Evaluation of energy efficiency of external stud partitions with use of numerical analysis

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Abstract. The need to save energy necessitates the search for solutions that would enable us to reduce heat losses. Currently the majority of investments are financed with use of mortgages, that is why the investors search for optimal technological solutions i.e. guarantee high energy savings. One of those solutions is construction in frame technology. This technology allows to achieve the heat transfer characteristics of a passive house with partitions that are ca. 40% thinner than their counterparts in traditional brick technology. According to different sources detached houses use ca. 70 ÷ 80% of the energy for heating. The subject of the article was the analysis of total heat loss through vertical wall of detached home made of wooden stud structure and for two types of steel stud structure – made of fully enclosed and THERMO profiles. On the basis of the literature recommendations and normative documents dependency calculated heat loss by transfer while computer simulation shows how thermal bridges of adopted solutions affect heat loss. For the purpose of analyzed external partitions heat loss was compared for heating season in buildings in each of the climate zones of Poland. What was also analyzed was the cost of heating for different fuels. The analysis showed significant differences in the adopted solutions. For example in case of gas central heating the difference in annual bills for different climatic zones can be ca. 20%, and the difference in costs of heat loss between the wooden stud framing and the steel stud framing is over 30%. The results show that use of appropriate technology can minimize those losses, thus securing significant lowering of heating bills. In turn, thanks to MES-e-based calculations, it is possible at the design stage to analyze the technological and construction solutions which are extremely important during the operation of the facility.

1. Introduction

The energy quality of building is the set of its properties that determine the annual energy consumption connected with its use. It is defined by the building heat protection and heating, ventilation and hot water supply systems properties [1].

Currently the majority of investments is completed with use of mortgage loans and that is why the investors seek for optimal technological solutions that will shorten construction periods and secure the requirements pertaining to physical properties of structure. One of solutions is the frame structure technology. This technology utilizes partitions that are up to 20% thinner than comparable traditional brick walls, which are sufficient to achieve thermal transmittance (U value) required for passive houses. According to different sources detached houses use ca. 70 ÷ 80% less energy, with main savings on heating energy. This high energy consumption levels are mainly the result from heat
escaping from external divisions and also inappropriate ventilation means. Still we have to stress that the load-bearing elements of frame structures form, at their locations, linear thermal bridges that increase building heat loss and consequently generates increase in operating costs. That is why optimal solutions are sought for this type of structures [2-4]. An example of such solutions is the use of thin wall perforated profiles, so called thermo-profiles. The present paper analyses the energy efficiency of external divisions made in light steel frame and timber frame technologies.

2. Aim and scope of work

The aim of the paper is to perform comparative analysis of total heat loss through vertical division of detached home made with use timber frame and light steel frame technologies. The calculations for thin steel frame technology included both those for full-wall formwork and the so called “thermo” perforated ones. Additionally the work is to present essential differences in heat parameters resulting from the adopted structural solutions.

The article presents the characteristic of the analysed technologies and calculations of heat parameters required to ascertain the heat loss. Furthermore the heat losses during heating season for buildings located in each of Poland’s climate zones were compared. We also present the cost of heat loss for analysed divisions for different heating fuels. Apart from that, by using software based on the finite element method (FEM) we also determined basic heat parameters and temperature distribution.

3. Characteristic of frame technology houses

Independently from the type of frame technology applied, i.e. whether it is based on thin wall steel formwork or timber, both technologies are similar. The load-bearing structure of a wall is based on modular distribution of elements based on a horizontal beam anchored to foundation. The cross sections of used element depend, among others, from the building loading. The space between the columns that form the frame for the partition is filled with insulating material. From the outside the insulating material is covered with wind-protecting film, from inside with vapour barrier film. The wall skins increases the stability of structure from outside and inside, and are usually made of chipboards. The ceilings of frame structure buildings usually have beam structure. The beams connecting the structural columns form a flange. This flange supports the structural elements of the ceiling and the space between them is filled with insulation material. The upper part is made of chipboard that is used as base for flooring. When it comes to rafter solutions similar to those used in traditional construction are used.

