Thermophysical analysis of heat-insulated glued laminated profiled timber for wooden houses

N A Tsvetkov¹*, A N Kozlobrodov¹, S Boldyryev², S V Romanenko³, T N Nemova¹ and D N Tsvetkov¹

¹ Tomsk State University of Architecture and Building, Solyanaya Sq., 2, Tomsk, 634003, Russia
² National Research Tomsk Polytechnic University, 30 Lenin Ave., Tomsk, 634050, Russia
³ Siberian State Medical University, Moskovsky trakt 2, Tomsk, 634050, Russia

E-mail: nac.tsuab@yandex.ru

Abstract. The paper presents the thermophysical analysis of two types of the wall system made of heat-insulated glued laminated timbers with connectors comprised of water-resisting multilayer plywood. The paper describes a novel timber configuration, which reduces the weight of one square meter area by 55% compared with an ordinary timber having a cross-section of 0.21 m × 0.21 m and saves not less than 60% of wood. The latter is highly relevant because forests remove carbon dioxide emissions from the atmosphere; reducing the use of wood in construction is of great importance for ecology. The ANSYS finite element program is used for calculating temperature fields and heat fluxes. It is found that one connector affects not more than 0.2 m of the exterior wall length in relation to the temperature and heat flux fields, whereas the heat loss increase is not over 0.44%.

1. Introduction

The extraction and use of fossil fuels will be intensified in the foreseeable future, despite the apparent increasing trend to their depletion [1]. At the same time, the requirements for the efficient application of fossil fuel are being strengthened in all countries due to the real threat to humanity, namely global warming [2], because by-products of hydrocarbon combustion released into the atmosphere intensify this process. In the 21st century, the most pressing challenge for all countries is a quick transfer to a new energy economy [3] in the society, policy, science, and technology, maximizing the elimination of greenhouse gas emission. According to Okorie [4], the reduction in the fossil fuel consumption and carbon emissions into the atmosphere is possible in using the fossil fuel as capital inputs. Among other results, Okorie shows that the energy efficiency in Abuja (Nigeria) is on average 19%.

Energy consumption by buildings [5–6] is a significant part of energy consumption in the world. Abikoye et al. [7] report that the global energy consumption by the construction industry was 32% in 2018 against 30% in 2019. And buildings produce almost 40% of the total carbon emissions.

The wall system parameters are important for a maintenance of the required room temperature and moisture [9] and determine the thermal energy consumption by the heating system of buildings. Meukam and Noumowé [10] propose a model of the heat and mass transfer in building envelopes consisting of local laterite brick with the addition of natural pozzolana (volcanic ash) or sawdust. They
show that the relative moisture and moisture in such building envelopes do not exceed 87 and 5%, respectively. Therefore, the strength of these building envelopes weakly depends on tropical and equatorial climates. In our recent research [11–12], we present the numerical results of the heat and mass transfer in new wall systems made of heat-insulated glued laminated timbers with connectors of various configurations. The proposed physico-mathematical model can be used in northern conditions as it considers phase transitions of water in the structural materials. Nonstationary temperature fields and moisture fields are calculated for the exterior wall fragments made of heat-insulated glued laminated timbers with connectors of different configurations comprised of ten-layer plywood.

The aim of this work is to conduct a comparative analysis of the thermal state and heat-shielding properties of the exterior wall system of the proposed novel configuration, made of heat-insulated timber intended for construction of wooden houses in the climatic conditions of Tomsk.

2. Materials and methods

The cross-sectional view of the proposed exterior wall system made of heat-insulated timbers with an insulant and connectors is illustrated in figure 1. This wall system allows utilizing different woods for lamellae 1 and 4. Due to healing properties of cedar, it is advisable to use it for the lamella 1 facing inward, whereas for the outer lamella 4, most exposed to weather and environmental influences, we offer to use larch. This wall system has two types differing from each other by the insulant, i.e., polyurethane foam and a mixture of peat and sawdust [13] applied for inexpensive wall systems made of environmentally friendly pine timber with lamellae 1 and 4. The housing technology used for the second type of the wall systems is much simpler and includes in-situ assembling of two or three timber works with the insulant placed between lamellae 1 and 4. The availability of renewable materials such as pine, sawdust, or peat applied in this type of the wall system reduces the cost of one square meter area 1.34 times as compared to that of the wall system of the first type applied in the same conditions. Moreover, the first-type configuration of the wall system has more advantages and can be exported. In this case, it is preferable to use the insulant based on a mixture of peat and wooden sawdust.

