual TB deviation with the smallest simulated pipe distance was only 0.1 °C (0.3 °C max instantaneous value), this was 0.7 °C (1.4 °C max) at 250 mm distance between pipes (Fig. 7). On the other hand, smaller distance between the pipes does not provide proportionally higher energy through the TB layer in comparison to the higher fluid mass flow rate. While the fluid flow rate at 100 mm was 2.5 times higher than at 250 mm, the total TB heat was only 16 % higher (Table 1). This may be explained by the fact that the TB layer is on both sides well insulated and the heat flux is therefore limited, which in case of smaller distance results in higher TB temperature stability or, with other words, more uniform temperature distribution across the active layer and smaller TB temperature deviation, e.g. temperature difference between the operating fluid and the TB layer.

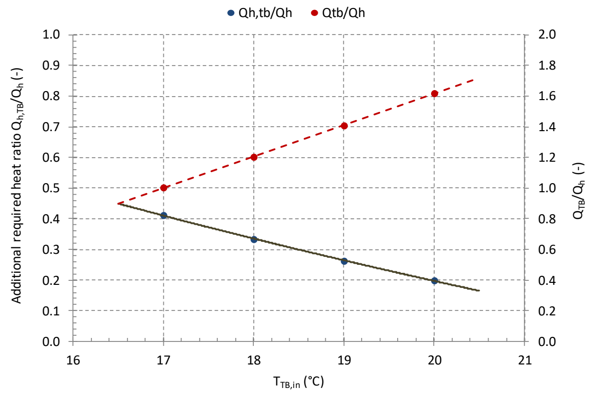

Fig 6. The effect of the TB fluid inlet temperature and the distance between pipes

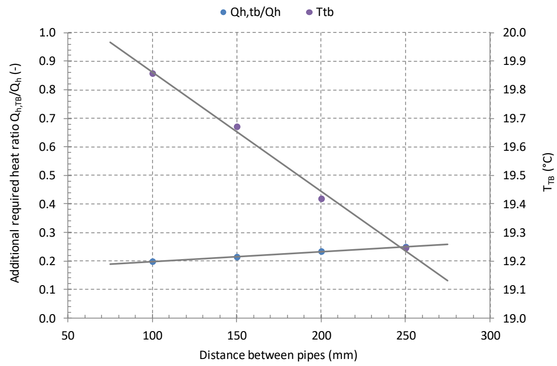

Fig 7. The effect of the TB fluid inlet temperature on the TB system performance

C. Numerical results of micro model

Results of performed numerical simulations on the micro model have confirmed a significant influence of the thermal barrier fluid inlet temperature as well as the distance between the pipes on the overall heat transfer through the wall section, as shown in Table 2.

Table 2. Results of the micro model.

Case	Pipe distance [mm]	$T_{TB,in}$ [°C]	Heat Flux, intern. wall [W/m^2]	Difference [%]
Ref	-	-	2.899	0.0
1	50	20.0	0.092	96.8
2	50	19.0	0.439	84.9

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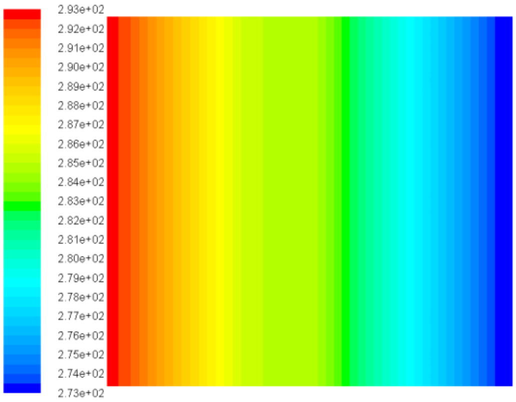
3	50	18.0	0.786	72.9
4	50	17.0	1.133	60.9
5	100	20.0	0.227	92.2
6	100	19.0	0.558	80.8
7	100	18.0	0.888	69.4
8	100	17.0	1.219	58.0
9	150	20.0	0.373	87.1
10	150	19.0	0.686	76.3
11	150	18.0	0.999	65.6
12	150	17.0	1.312	54.8
13	200	20.0	0.524	81.9
14	200	19.0	0.818	71.8
15	200	18.0	1.113	61.6
16	200	17.0	1.407	51.5
17	250	20.0	0.675	76.7
18	250	19.0	0.951	67.2
19	250	18.0	1.226	57.7
20	250	17.0	1.502	48.2
21	300	20.0	0.821	71.7
22	300	19.0	1.079	62.8
23	300	18.0	1.336	53.9
24	300	17.0	1.594	45.0

Although the pipe distance is very crucial parameter as well, it does not have as high influence on the total heat flux deviation since it affects the total heat flux by 16 % in case of the lowest TB temperature to 25 % in case of the highest TB temperature. According to performed simulations the temperature distribution in the wall cross-section is very much affected by the active thermal barrier layer, as can be seen from Fig 8.

a)



b)

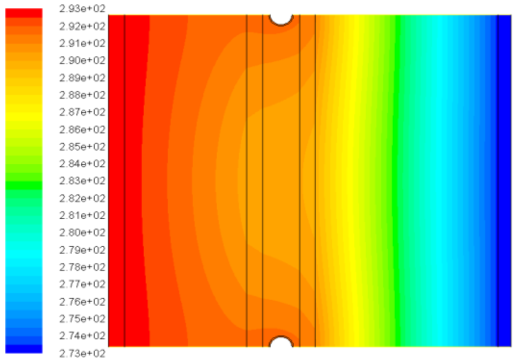


Fig 8. Temperature distribution over the wall cross-section for: (a) reference case without TB; (b) case 21 (20 °C, 300 mm). Temperature scale is in [K].

VI. CONCLUSION

This study provides valuable information and confirms the real potential and effectiveness of the presented thermal barrier technology. The annual simulation results of the reference residential building with the implemented TB, incorporating realistic temperature profile of the seasonal heat storage, have shown that the active indirect heating system was able to reduce heating demand of the house by more than a half. Furthermore, simulation results of ideal operating conditions with assumed seasonally constant TB fluid inlet temperature have shown that the system is able to reduce heating demands by three to four times in comparison to the reference building without the system, depending on the TB temperature. According to the present findings the TB technology is energy sustainable system, not only from the point of view of renewable energy sources usage, but also from thermodynamic point of view using the lowest temperature difference, which brings greater energy efficiency than conventional systems. This basically means that a TB technology implementation in the low-energy residential buildings is able to easily achieve the passive house requirements in terms of annual heat demand for heating and ventilation or, in case of buildings meeting the passive house requirements, it is capable to decrease the total annual heat demand almost to zero. This confirms potential of the technology to comply with a 'nearly zero-energy building' requirements introduced by the Directive on energy performance of buildings (EPBD).

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