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ASSESSMENT OF INFILTRATION AND TRANSMISSION HEAT LOSSES IN BUILDINGS

Abstract. *Reducing heat loss in buildings is a critically important task in the context of increasing energy efficiency and complying with modern environmental standards, particularly given the rising cost of energy resources. The aim of this study is comprehensive assessment of infiltration and transmission heat losses, taking into account the influence of external factors and the structural features of buildings. To achieve this, numerical modeling of thermal processes, analytical calculations, and experimental methods were used, such as thermographic analysis and airtightness measurements. Based on the analysis of the obtained geometric parameters and thermophysical material properties, a calculation of heat losses through wall, window, and door structures was performed, specifically considering external factors such as wind speed, atmospheric pressure, and temperature differences. The study found that infiltration heat losses are highly dependent on the airtightness of the building envelope and can account for 10–15 % of total losses. The investigation of heat loss through windows confirmed the need to improve regulatory approaches for assessing their heat transfer. It was established that calculations based on current standards which affects up to 25 %, which affects the accuracy of energy audits. Transmission losses depend on the thermal resistance of the building envelope, and standard calculation methods can overestimate them by 17–51 %. It was found that with an increase in wind speed up to 20 m/s, heat losses grow by 20–30 %, which confirms the necessity of accounting for mixed convection regimes. Comparing the obtained experimental data with the calculation results allowed for the evaluation of errors in existing regulatory methods and the refinement of calculation approaches for determining heat losses. This study confirms the need to improve building heat loss assessment methods, considering the specific air permeability of materials. The results of this research can be used to improve methods for the energy analysis of buildings, develop more effective strategies for the thermal modernization of the building stock, and create scientifically-based recommendations for reducing energy consumption.*
Keywords: air permeability, energy efficiency, airtightness, building envelope, infiltration heat losses, transmission heat losses, thermal imaging inspection.

1. Introduction

Ensuring energy efficiency in buildings is one of the key challenges in modern energy. A significant portion of heat losses in buildings occurs due to infiltration and transmission processes, which substantially impacts the level of energy resource consumption [1]. Optimizing the thermal protection of building structures and controlling air exchange play a decisive role in reducing energy costs, as well as improving indoor environmental comfort [2].

Assessing infiltration and transmission heat losses allows to identify potential ways to improve building energy efficiency by developing ways to minimize heat loss. Despite the wide range of existing calculation methods and experimental studies, the issue of increasing the accuracy of determining heat flows through building envelope and air leakages through the building's airtightness deficiencies remains relevant [3].

Modern studies show that the influence of external factors, such as meteorological conditions, building envelope materials, and peculiarities of ventilation systems, plays a significant role in heat loss processes [4]. Using innovative diagnostic methods such as thermographic analysis, numerical modeling, and the application of wireless technologies allows for obtaining more accurate data on the characteristics of the building envelope [1].

An analysis of literature sources on assessing heat losses in buildings demonstrates a wide range of measurement approaches and methods for reducing energy consumption. Work [5] describes experimental methods for determining infiltration losses, based on the use of aerometric studies and thermographic analysis. Study [6] emphasizes the importance of considering meteorological conditions when assessing transmission heat losses. Work [7] describes the methodology of thermographic surveys of residential buildings, identifying the main areas of heat leakage, particularly through window and door units. Work [8] investigates heat and moisture processes in building envelope structures, highlighting their influence on the overall level of heat loss. The author examines the impact of changes in humidity and temperature on the characteristics of building materials, concluding that seasonal fluctuations can lead to increased heat losses. Study [9] conducted a comprehensive analysis of building heat losses using thermographic surveys, confirming the effectiveness of this method in identifying areas of increased heat loss. Additionally, the dependence of the heat transfer coefficient on wind speed was determined. In the study [10], the influence of material air permeability on the overall level of heat loss was investigated. The authors concluded that additional sealing of structures can reduce infiltration losses by 15−20 %. It is also worth noting that regulatory documents, such as DSTU B V.2.6-23 [11], DSTU EN 14351-1 [12], and DSTU EN ISO 10077-1 [13], regulate approaches to calculating heat losses, but they have certain limitations that require further clarification through experimental research.

The aim of this study is to assess infiltration and transmission heat losses in buildings using modern numerical and experimental methods. This work specifically focuses on analyzing the impact of structural features of building materials, the level of airtightness of the building envelope, and external factors (wind flows, temperature differences) on heat transfer processes. The proposed approaches allow for improving energy audit methods, increasing the accuracy of heat loss assessment, and developing effective measures for the thermal modernization of buildings.

