Optimal rammed earth wall thickness for a single-family house in Serbia

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ABSTRACT: Sustainability and energy efficiency have become important factors in modern architecture, with additional momentum generated by the revised European Building Performance Directive 2010/31/EU, which set the goal that all buildings in European Union constructed after 2020 have to be nearly zero energy buildings. The sustainability of rammed earth walls is unquestionable, however, their large U-value implies that they have to be combined with external insulation in climates with cold winters, as is the case in Serbia. The aim is to study, through building energy performance simulations in Energyplus, to what extent a combination of rammed earth walls and external insulation may accomplish the goal for a single-family house in Serbian city of Belgrade to become a nearly zero energy building, provided the house is equipped with properly shaded, high performance windows, and highly insulated floor slab and roof.

1 INTRODUCTION

Increased demand for sustainability in architecture renewed interest in traditional building methods which use locally available resources. Building with earth is one such method, present in different forms throughout the world since ancient times. Earthen architecture in Serbia mostly used adobe bricks, followed by wattle and daub technique, while rammed earth technique, widespread in arid and semi-arid climates, has been present in Vojvodina region in the Pannonian plane (Kojić 1949; Đekić 1994). However, with the establishment of brick factories in Serbia, and especially after the World War II, the practice of earthen building gave way to building with baked bricks and concrete, due to their better structural characteristics and ability to build taller structures.

An important characteristic that was neglected at the time is earth’s much higher ability to control humidity by reducing the amplitude of relative humidity fluctuations inside the building and the frequency of high humidity periods at the wall surface (Allinson & Hall 2010), thus managing to maintain relative humidity levels within the range of 40-60%, deemed as most comfortable for humans. Combined with earth’s high thermal inertia, which enables it to store and reradiate heat, this often results in more satisfactory indoor thermal comfort.

Energy efficiency is another important factor in modern architecture, emphasized by the influence that the consumption of energy from nonrenewable sources within buildings has on climate change, and put forward by current legislation, especially in regions with cold winters. For example, the most recent Serbian regulations on energy efficiency in buildings (Government of the Republic of Serbia 2011) prescribe that external walls in new buildings may have the maximal U-value of 0.40 Wm$^{-2}$K$^{-1}$. Having in mind that rammed earth has a low resistance to heat transfer, with a dry conductivity in the range of 0.8-1.0 Wm$^{-1}$K$^{-1}$ (Hall 2008), meeting this limit with rammed earth only would result in unacceptably thick walls. Hence, rammed earth walls in Serbia should be coupled with thermal insulation in order to attain higher thermal resistance. Fix (2009) recommends the use of external insulation in combination with rammed earth in cold climates, as it completely protects rammed earth from freezing during winter, and thus from spalling damage, while it leaves unhindered contact with the indoor air, facilitating the use of rammed earth’s thermal mass and humidity control.

Even further, the revised European Building Performance Directive 2010/31/EU (European Parliament 2010) sets the goal for all buildings in European Union constructed after 2020 to be nearly zero energy buildings. This means that the building will have very high energy performance, determined on the basis of actual or predicted energy consumption
for its typical use, which includes energy for space heating and cooling and sanitary water heating, while the nearly zero or small amount of energy needed should be, in largest part, produced from renewable energy sources at the building site or in its vicinity.

Our goal here is to study to what extent a combination of rammed earth walls and external insulation may be used to accomplish the goal of a nearly zero energy building, through simulations of building energy performance in Energyplus, for a case study of a single-family house in Serbian city of Belgrade, provided the house is equipped with properly shaded, high performance windows and highly insulated floor slab and roof.

The plan of the paper is as follows. In Section 2 we briefly analyze the climate of Belgrade, while in Section 3 we present the structure and characteristics of the case study house. The simulation results for the different combinations of thicknesses of external insulation and rammed earth are discussed in Section 4, while establishment of net zero energy goal is discussed in Section 5.