Polyurethane put in the wall system of the second type provides the increase in its service life, high operational readiness of commercial housing, and consequently better competition of these timbers in the Russian market.

A fragment of the wall system made of heat-insulated timbers was investigated in this work for application in construction of wooden houses in the northern regions. The thermophysical analysis was carried out for the two types of the wall system. The finite element model (FEM) in figure 2 was obtained for the wall system fragment a with a plywood connector consisting of two wood strips, both 0.04 m thick and 0.13 m effective insulation. The choice of the fragment geometry was founded in [12]. The reference area of 0.42 × 0.210 × 0.065 m was obtained by sectioning horizontal and vertical planes parallel to the symmetry axis of the connector. The connector geometry was selected to provide its strength properties and lamella mounting conditions (0.19 m length, 0.04 m width, 0.005 m height).

In extreme heat-exchange conditions, the outside air temperature must be −39 °C, and room temperature must be 20 °C in accordance with the Building Codes and Regulations of the Russian Federation. The thermal conductivity equals 23 and 8.7 W/(m²·K) for outside and room temperature, respectively. The maximum design capacity of the heating system of a house in the city of Tomsk
locating in south-west of Siberia is determined according to these conditions. The convective heat transfer coefficient on the outer and inner lamellae is 23 and 8.7 W/(m²-K), respectively.

![Figure 2](image)

**Figure 2.** FEM of the wall system fragment with the connector: 1, 4 – wood strips, 2 – insulation, 3 – connector.

The thermal conductivity of all materials involved in the wall system fragment is considered as temperature-independent and presented in table 1.

| Table 1: Thermal conductivity of wall system materials. |
|--------------------------------------------------------|
| Wall system types | Materials and thermal conductivity, W/(m·K) |
| Element 1 | Element 2 | Element 3 | Element 4 |
| Pine | Polyurethane foam | Plywood | Pine |
| 1 | λ₁ₓ = 0.18 | λ₂ₓ = 0.04 | λ₃ₓ = 0.12 | λ₄ₓ = 0.18 |
|  | λ₁ᵧ = 0.18 | λ₂ᵧ = 0.04 | λ₃ᵧ = 0.12 | λ₄ᵧ = 0.18 |
|  | λ₁ₚ = 0.35 | λ₂ₚ = 0.04 | λ₃ₚ = 0.12 | λ₄ₚ = 0.35 |
| Larch | Peat and sawdust | Plywood | Cedar |
| 2 | λ₁ₓ = 0.13 | λ₂ₓ = 0.065 | λ₃ₓ = 0.12 | λ₄ₓ = 0.095 |
|  | λ₁ᵧ = 0.13 | λ₂ᵧ = 0.065 | λ₃ᵧ = 0.12 | λ₄ᵧ = 0.095 |
|  | λ₁ₚ = 0.25 | λ₂ₚ = 0.065 | λ₃ₚ = 0.12 | λ₄ₚ = 0.18 |

Along the wood fibers (Z-axis), the thermal conductivity of lamellae is almost 2 times higher compared with that in the perpendicular direction (X-axis).

The mathematical formulation of this spatial stationary problem, including the system of the differential equations and the boundary conditions were described in [2]. The FEM analysis of the connector influence on the temperature fields and the heat flux in the wall system fragment was carried out using the ANSYS finite element program. The finite element modeling of the thermal state of the wall system fragment was performed in Solid 90 also using the ANSYS finite element program.

It is difficult to ensure the absence of thermal resistance between the surfaces of elements 2 and 3 for a type 1 wall system due to the use of sheets made of polyurethane foam.

For a type 2 wall system, tight contact is ensured when forming insulation containing peat and sawdust.
3. Results and discussion

Figures 3 and 4 illustrate the FEM of the isothermal temperature field for the surfaces of the types 1 and 2 wall system with the plywood connector. In these figures, one can see the temperature values that allow us to visualize the thermal state of the wall system fragment at various points.

The type 1 wall system fragment presented in figure 3 has the outer and inner lamellae made of pine. The insulant is polyurethane foam.