2. Methods and materials

In this study, a combination of numerical modeling and experimental methods was used to assess infiltration and transmission heat losses in buildings. The main stages of the research were:

- analysis of room structural characteristics;
- heat loss calculation;
- modeling the influence of external factors;
- experimental studies;
- results evaluation.

Heat losses in residential and public buildings consist of heat losses through external structures (walls, windows, floors, ceilings) and the heat consumed for warming air that infiltrates the premises through airtightness deficiencies.

Infiltration and transmission heat losses are the two primary mechanisms of heat loss that impact a building's energy efficiency. Infiltration heat losses are heat losses that occur due to the uncontrolled penetration (infiltration) of cold air from the outside into the building's interior and the leakage of warm air to the outside through cracks, gaps in windows and doors, construction joints, etc. These losses depend on the building's airtightness level, wind speed, and the pressure and temperature differences between the internal and external environments. Transmission heat losses through the building's building envelope (walls, windows, doors, etc.) depend on the thermal resistance of the materials, the thickness of the structures, the presence of thermal insulation, and the temperature difference between the internal and external environments. Both types of heat losses significantly affect a building's energy consumption, and their reduction is a key objective during thermal modernization and the design of energy-efficient structures [14].

In this study, the heat loss calculation was performed for an room in an academic building of the National University of Life and Environmental Sciences of Ukraine. The lecture hall is located on the third floor of a multi-story building. It measures 11.7 x 5.9 x 3.2 m and is situated in the end section of the building, where two of its walls are external. The end wall of the room (5.9 m wide) is on the eastern side, while the other wall (11.7 m wide) is on the southern side. The internal volume of the lecture hall is V=220.9 m^3.

The wall structure has the following layers: inner plaster – 0.02 m; solid clay brick masonry on cement-sand mortar – 0.51 m; ceramic facing tile – 0.02 m; adhesive mortar layer – 0.01 m; mineral wool insulation layer – 0.1 m; outer finish layer – 0.005 m. The room has four metal-plastic double-pane windows measuring 2.1x2.2 m, for which the height from the floor level to the windowsill is 0.9 m (thermal resistance of windows 0.6 $m^2 \cdot °C/W$). The wooden door in the room measures 2.05x0.95 m and opens into the corridor of the heated building's interior. The room is not equipped with an air ventilation system. Lighting is provided by 40 fluorescent lamps, each with a power of 18 W (the conversion coefficient of electrical energy to thermal for such lamp is 0.4). The room contains one computer (laptop) with a power of 60 W; additionally, 25 people are simultaneously present in the room (under conditions of working with computer equipment, the heat dissipation of one person is 125 W). The room also has four heating radiators with a total power of 4.0 kW (1.0 kW each).

A calculation of the room's heat gains from lighting, occupants, household electrical appliances, and solar radiation must be performed. The amount of heat emitted by lighting lamps can be found using the formula:

$$Q_{os} = n_l \cdot P_l \cdot \eta_l = 288\ W, \tag{1}$$

where n_l – number of fluorescent lamps in the room, pcs; P_l – power of one lamp, W; η_l – coefficient indicating the proportion of power expended on heating the surrounding environment.

The amount of heat gain from people in the room can be calculated using the ratio:

$$Q_{lud} = n_{lud} \cdot P_{lud} = 3125\ W, \tag{2}$$

where n_{lud} – the number of people in the room, persons; P_{lud} – the average value of the amount of heat released by a person into the environment, W.

The amount of heat gain from household electrical appliances can be determined using the ratio:

$$Q_{pryl} = \sum_i^m P_{i,j} \cdot \eta_{i,j} = 48\ W, \tag{3}$$

where m – number of devices, pcs; $P_{i,j}$ – electrical power of the source, W; $\eta_{i,j}$ – coefficient indicating the proportion of appliance power that is converted into thermal energy.

The amount of heat entering the room from solar radiation is determined as follows:

$$Q_{vypr} = P_{vypr} \cdot n_{vk} \cdot F_{vk} \cdot \eta_{prop}, \tag{4}$$

where P_{vypr} – the amount of thermal energy (incident from the Sun per 1 m^2 of the object's surface when windows are vertically positioned, which depends on the window's orientation relative to North, East, West, South, the month of the year, and the geographical location of the settlement where the building is situated); n_{vk} – number of windows, pcs; F_{vk} – window surface area, m^2; η_{prop} – coefficient of transmission of thermal rays through the window surface, which depends on the type of window (single-chamber, double-chamber, etc.), optical properties of glazing and other factors.