2 CLIMATE DATA ANALYSIS

Representative Belgrade weather data are analyzed from the aspect of temperatures, wind and solar radiation.

Figure 1 shows the distribution of average and absolute minimal and maximal monthly temperatures in Belgrade. The highest average maximal monthly temperatures are 27.3°C in July and August, while the lowest average minimal monthly temperature is -2.3°C in January. The distribution of monthly temperatures reflects the high demand of heating for buildings in Belgrade, and the low demand of cooling for buildings with no large amounts of internal heat gains.

There are two dominant wind directions in Belgrade: north-west and south-east. The north-west wind from Atlantic mostly blows in late spring and early summer and has smaller speeds, while the south-east wind, so-called košava, is turbulent in nature and blows at its fullest in February and March, when the gusts may reach 18 m/s, indicating the need for wind protection from the south-east. However, about 93% of wind in Belgrade ranges in speed from 1 m/s to 5 m/s.

Figure 2 shows the distribution of average monthly global solar radiation on horizontal surface in Belgrade is 1396 kWh/m2 with approximately 2025 hours of sunshine. The amount of solar radiation is generally high throughout March-September and is indicative of the possibility to use solar energy both for sanitary water heating and electricity production.

3 CASE STUDY HOUSE

The single-story house under considerations is designed for a four-person family. It has gross area of 83 m², featuring an open plan for the living, dining and kitchen area in the southern part of the house, and two bedrooms and a bathroom in the northern part. An option exists to further expand the common areas with an office/studio in the loft above the bedrooms. The house floor plan is shown in Figure 3.

We have already seen that the rammed earth walls have to be externally insulated in order to meet regulatory demand for U-value of at most 0.40 Wm⁻²K⁻¹, while still providing thermal mass and indoor humidity control. The expanded polystyrene (EPS) is chosen as insulating material for walls in this research, due to its small price and prevalence in Serbia. If sustainability would be the main priority, then the natural fiber or cellulose insulation have to be considered instead of EPS, however we have to note
that these materials are not presently available in Serbian market. The external walls consist of 20 mm rendering on the outside, EPS ranging in thickness from 10 cm to 20 cm, stabilized rammed earth (SRE) ranging in thickness from 30 cm to 50 cm, and 13 mm dense plaster on the inside. In order to prevent capillary rise of water from soil, the stabilized rammed earth walls are erected on a concrete foundation with a 25 cm base exposed above ground level, and a bituminous painted layer on top of the base.

The internal walls consist of 30 cm thick stabilized rammed earth, covered with 13 mm dense plaster on both sides.

4 ENERGY PERFORMANCE SIMULATIONS

The house was modeled in Energyplus as a single zone with an infiltration rate of 0.7 ach. Stabilized rammed earth walls are supposed to contain 40% sands. Twelve different external walls types have been simulated. Their structure, exclusive of 20 mm external rendering and 13 mm internal dense plaster, is given in Table 1.

Table 1. Structure of simulated rammed earth walls.

<table>
<thead>
<tr>
<th>Wall</th>
<th>EPS thickness cm</th>
<th>SRE thickness cm</th>
<th>U-value Wm⁻²K⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>30</td>
<td>2.07</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>40</td>
<td>1.76</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>50</td>
<td>1.54</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>30</td>
<td>0.34</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>40</td>
<td>0.33</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>50</td>
<td>0.32</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
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<td>8</td>
<td>15</td>
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<td>11</td>
<td>20</td>
<td>40</td>
<td>0.18</td>
</tr>
<tr>
<td>12</td>
<td>20</td>
<td>50</td>
<td>0.18</td>
</tr>
</tbody>
</table>

The house was first simulated in a free floating mode, without any HVAC system installed. The average monthly indoor temperatures, together with average monthly outside temperature, are illustrated in Figure 4. As the figure shows, there is a clear distinction between uninsulated walls (types 1-3) and insulated walls (types 4-12), with the uninsulated houses being 2°C to 5°C colder than the insulated houses, both during winter and summer. Interestingly, the range of average temperatures for insulated walls (types 4-12) is narrower than 2°C, except during May and October, when wall types 4 and 5 present outliers.