The type 2 wall system fragment presented in figure 4 has the outer and inner lamellae made of larch and cedar, respectively. The insulant is a mixture of peat and sawdust. The connectors between the outer and inner lamellae are made of ten-layer moisture-resistant plywood.

**Figure 3.** FEM of the temperature field in the type 1 wall system fragment. Insulant: polyurethane foam

**Figure 4.** FEM of the temperature field in the type 2 wall system fragment. Insulant: peat and sawdust mixture.
According to a comparative analysis of temperature fields shown in figures 3 and 4, the surface temperature of the inner lamella in the 2nd type is ~0.6 °C lower than that in the 1st type. At different distances from the connector, the temperature values show that its influence on the temperature fields is negligible for both types of the wall system. Moreover, the temperature of the inner lamella is much higher than the dew-point temperature, which is 15.2 °C even at rather high relative moisture of 75 %. In practice, the relative moisture of room air does not exceed 60% that confirms the operability of these wall systems with the inner lamellae applied in the considered climatic conditions.

The temperature distribution in the transverse and longitudinal directions of the heat-insulated timbers for both types of the wall system are shown in figures 5 and 6.

According to the temperature curves (figure 6, curves 1-2 and 2-2), the effect of the plywood connector on the temperature field is negligible, especially along the Z-axis. Along the Y-axis, the temperature field on the lower timber surface remains almost constant.

At Z = 0, the effect of the plywood connector on the upper timber surface is more pronounced (figure 6, curves 1-1, 2-1). In this regard, the number and location of connectors in these types of the wall system can be completely determined by the strength properties of the structural elements.

The heat flux in the wall system fragments presented in figures 7 and 8 allows us to evaluate the connector influence on the thermal state of the whole wall system.
Fig. 7. The heat flux in type 1 of the wall system fragment.

We identify the following general patterns based on the analysis of the heat fluxes presented in figures 7 and 8. The connector influence on the temperature and heat flux fields along the $Z$-axis is limited to a 0.1 m area. In the heat-insulated timber, the connectors are thus placed at a 0.2 m distance from each other. In this case, the exterior wall system is the most durable. The heat flux along the connector reaches its maximum at the center of the wall thickness.

The finite element analysis shows significant changes in the heat flux near the connector in $X$, $Y$ and $Z$ coordinates. In positioning the connectors at a 0.2 m distance from each other, we observe their insignificant effect on the heat loss through the exterior wall due to a small size of the zone of these changes. Beyond the zone of the connector influence, the heat flux through the exterior wall increases up to 0.36 and 0.44% in the wall system of types 1 and 2, respectively.

Figure 8. FEM of heat flux in the type 2 wall system fragment.

Figures 9 and 10 contain the plots of the heat flux distribution in the transverse ($X$-axis) and longitudinal ($Y$-axis) directions in the wall systems of both types.
Figure 9. Heat flux curves along X-axis \((Y = 0; Z = 0); 1 - \text{type } 2; 2 - \text{type } 1\).

Figure 10. Heat flux curves along Y-axis \((Y = 0; Z = 0); I-I - \text{type } 2; 2-I - \text{type } 1; X = 0; Z = 0.065 \text{ m}; I-2 - \text{type } 2; 2-2 - \text{type } 1\).

Figure 9 presents the heat flux curves along the X-axis of symmetry for the types 1 and 2 wall system. It should be noted that the maximum density of the heat flux achieved at the center of the heat-insulated timber \((X = 0.11 \text{ m})\) for the type 2 is approximately 16% less than that for type 1.

Figure 10 shows the change in the heat flux along the Y-axis. Based on the results obtained, we determine the connector influence zone and show that along the Y-axis, this zone is negligible and limited to 0.12 m.

4. Conclusions
The ANSYS finite element program was used for the FEM analysis of the connector influence on the temperature and heat flux fields in the energy-efficient heat-insulated glued laminated timbers with different insulators intended for construction of wooden houses in the climatic conditions of Tomsk. It was found that the influence of one connector on the temperature field did not exceed 0.2 m of the exterior wall length, whereas its influence on the heat flux field did not exceed 0.12 m of the exterior wall height.

It was shown that the influence of the plywood connector on the temperature and heat flux fields was insignificant. The number and location of connectors in the wall system could be completely determined by the strength properties of its structural elements.