The calculation was performed according to the DSTU 9190 [15] methodology. In this room, the windows are located on a wall structure with a southern orientation. The windows are made of transparent glass. The thermal resistance through the windows, Q_{win} (according to DSTU B V.2.6-23 [11]), is in the range of R=0.32−0.75 m^2·°C/W, and the solar transmittance coefficient is in the range of τ=65−80 %. The calculation was performed for January, for which the average monthly outdoor air temperature is minimal. For one window (south-facing) $F_{vk,1} = 2.1 \cdot 2.2 = 4.62$ m^2, according to the recommendations given in DSTU 9190:2022 [15] – P_{vypr}= 50 W/m^2, $\eta_{prop} = 0.675$. Heat gains from solar radiation are calculated using formula (4), resulting in $Q_{vypr,1} = 144.375$ W. Accordingly, for four south-facing windows, the heat flow from solar radiation through the windows is: $Q_{vypr,0} = 577.5$ W.

When calculating the amount of heat entering the room from solar radiation, it's also necessary to consider the shading reduction factor for movable devices – curtains, blinds [11]. In our case, colored textile curtains are used for shading, for which, according to the DSTU standard [13], the reduction factor η_{zh} can range from 0.42 to 0.77. As a result, the total heat flow from solar radiation can be determined through calculation.

$$Q_{vypr} = Q_{vypr,0} \cdot \eta_{zh} = 346.5 \text{ W}, \tag{5}$$

a. Calculation of heat losses through the wall structure

The heat transfer coefficient through a multi-layered building wall is found from the ratio:

$$K = \frac{1}{1/\alpha_{vn} + \sum_{i=1}^{m} \delta_i/\lambda_i + 1/\alpha_{zov}}, \tag{6}$$

where $\alpha_{vn}, \alpha_{zov}$ – heat transfer coefficient on the inner and outer surfaces of the wall, W/m^2·^{0}C; δ_i - thickness of the i-th layer of the wall, m; λ_i - thermal conductivity coefficient of the material from which the i-th layer of the wall is made.

The heat exchange coefficient on the inner and outer surfaces of the wall under conditions of natural convection α_{vn}, α_{zov} is calculated based on experimentally determined temperature readings from the internal and external sides of the room: the average temperature of the inner wall surface $T_{st1,vn}$ = 15 ^{0}C (for the 11.7x3.2 m wall), $T_{st2,vn}$= 15 ^{0}C (for the 5.9x3.2 m wall), the air temperature in the room $T_{pov,vn}$= 20 ^{0}C, the average temperature on the outer wall surface $T_{st,zov}$= 5.2 ^{0}C, and the ambient air temperature $T_{pov,zov}$= 5.4 ^{0}C. The heat transfer coefficient on the wall surfaces under natural convection conditions is found as follows:

$$\alpha_{vn} = C_0 \frac{\lambda_{pov,vn}}{L} (Gr_L \cdot Pr_{pov})^n, \tag{7}$$

where $\lambda_{pov\,vn}$ – thermal conductivity coefficient of air, W/m·°C; Pr_{pov} – Prandtl number for air; $Gr_L = \frac{g \cdot \beta \cdot \Delta T \cdot L^3}{\nu^2}$ – Grashof number, where $g = 9.8 \text{ m/s}^2$ – gravitational constant, β – coefficient of volumetric thermal expansion of air, $\Delta T = T_{st} - T_{pov}$ – temperature head on the wall surface, ^{0}C, ν – kinematic viscosity coefficient of air, m/s^2; L – characteristic vertical dimension of the wall.

In the calculations, we will assume the values for the air parameters as follows:

1. At 20 ^0C: $\rho_{pov} = 1.21$ kg/m^3, $\upsilon_{pov} = 14.8 \cdot 10^{-6}$ m^2/s, $\lambda_{pov} = 0.0256$ $W/m \cdot K$, Pr_{pov}=0.703, β =0.0034;

2. At 5,4 ^0C: $\rho_{pov} = 1.28$ kg/m^3, $\upsilon_{pov} = 13.4 \cdot 10^{-6}$ m^2/s, $\lambda_{pov} =.,0246$ $W/m \cdot K$, Pr_{pov}= 0.707, β = 0.0036.