Figure 1. Exemplary structure of a detached home made in frame technology.
4. Characteristics of analysed partitions

According to the national addendum to the PN-EN 12831:2006 standard, when calculating heat loss by permeation through external partitions outside dimensions, that is the dimensions measured on the outside of building, are to be used. Figure 2 presents the geometry of analysed wall and the location of linear thermal bridges.

Figure 2. Geometry of the analysed partition with dimensions and location of linear thermal bridges [4].

Structure of frame technology building should be such as to limit the heat loss. Securing appropriate thermal transmittance for external walls, ceilings, floor and roof does fulfil the requirements for passive housing in the majority of applied solutions, without the need to introduce additional means.

Figure 3. Adopted computational models for linear thermal bridges of analysed frame technology partitions: a) wall corner, b) wall-ceiling connection, c) wall-floor connection at ground level.

1– thin layer plaster – 0.5 cm thick; 2, 15 – 16 cm thick mineral wool; 3, 7 – 1.2 cm cement – chipboard; 4 – vapour penetrable film; 5 – vapour barrier film; 6, 14 – 0.15 cm full wall and Thermo C 140 steel profiles, 14 cm timber profile; 8 – 1.25 cm plasterboard; 9 – 2 cm thick parquet; 10 – 5 cm thick screed; 11 – PE Film; 21, 12 – 5 cm thick EPS Styrofoam; 13 – 2 cm thick cement – chipboard; 16 – 20 cm thick foundation slab; 17 – 20 cm thick XPS Styrofoam.

The characteristics of materials used for analysed solutions of external partition is presented in table 1. According to the following algorithm thermal transmittance $U_c \ [W/(m^2K)]$ was calculated in computer simulations for the analysed wall solutions by [5, 6]:

| Material                        | Description                  |
|--------------------------------|------------------------------|
| 1                              | Thin layer plaster – 0.5 cm thick |
| 2, 15                           | 16 cm thick mineral wool |
| 3, 7                            | 1.2 cm cement – chipboard |
| 4                              | Vapour penetrable film |
| 5                              | Vapour barrier film |
| 6, 14                           | 0.15 cm full wall and Thermo C 140 steel profiles, 14 cm timber profile |
| 8                              | 1.25 cm plasterboard |
| 9                              | 2 cm thick parquet |
| 10                             | 5 cm thick screed |
| 11                             | PE Film |
| 12                             | 5 cm thick EPS Styrofoam |
| 13                             | 2 cm thick cement – chipboard |
| 16                             | 20 cm thick foundation slab |
| 17                             | 20 cm thick XPS Styrofoam |
calculation of average elementary heat flow density \( q \) [W/m²] for joint parts \( q_1 \) and \( q_2 \),

- calculation of thermal transmittance on the basis of:

\[
U_{c1} = \frac{q_1}{(t_i - t_e)} \\
U_{c2} = \frac{q_2}{(t_i - t_e)}
\]

where:

\( U_{c1}, U_{c2} \) – is thermal transmittance of the partition, W/(m²K),

\( t_i, t_e \) – are the inside and outside air temperatures, K.

### Table 1. Heat conductivity coefficients for materials used.

| Nos. on Fig. 3 | Type of material                     | Thickness \( d \) (m) | \( \lambda \) Heat conductivity (W/mK) |
|----------------|--------------------------------------|-----------------------|---------------------------------------|
| 1              | Thin layer plaster                   | 0.005                 | 0.7                                   |
| 2, 15          | Rock wool                            | 0.16\(^1\) / 0.14\(^2\) | 0.035                                 |
| 3, 7           | Cement – chipboard                   | 0.012                 | 0.215                                 |
| 6, 14          | Full and Thermo C140 steel profiles/ Timber profile | 0.0015\(^3\) / 0.038\(^4\) | 50\(^5\) / 0.16\(^6\) |
| 8              | Plasterboard                         | 0.0125                | 0.25                                  |
| 9              | Parquet                              | 0.02                  | 0.16                                  |
| 10             | Screed                               | 0.05                  | 1                                     |
| 12             | EPS Styrofoam                         | 0.05                  | 0.04                                  |
| 13             | Cement – chipboard                   | 0.02                  | 0.215                                 |
| 16             | Foundation slab                      | 0.2                   | 2                                     |
| 17             | XPS Styrofoam                         | 0.2                   | 0.04                                  |

\(^1\)Wall insulation rock wool thickness, \(^2\)Rock wool thickness between steel profiles, \(^3\)Thickness of thin wall profiles, \(^4\)Timber profile thickness, \(^5\)Heat conductivity coefficient for steel profile, \(^6\)Heat conductivity coefficient for timber profile

5. **Computational assumptions for numeric calculations**

The numeric analysis was performed with use of ANSYS software based on finite element methods [8]. We conducted the analysis with assumption of homogeneity and isotropism of materials used to construct the respective layers.