The application of heat-insulated timbers in the construction of wooden houses will save more than 50% of wood in manufacturing external wall systems. The following outcomes can be achieved:

- forest conservation as the most important natural absorption system of CO2;
- over 2 times increase in the energy efficiency of buildings under construction resulting in lower consumption of thermal energy and lower carbon emission during thermal energy generation;
- significant reduction in the wall system weight, which will save money on the foundations for wooden houses;
- reduction of costs for construction and utilities of a house in its maintenance.

Acknowledgment
The authors acknowledge the members of the Program Committee of the 3rd International Scientific Conference “Sustainable and Efficient Use of Energy, Water and Natural Resources” (SEWAN-21) and all its organizers for the opportunity of making a report based on this work.
References

[1] Tsvetkov P 2021 Climate policy imbalance in the energy sector: time to focus on the value of CO$_2$ utilization *Energies* 14 411 DOI: 10.3390/en14020411

[2] Bompard E, Botterud A, Corgnati S, Huang T, Jafari M, Leone P, Mauro S, Montesano G, Papa C and Profumo F 2020 An electricity triangle for energy transition: application to *Italy Appl. Energy* 277 115525 DOI: 10.1016/j.apenergy.2020.115525

[3] Peña-Ramos J A, Bagus P and Amirov-Belova D 2021 The North Caucasus Region as a blind spot in the “European Green Deal”: energy supply security and energy superpower Russia *Energies* 14 17 DOI:10.3390/en14010017

[4] Okorie D I 2021 The energy use of capital inputs: towards cleaner production in Nigeria *Environmental Challenges* 4 100104 DOI:10.1016/j.envc.2021.100104

[5] Liu P, Lin B, Zhou H, Wu X and Little J C 2020 CO$_2$ emissions from urban buildings at the city scale: system dynamic projections and potential mitigation policies *Appl. Energy* 277 115546 DOI: 10.1016/j.apenergy.2020.115546

[6] Wei S, Tien P W, Calautit J K, Wu Y and Boukhanouf R 2020 Vision-based detection and prediction of equipment heat gains in commercial office buildings using a deep learning method *Appl. Energy* 277 115506 DOI: 10.1016/j.apenergy.2020.115506

[7] Abikoye B, Čuček L, Isafiade A J and Kravanja Z 2019 Synthesis of solar thermal network for domestic heat utilization *Chem. Eng. Trans.* No. 76 1015–20 DOI:10.3303/CET1976170

[8] Canale L, Di Fazio A R, Russo M, Frattolillo A and Dell’Isola M 2021 An overview on functional integration of hybrid renewable energy systems in multi-energy buildings *Energies* 14 1078 DOI: 10.3390/en14041078

[9] Liu F, Jia B, Chen B and Geng W 2017 Moisture transfer in building envelope and influence on heat transfer *Procedia Eng.* 205 3654–61 DOI: 10.1016/j.proeng.2017.10.229

[10] Meukam P and Noumowé A 2005 Modeling of heat and mass transfer in lateritic building envelopes *Heat Mass Transf.* 42(2) 158–67 DOI: 10.1007/s00231-005-0006-5

[11] Tsvetkov N A, Boldyryev S, Tolstykh A V, Tsvetkov D N and Doroshenko Ju N 2021 Refinement and testing of the mathematical model of heat and moisture transfer in envelope structures of profiled insulated timber with connectors *IOP Conf. Ser.: Earth Environ. Sci.* 751 012094

[12] Tsvetkov N A, Tolstykh A V, Khutornoi A N, Boldyryev S, Kolesnikova A V and Tsvetkov D N 2021 Mathematical modelling of renewable construction materials for green energy-efficient buildings at permafrost regions of Russia *Environmental Challenges* 4 100101 DOI: 10.1016/j.envc.2021.100101

[13] Kopanitsa N O, Safronov V N, Kovaleva M A, Kudyakov A I, Kugaevskaya S A, Savchenkova T V and Kasatkina A V 2015 Peat-wood molding mixture for the manufacture of heat-insulating and structural-heat-insulating products. Available online: http://innsbornik.extech.ru/docs/sbornik/2015_02/234-247.pdf (accessed on 9 June 2021)