We assume that the characteristic vertical dimension of the wall is L=3.2 m, the flow regime is laminar, with C_0 = 0.59; n=0.25. As a result of the calculations, we find the following for internal wall 1 and wall 2: $\alpha_{st,vn} = 1.82$ W/(m^2·K). The heat transfer coefficient on the outer surface of the walls is: $\alpha_{st2,vn} = 0.834$ W/(m^2·K).

Considering the values of the thickness and thermal conductivity coefficient for each layer of the wall: 1 – plaster layer $\delta_1 = 0.02$ m, $\lambda_1 = 0.7$ $W/$m·K, 2 – solid clay brick masonry on cement-sand mortar layer $\delta_2 = 0.51$ m, $\lambda_2 = 0.81$ W/m·K, 3 – ceramic facing tile layer $\delta_3 = 0.02$ m, $\lambda_3 = 3.49$ W/m·K, 4 – adhesive mortar layer $\delta_4 = 0.01$ m, $\lambda_4 = 0.87$ W/m·K, 5 – mineral wool insulation layer $\delta_5 = 0.1$ m, $\lambda_5 = 0.05$ W/m·K, 6 – outer finish layer $\delta_6 = 0.005$ m, $\lambda_6 = 0.87$ $W/$m·K.

We find the thermal resistance of the wall: $\sum_{i=1}^{6} \delta_i/\lambda_i = 2.93$ m$\cdot\frac{K}{W}$. Next, using formula (6), we find the heat transfer coefficient through the wall, assuming only natural convection on the outer surface (no wind flow present): $K = \frac{1}{1/\alpha_{st,vn} + \sum_{i=1}^{m} \delta_i/\lambda_i + 1/\alpha_{st,zov}} = 0.214$ W/m^2·K.

The total surface area of the building walls bordering the external environment is found using the formula: $F_{st} = F_{st,pov} - F_{vk} = 37.84$ m^2, where $F_{st,pov} = 56.32$ m^2 – total area of two walls, $F_{vk} = 18.48$ m^2.

We find the heat losses to the environment from the building's wall enclosures using the formula:

$$Q_{st} = K \cdot F_{st}(T_{pov,vn} - T_{pov,zov}). \quad (8)$$

We assume that $T_{pov,vn} = 20$ ^{0}C, $T_{pov,zov} = -7.4^0$C are the internal temperature and the minimum external air temperature during the cold period of the year. As a result of calculations using formula (8), we obtain the heat loss value for wall surfaces (without considering wind flow) as $Q_{st} = 221.64$ W.

On the outer surface of the wall, there can be a mixed heat exchange regime with natural convection (in the absence of wind) and forced convection (in the presence of wind flowing around the building). Wind speed in Ukraine can vary in the range of $W_{wit} = 0 - 20$ m/s. For forced air flow, the heat transfer coefficient on the wall surface is found using the formula:

$$\alpha_{zov,vm} = C_1 \cdot \frac{\lambda_{pov,zov}}{L} \cdot Re_Z{}^n \cdot Pr^m, \quad (9)$$

where $Re_Z = \frac{W_{wit} \cdot Z}{\upsilon_{pov}}$ – Reynolds number, υ_{pov} – coefficient of kinematic viscosity of air, m^2/s; Z – characteristic horizontal dimensions of the external wall in the direction of the wind, *Pr* – Prandtl number for outdoor air, and coefficients C_l and exponents *n* and *m* depend on the Reynolds number Re_Z and take the following values:

- in the range $Re_Z \leq 10^{10}$ *C_l = 0.66; n = 0.5; m = 0.33;*
- in the range $Re_Z \geq 10^{10}$ *C_l = 0.037; n = 0.8; m = 0.43.*

When mixed convection is present, accounting for the combined contribution of natural and forced convection on the external wall of the building, the heat transfer coefficient is calculated using the formula:

$$\alpha_{zov} = (\alpha_{zov,pr}^3 + \alpha_{zov,vm}^3)^{1/3}. \quad (10)$$

As the characteristic dimension of the wall for transverse wind flow, we will choose the average transverse dimension of the room walls Z = 8.8 m. In calculations, we adopt the following air parameter values at 7.4 ^{0}C: $\rho_{pov} = 1.395$ kg/m^3, $\upsilon_{pov} = 12.78 \cdot 10^{-6}$ m^2/s, $\lambda_{pov} = 0.0228$ W/m·K, $Pr_{pov} = 0.716$.