The house was then simulated with HVAC system installed, which consisted of underfloor heating system using the natural gas boiler and electric chiller. As the heating source is at the floor, the air temperature at the lower level is warm and cool at the higher level (warm feet, cool head), which provides the same thermal comfort level at lower temperature than the conventional heating systems. Hence, the heating setpoint in this case was 18°C, while the cooling setpoint was set at still comfortable 28°C. For all wall types, the cooling energy needs from May until September are extremely low, ranging annually from 64 kWh to 72 kWh of electricity, which is less than monthly lighting electricity use. This can be contributed to rammed earth’s thermal mass work, as the thickness of external insulation (or its absence) does not appear to have influence on the cooling energy needs. Thus, this fully confirms numerous subjective claims that the indoor temperatures in earthen houses are very comfortable during the summertime.
Figure 4. Average monthly indoor temperatures in free floating simulations for different wall types, with ambient temperature shown at the bottom.

Figure 5. Monthly heating energy needs (kWh) for different wall types.

Table 2. Total heating energy needs (kWh) for different wall types.

<table>
<thead>
<tr>
<th>Wall type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas (kWh)</td>
<td>8340</td>
<td>7596</td>
<td>7004</td>
<td>4361</td>
<td>3412</td>
<td>3366</td>
<td>3120</td>
<td>3083</td>
<td>3047</td>
<td>2931</td>
<td>2901</td>
<td>2870</td>
</tr>
</tbody>
</table>
Total heating energy needs for different wall types are given in Table 2, while the monthly heating energy needs from October until April (until May for uninsulated wall types) are illustrated in Figure 5. The role of external insulation in Serbian climate is obvious from this figure, as the presence of at least 10 cm of EPS reduces the heating needs by a factor of two. Still, the thickness of only 10 cm of EPS is apparently below the critical value, as the increase of SRE thickness from 30 cm to 40 cm further decreases heating energy needs for 21.8%. On the other hand, the 15 cm of EPS appears to be above the critical value, since the increase in SRE thickness then has a marginal effect on heating energy needs – the increase in SRE thickness from 30 cm to 50 cm decreases the heating energy needs by at most 2.3%. The increase in EPS thickness from 15 cm to 20 cm yields further 5.8-6.1% decrease in heating energy needs and is worthwhile to be considered, taking into account relative inexpensiveness of EPS and future price escalation of natural gas. Hence, the optimal external wall for the studied house appears to be type 10, consisting of 20 cm expanded polystyrene external insulation and 30 cm of stabilized rammed earth.

5 NEARLY ZERO ENERGY GOAL

For the wall type 10, the total heating and cooling energy needs amount to 3003 kWh, while the simulated annual consumption of electricity for interior lighting and appliances is 2117 kWh. These amounts do not include sanitary water heating, for which solar water heating system may be used. It was shown in Stevanović & Pucar (2011) that roof-mounted solar collectors with 4.8 m² of aperture area in Belgrade yield a solar fraction of 61% for the daily hot water usage of 220 liters. The remaining 39% of hot water needs, when covered by backup electric resistance storage water heater, uses approximately 1300 kWh of electricity. Hence, the case study house total energy needs amount to 6420 kWh.

Solar energy is the most abundant renewable energy source in Belgrade, and Stevanović & Pucar (2012) estimated that the roof-mounted photovoltaic plant, installed at tilt of 35°, has annual specific production of 1246 kWh/kWp in Belgrade. Thus, the house total energy needs may be fully offset by installing 5.15 kWp photovoltaic plant (which takes up approximately 36 m² of roof area), in which case the house would become a net zero energy building.

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REFERENCES