The phenomenon of heat exchange occurs through radiation, convection and conduction. Very often these three phenomena occur simultaneously, but in engineering practice in general, one of them prevails and can be considered separately. The work was taken under attention should only be given to heat transfer through conduction considering the condition convection on the outer edges. To determine the temperature distribution, heat flux density and gradient temperature, heat conduction should be described by mathematical equations, taking into account the relevant boundary and initial conditions [7]. For the analysis, a spatial model was adopted, assuming a steady state, where in each area the temperature distribution in the steady state is described by the Laplace equation and between the individual areas located inside the object there is an ideal contact:

\[
\nabla \cdot \left( \lambda \nabla t \right) + \frac{\partial}{\partial x} \left( A \frac{\partial t}{\partial x} \right) + \frac{\partial}{\partial y} \left( A \frac{\partial t}{\partial y} \right) = 0
\]

where:

\( t \) – temperature, K,

\( \lambda \) – heat conductivity, W/(mK).
In order to find a solution, the following boundary conditions were adopted. Based on [9] we assumed the internal temperature \( t_i = 293.15 \text{ K} \) and according to [10] the design external temperature of \( t_e = 253.15 \text{ K} \). We assumed the thermal surface coefficient for internal side we adopted the following FEM analysis values: horizontal \( h_i = 7.69 \text{ W/(m}^2 \text{K)} \), vertical downward \( h_i = 5.88 \text{ W/(m}^2 \text{K)} \), vertical upward \( h_i = 10 \text{ W/(m}^2 \text{K)} \); and for external side \( h_e = 25 \text{ W/(m}^2 \text{K)} \), which are the opposites of resistances \( R_{si}, R_{se} \text{ m}^2 \text{K}/\text{W} \) [5, 11].

6. Analysis of heat loss

Heat loss in external partition was analysed on example of a building constructed with use of different frame technologies. The differences were the result of structural material used. One example featured timber elements, the other thin wall profiles. In case of thin wall profiles we analysed both full wall formwork and the perforated, so called “thermo” ones.

See table 2 for values of the linear thermal transmittance of the thermal bridge \( \Psi_e \text{ [W/(mK)]} \), the length of linear thermal bridges \( L_e \text{ [m]} \) and the area of external wall that participates in heat transfer \( A_i \) were both adopted after external dimensions [4].

| Linear thermal bridge                        | Linear thermal transmittance on external dimensions \( \Psi_e \text{[W/(mK)]} \) | Length of thermal bridge on external dimensions \( L_e \text{[m]} \) | Heat loss due to presence of thermal bridge on external dimensions \( \sum \Psi_e L_e \text{[W/K]} \) |
|---------------------------------------------|---------------------------------|-----------------|----------------------------------|
| Corner connection of external walls (Fig. 3a)| Full Thermo Timber             | 3.05            | -0.064 -0.110 -0.151            |
| Connection of external wall and ceiling (Fig. 3b)| 0.150 0.133 0.099           | 6.3             | 0.948 0.838 0.626               |
| Connection of external wall and floor on the ground (Fig. 3c)| 0.581 0.454 0.386           | 6.3             | 3.659 2.863 2.433               |
| \( \sum \)                                 |                                 | 4.543           | 3.591 2.908                     |

Table 3 includes, among others, the calculations of thermal transmittance \( U_k \text{[W/(m}^2 \text{K)]} \) for the analysed wall, including linear thermal bridges. The calculations were performed according to procedures listed in [11]. Thermal transmittance \( U_k \text{[W/(m}^2 \text{K)]} \) allows us to determine the influence of thermal bridges on total heat loss. Table 3 also list the results of calculation of transfer heat loss coefficient \( H_{l,t} \text{[W/K]} \). This parameter is required to determine monthly heat loss due transfer and ventilation, and then the \( EU, EK \) and \( EP \) indicators \([\text{kWh/m}^2 \text{per annum}]\). The values of corrective coefficients \( e_1 & e_2 \) were adopted pursuant to the [PN-EN 12831:2006] standard.