Table 1 presents the results of calculating the Reynolds number, the heat transfer coefficient for natural convection, and mixed convection on the external wall surface at various wind flow speeds, which were calculated using formulas 6−10.

Table 1. Calculation of heat losses from wall structures at various airflow speeds

Air speed, *m/s*	0	1	5	10	15	20
Reynolds number Re_Z		588 760.875	2 943 806.6	58 875 112.1	8 831 419.87	11 775 227.6
Heat transfer coefficient $\alpha_{zov,vm}$, *W/m²·K*	0.834	1.22	2.73	3.86	4.72	6.83
Heat transfer coefficient α_{zov}, *W/m²·K*	0.834	1.34	2.76	3.87	4.73	6.85
Overall heat transfer coefficient *K*, *W/m²·K*	0.214	0.237	0.26	0.268	0.271	0.276
Heat Loss Magnitude Q_{st}, *W*	221.64	245.73	269.57	277.87	280.98	286.16

For a comparative characteristic of the proposed approach, we will calculate the heat losses from the wall structures of this room using the traditional method, which is outlined in DSTU 9191 [16]. According to this standard, the following values for the heat transfer coefficients on the internal wall surfaces are used for calculating heat losses through vertical wall structures $\alpha_{st,vn} = 8.7\ W/(m^2 \cdot K)$ and for the outer surface of the wall $\alpha_{st,zov} = 23$ W/(m^2·K) [17]. The heat transfer coefficient through a multi-layered wall is calculated using formula (6), considering the thermal resistance of the wall, which consists of six layers: $K = \frac{1}{1/\alpha_{\text{ст},vn} + \sum_{i=1}^{m} \delta_\text{i}/\lambda_\text{i} + 1/\alpha_{\text{ст},zov}} = 0.324$ W/(m^2·K). Using formula (8), we calculate the heat losses through the wall structures of the room: $Q_{st} = 334.48$ W.

A comparison of these results with those obtained using the methodology proposed above (for which heat losses Q_{st} are in the range of 221.64 W to 286.16 W depending on the airflow speed (see Table 1)) shows that using the current methodology according to DSTU 9190 [15] leads to an overestimation of heat losses from wall structures by 17 %−51 %. This results in an increase in heating appliance capacity and overconsumption of heat for heating the room [18, 19].

b. Calculation of heat losses through window structures

The coefficient of heat transfer through windows is found from the ratio:

$$K = \frac{1}{1/\alpha_{vk,vn} + \sum_{i=1}^{m} \delta_\text{i}/\lambda_\text{i} + 1/\alpha_{vk,zov}}, \tag{11}$$

where $\alpha_{vk,vn}, \alpha_{vk,zov}$ − heat transfer coefficients on the internal and external surfaces of the windows, respectively, W/m^2·^{0}C; δ_i − thickness of the i-th window layer, m; λ_i − thermal conductivity coefficient of the material of the i-th window layer.

For calculations, the values for the thermal resistance of windows can be used from the data provided in DSTU B V.2.6-23 [11]. Specifically, this applies to single-chamber windows which consist of two glass panes and one air gap $\sum_{i=1}^{5} \delta_\text{i}/\lambda_\text{i}$= 0.5 m^2·^{0}C/W. The values for the heat transfer coefficients on the external and internal surfaces of the windows, under conditions of natural convection (without wind flow), are assumed in accordance with the requirements of Table B, Annex B of DSTU 9191 [16], respectively: $\alpha_{vk,vn} = 8$ W/m^2·K, $\alpha_{vk,zov} = 23$ W/m^2·K. From relation (11), we find: $K_{vk} = 1.49$ W/m^2·K.

A comparative calculation is performed according to the methodologies outlined in DSTU 9191 [16] and DSTU EN ISO 10077-1 [13]. The thermal resistance of the window is determined by selecting a combination of the transparent (glazing unit) and opaque (PVC profile, aluminum profile, or wooden elements) parts of the window to meet the requirements: $R_{pr} \geq R_{q\ min}$. The calculation of the equivalent thermal resistance is performed according to DSTU EN ISO 10077-1 [13]. Based on the data:

- glazing area of the largest light-transmitting structure A_g = 4.62 m²;
- area of opaque infill A_f = 1.16 m²;
- length of the glazing perimeter l_g = 8.6 m;
- heat transfer coefficient of distance frames ψ_g = 0.06 m².

The equivalent thermal resistance of the entire window unit is:

$$R_{pr} = \frac{1}{U_w}. \tag{12}$$

The heat transfer coefficient, U_w, of a single-glazed window is calculated according to DSTU EN ISO 10077-1 [13]:

$$U_w = \frac{\sum A_g \cdot U_g + \sum A_f \cdot U_f + \sum l_g \cdot \psi_g}{\sum A_g + \sum A_f} = 0.85\ \frac{W}{m^2 \cdot K}, \tag{13}$$

where U_f − heat transfer coefficient of the frame, which is determined in accordance with Annex D [13], U_f = 1,2 W/(m²·K); U_g − the heat transfer coefficient of the glazing unit is calculated using the formula, W/(m²·K):

$$U_g = \frac{1}{R_{se} + \sum j \frac{d_j}{\lambda_j} + \sum j R_{s,j} + R_{si}} = 0.79 \frac{W}{m^2 \cdot K}, \tag{14}$$

where R_{se} − thermal resistance on the external side, m²·K/W; λ_j − thermal conductivity of the glass or coating j, W/(m·K); d_j − thickness of the glass or coating j, m; R_{si} − thermal resistance of the glass from the internal side, m²·K/W; $R_{s,j}$ − thermal resistance of the j-th air gap is determined in accordance with Annex C [13], m²·K/W. We compared the calculation results from formula (13) with the methodology provided in the regulatory documents DSTU 9191 [16] and DSTU EN ISO 10077-1 [13]. The difference is approximately 25 %, which is considered satisfactory. For subsequent calculations, we will use the results obtained in accordance with the regulatory documents.

Heat losses through windows are calculated using the formula:

$$Q_{vk} = U_w \cdot (F_{vk,1} + F_{vk,2}) \cdot (T_{pov,vn} - T_{pov,zov}) = 592.43\ W, \tag{15}$$

where F_{vk} − total surface area of the windows in a, m²; $T_{pov,vn}$, $T_{pov,zov}$ − internal and external air temperatures, respectively, ⁰C.

When wind flows are present, calculations are performed according to the methodology used for wall structures. The average value of the transverse dimensions of the windows, Z_{vk} = 2.2 m, was chosen as the characteristic size for calculating the Reynolds number. The calculation results for various wind flow velocities are presented in Table 2. It should be noted that the heat transfer coefficients for the outer glass surface recommended in DSTU B V.2.6-23 [11] $\alpha_{vk,zov} = 23\ \mathrm{W/m^2 \cdot K}$ are overstated in the absence of wind flow, since only the contribution of natural convection is taken into account.

Table 2. Calculation of heat loss from window structures at different airflow velocities

Air speed, m/s	0	1	5	10	15	20
Reynolds number, Re_Z		196 487.5	982 437.01	1 964 873.99	2 947 311.0	3 929 747.7
Heat transfer coefficient $\alpha_{zov,vm}$, *W/m²·K*	23*	2.667	5.964	8.43	10.04	11.92
Heat transfer coefficient α_{zov}, *W/m²·K*	23*	23.006	23.06	23.2	23.59	24.02
Heat transfer coefficient *K*, *W/m²·K*	1.17	1.18	1.19	1.21	1.26	1.31
Heat loss value Q_{vk}, *W*	592.43	699.07	823.99	837.34	872.46	907.08

*The numerical values of the heat transfer coefficient are provided according to the current methodology and the data from Table B, Annex B of DSTU 9191 [16], which does not account for changes in airflow velocity.

Next, we will evaluate the heat transfer coefficient on the outer surface of the glass in the absence of wind.

The calculation is performed using formula (6) with the following input parameters: $T_{vk,zov} = 10.2\ ^0\mathrm{C}$, $T_{pov,zov} = 5.2^0\mathrm{C}$ - the outer glass surface temperature and the external air temperature, respectively; L=2.1 m – typical vertical window size; $\rho_{pov} = 1.28 kg/m^3$, $\upsilon_{pov} = 13.4 \cdot 10^{-6} m^2/s$, $\lambda_{пов} = 0.0246 W/m \cdot K$, $Pr_{пов} = 0.707$, $\beta = 0.0036$ – thermophysical properties of the external air at 5.2 °C. As a result of the calculations, we get: $\alpha_{vk,zov} = 1.95\ \frac{W}{m^2 \cdot K}$. The heat transfer coefficient is found using formula (11): $K_{vk} = 1.55$ W/(m²·⁰C). The difference between the results obtained and the results found according to the methodology of DSTU B V.2.6-23 [11] is approximately 25 %

As a conclusion, it can be stated that the current methodology of DSTU 9190 [15] provides a certain error when calculating heat loss from window structures under external environmental conditions with low wind flow velocities.

c. Calculation of heat loss due to air permeability

Heat loss through window air permeability is determined by the window's class. According to the European standard EN 14351 [1], the air permeability class for a room is Class 4 (hermetic), which corresponds to a value of $\eta_{pov,vk}$= 3 m³/(m²·h) at a pressure of 100 Pa.