We then calculated heat losses \( Q_{tr,s} \text{[GJ]} \) for all climate zones of Poland for the calculated heat loss coefficients \( H_{l,t} \text{[W/K]} \), and the adopted partition area of \( A_i = 18.3 \text{ m}^2 \). Heat loss values for whole heating season are presented in table 5.

Equation (8) of table 4 sets the amount of energy (in GJ) that we lose through construction partition with average monthly temperatures of heating season for the selected meteorological station throughout Poland, after assuming constant normative temperature in the heated room [13]. This loss of energy is calculated with Day*Degree that is annual method of heat loss balance, assuming the length of heating season as quoted by [14].
Table 3. Determination of transfer heat loss coefficient $H_{tie}$ [W/K] for analysed partition.

| Computational parameters                                         | Full     | Thermo   | Timber   |
|------------------------------------------------------------------|----------|----------|----------|
| Partition thermal transmittance $U_t$ (W/m²K)                    | 0.138    | 0.141    | 0.121    |
| Area of wall participating in heat transfer in the light between the partitions that are perpendicular to it $A_t$ (m²) |          |          |          |
| Heat loss coefficient for transfer of heat from heated space to environment $H_{tie} = A_t U_t$ (W/K) | 2.525    | 2.580    | 2.214    |
| Heat loss due to presence of thermal bridges $\sum \psi_e l_e$ (W/K) | 4.543    | 3.591    | 2.908    |
| Heat transfer coefficient between heated space and outsider environment $H_D = A_t U_t + \sum \psi_e l_e$ (W/K) | 7.069    | 6.171    | 5.122    |
| Thermal transmittance $U_k = H_D/A_t$ (W/m²K)                    | 0.386    | 0.337    | 0.280    |
| Heat loss coefficient due to presence of thermal bridges $H_{tie} = \sum A_k U_k e_k + \sum \psi_e l_e e_i$ (W/K) | 11.612   | 9.762    | 8.030    |

Values for corrective coefficients due to orientation, are given in the national annex to the standard PN-EN 12831: 2006:
- $e_k = 1.0$
- $e_l = 1.0$

Total area of partition surrounding the heated space, as calculated according to its outsider diameters $A_k$ (m²): 18.3

Heat lost through the analysed external partition $A_t U_k$ (W/K) | 7.069    | 6.171    | 5.122    |

Heat loss due to presence of thermal bridges $\sum \psi_e l_e$ (W/K) | 4.543    | 3.591    | 2.908    |

Table 4. $Q_{tie}$ (GJ) heat losses through the analysed partition throughout the heating season.

| Location             | DayDegrees | Full     | Thermo   | Timber   |
|----------------------|------------|----------|----------|----------|
| Gdańsk               | 4145.4     | 4.159    | 3.496    | 2.876    |
| Poznań               | 3613.2     | 3.625    | 3.047    | 2.507    |
| Częstochowa          | 3707.9     | 3.720    | 3.127    | 2.573    |
| Olsztyn              | 4084.9     | 4.098    | 3.445    | 2.834    |
| Zakopane             | 4569.1     | 4.584    | 3.854    | 3.170    |

The Day*Degrees are calculated from the difference between internal temperature (usually constant throughout the season) and the average monthly temperature multiplied by number of days of heating in the respective month. The sum of all monthly Day*Degrees gives us annual value that is used to compare, e.g. different areas of Poland, when it comes to severity of winter [12, 14].

The conducted analysis proved, among others, that timber frame structure results in ca. 30% lower heat loss than in the structures with light steel frames based on full profiles. If we consider the differences between thin wall steel profiles in this field, the perforated element, so called thermo, structure proves to be more beneficial.