The airflow rate due to air permeability through windows, given a known pressure difference between the room and the external environment, is typically determined by the following formula:

$$G_{vk,v} = n_{vk} \cdot F_{vk} \cdot \eta_{pov,vk} (\Delta P_{pov}/100)/3600, \quad (16)$$

where $G_{vk,v}$ – volumetric airflow rate through all the windows of the building, m²; n_{vk} – number of windows in the building, pcs; F_{vk} – area of one window, m²; $\eta_{pov,vk}$ – the specific air permeability for windows, which is selected depending on the window class, m³/(m²·h); ΔP_{pov} – pressure difference between the room and the external environment.

The pressure difference is found using the formula:

$$\Delta P_{pov} = g \cdot h_{vk} \cdot (\rho_{pov,vn} - \rho_{pov,zn}), \quad (17)$$

where h_{vk} – window height.

We calculate according to formula (17), $\Delta P_{pov} = 3.35\ Pa$.

The airflow rate through the windows due to air permeability is calculated using formula (16): $G_{vk,v} = 0.000516$ m³/s.

The amount of heat loss due to window air permeability is found using the formula:

$$Q_{inf,vk} = G_{vk,v} \cdot c_{r,pov,vn} \cdot T_{pov,vn}, \tag{18}$$

where $c_{r,pov,vn}$ – specific heat capacity of internal air, J/kg·^{0}C; $T_{pov,vn}$ – its temperature, ^{0}C.

The heat loss value due to window air permeability is found using formula (16) $Q_{inf,vk} = 0.0104$ kW. The amount of heat loss due to air permeability through walls, which consist of several layers of building materials, depends on the air permeability coefficient of each layer and is calculated according to DSTU-N B V.2.6.-191 [20].

The total value of the heat transmittance coefficient for a wall with n layers G^k is determined by the formula:

$$G^{к} = \left(\sum_{i=1}^{n} \frac{1}{G_i^{\Delta P}}\right)^{-1}, \tag{19}$$

where $G_i^{\Delta P}$ – is the air permeability coefficient for the i-th layer.

The mass air permeability of a single-layer construction $G^{к}$ or an individual homogeneous layer of a structure $G^{\Delta P}$ is determined based on the pressure drop. This can be done either from the results of tests carried out by accredited laboratories in accordance with DSTU-N B V.2.6.-191 [20], or by a formula:

$$G^{к} = G^{\Delta P} = G^{\Delta P0} \cdot (\Delta p / \Delta p_0)^n, \tag{20}$$

where $G^{\Delta P0}$ – is the mass air permeability of the building envelope at Δp_0, which is determined for specific types of wall materials based on test results according to DSTU-N B V.2.6.-191 [20]; Δp_0 – is the pressure difference at which the mass air permeability of structures is determined experimentally (Δp_0=10 Pa); Δp is the calculated pressure difference, Pa; n is the filtration exponent, which is determined based on test results according to DSTU-N B V.2.6.-191 [20]. For mineral wool insulation, n=1.5.

The calculated pressure difference is determined by the formula:

$$\Delta p = (H - h_i) \cdot (\gamma_{zov} - \gamma_{vn}) + 0{,}03 \cdot \gamma_{zov} \cdot v^2 \cdot \beta_k, \tag{21}$$

where H – height of the building (from the first-floor level to the top of the exhaust shaft), m; h_i – height from the first-floor level to the center of the building envelope of the i-th floor for which the calculation is performed; v – wind flow velocity, m/s; β_k – coefficient for accounting for the velocity of external air movement, depending on the building's height and the external conditions in which the building is located (urban development with buildings over 25 m, etc.); γ_{zov}, γ_{vn} – specific weight of the external and internal air, respectively, N/m^3, which is calculated using the formulas:

$$\gamma_{zov} = 3463/(273 + t_{zov}); \gamma_{vn} = 3463/(273 + t_{vn}). \tag{22}$$

The coefficient for accounting for the velocity of external air movement, depending on the building's height, is selected according to DSTU-N B V.2.6.-191 [20]. For a building up to 10 m high in a forested area, we find that the coefficient is $\beta_к$= 0.65.