Results of heat loss cost calculation prove, that we cannot affect some of the factors. For example in case of timber frame partition in 1st climate zone and heated with natural or liquid gas the cost of energy loss is ca. 10% lower than for 5th climate zone of Poland. The difference in heat loss costs for the same sources of energy and climate zone, between timber and full steel profile structures is ca. 40%.

Figure 4 presents the heat loss costs for analysed partitions. On the basis of the presented data we ascertained that costs incurred due to heat loss are the highest in case of full thin-wall formwork in relation to all fuels investigated. The lowering of area of steel profiles through drilling longitudinal...
holes in them makes the wall built from it reduce heat loss by several percent, and thus lower heating bill. When the used building structural materials are considered the analysis proves that the use of wooden structural elements brings the biggest reduction of heat loss. In comparison of costs of 1 GJ of energy we should also take heat efficiency into account, as only that can allow us to objectively evaluate energy costs and compare different energy sources.

![Graph showing cost of heat loss through a wall made in timber and light steel frame technology for all climate zones of Poland.](image)

**Figure 4.** Cost of heat loss through a 18.3 m³ wall made in timber and light steel (full and perforated profile) frame technology for all climate zones of Poland.

7. **Results of numerical analysis**

The results of numerical analysis of temperature distribution in the construction joints subject to our analysis indicate their practical usability. The identification of weak spots for heat loss gives us the possibility to improve the adopted technical and structural solutions. What is worth noticing in the attached figures 5, 6 and 7 is the fact that in case of structure made in light steel frame technology, within the structural elements of the wall the temperature distribution is disturbed. It does look differently in case of timber frame, where the distribution is homogenous.

![Graph showing results of numerical calculations of 2D thermal bridge–distribution of temperatures in joints of external wall at the corner, for frame walls made of following profiles: full (a), thermo (b), timber (c).](image)

**Figure 5.** Results of numerical calculations of 2D thermal bridge– distribution of temperatures in joints of external wall at the corner, for frame walls made of following profiles: full (a), thermo (b), timber (c).

Geometric modelling of thermal bridges at the ground concerns the geometric introduction of section of the building solid that includes ground base to the bridge area [11, 15, 16]. It turns out that
heat currents flowing out of the heated interior do participate in temperature distribution in the ground underneath the building and in its surroundings. Due to large ground volume it was omitted in Figure 5.

![Figure 6](image)

**Figure 6.** Results of numerical calculations of 3D thermal bridge – distribution of temperatures in joints of external wall at the ground floor, for frame walls made of following profiles: full (a), thermo (b), timber (c).

Results of computer simulation presented in Fig. 6 indicate weak spots in form of supports of ceiling beams on the wall. This is particularly prominent in case of structures made in light steel frame technology.

![Figure 7](image)

**Figure 7.** Results of numerical calculations of 3D thermal bridge – distribution of temperatures in joints of external wall with ceiling, for frame walls made of following profiles: full (a), thermo (b), timber (c).

8. **Summary**

According to different sets of data detached homes use ca. 70 ÷ 80% that is most of the energy for heating purposes. This high rate of energy use is caused, among others, by heat lost through external partitions. It is worth stressing that we have no influence on some of the factors that influence energy loss. This is foremostly connected with building location. Poland is divided in 5 climate zones, depending on outside temperatures in winter period. 5th, southern zone is the coldest one, while the temperatures are highest in the 1st, north-western zone.

On the basis of analyses conducted we formulated the following conclusions:

- We found a significant difference, for the benefit of timber frame, in the calculated values of heat parameters,
The thermal transmittance is some 30% lower in timber frame structure than in structures made in light steel frame technology.

Light steel frame constructions made of thermo profiles are characterized by better heat parameters than full profile structures. This in the end means lower energy consumption and lower cost of heating such building type.

Differentiation of heat loss cost depends on energy sources and the climate zone chosen. For example the difference in energy cost for the same energy source and the same climate zone, between partition with timber structure and steel structure can be up to 35%.

Numerical calculations provide both information pertaining to the value of physical parameters and graphic representation of distribution of those parameters within the analysed partition. Thanks to this, at the design stage it is possible to recognize weak spots in the partition in terms of heat loss, which in turn gives the opportunity to improve the adopted construction and material solutions.

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