We then proceed with the calculation of air permeability for the walls in the room. Using formula (22), we find the specific weight of the external and internal air: $\gamma_{zov} = 13.8$ N/m^3, $\gamma_{vn} = 11.82$ N/m^3.

The pressure difference between the external and internal air is found in the absence of wind flow ($v = 0$) using formula (21), considering the room is on the second floor, for which $h_i = 4.8$ m, $\Delta p = 3.168$ Pa.

Using formula (20) with these values $G^{\Delta P0}$, we find the air permeability for each layer of the wall structure:

for the 1st layer:

$G_1^{\text{к}} = G_1^{\Delta P} = 0.0048$ *kg/m³·h*;

for the 2 st layer:

$G_2^{\text{к}} = G_2^{\Delta P} = 0.1$ *kg/m³·h*;

for the 3st layer:

$G_3^{\text{к}} = G_3^{\Delta P} = 0.00048$ *kg/m³·h*;

where 0.1 – is a coefficient that represents the percentage of sand-cement mortar located in the joint layer between adjacent tiles where;

for the 4st layer:

$G_4^{\text{к}} = G_4^{\Delta P} = 0.0226$ *kg/m³·h*;

for the 5st layer:

$G_5^{\text{к}} = G_5^{\Delta P} = 3.985$ *kg/m³·h*;

for the 6st layer:

$G_6^{\text{к}} = G_6^{\Delta P} = 0.0226$ *kg/m³·h*.

The total value of the air permeability coefficient for a 6-layer wall is determined using formula (19), $G^{\text{к}} = 0.000455$ kg/(m³·h).

The heat loss through a building's enclosing wall structure can be determined using the formula.

$$Q_{inf,st} = G^{\text{к}} \cdot F_{st} \cdot c_{r,pov,vn} \cdot T_{pov,vn} \cdot (\Delta P_{pov}/100)/3600, \tag{23}$$

where F_{st} − is the surface area of the entire building's enclosing wall structure, excluding the surface area of windows and doors, in m²; $c_{r,pov,vn}$ − is the specific heat capacity of the indoor air, in J/(kg·°C); $T_{pov,vn}$ − is its temperature, in ^{0}C; ΔP_{pov} − is the pressure loss, in Pa.

As a result of the calculations, we find the heat loss due to air permeability through the enclosing wall structure of the room to be $Q_{inf,st} = 3.05 \cdot 10^{-6}$ kW.

In addition to the heat loss from air permeability through the wall structure, it is necessary to account for the air permeability through the layer of foam sealant around the window structures. We calculate these losses using a method similar to the one used for the wall structure. According to this method, we determine the pressure difference between the indoor and outdoor air using formula (21) as $\Delta p = 3.168$ Pa. Using formula (20), and taking into account the values of $G^{\Delta P0}$, we find the air permeability for the foam sealant layer of the window structure to be $G_p^K = G_p^{\Delta P} = 0.0048$ kg/m³·h.

We determine the heat loss through the enclosing wall structure using formula (23), where $F_{p,vk}$ is the surface area of the enclosing wall structure of the entire building, which is determined by the expression:

$$F_{p,vk} = n_{vk} \cdot P_p \cdot \Delta l_p, \tag{24}$$

where $P_p = 2(h_{vk} + l_{vk})$ – is the external perimeter of the window; h_{vk}, l_{vk} – are the height and width of the window, Δl_p= 0.02 m – is the width of the mounting foam layer around the windows.

The calculation of heat loss due to air permeability through the polystyrene layer of mounting foam is performed, resulting in $Q_{inf,p} = 4.68 \cdot 10^{-6}$ kW.

Heat loss due to the air permeability of enclosing structures has three components: losses through window structures, wall structures, and the mounting foam layer around the windows. The total heat loss through these components can be found using the following formula:

$$Q_{inf} = Q_{inf,vk} + Q_{inf,st} + Q_{inf,p}. \tag{25}$$

As a result of the calculations, we find the total losses due to air permeability to be: $Q_{inf} =$ 0.010408 kW.

In the presence of wind flow, it is necessary to account for additional pressure losses, which depend on the wind speed v and a coefficient β_k, that considers the influence of the external environment. With a wind speed of v =*1 m/s* and in the presence of a forest area (for which the coefficient β_k is 0.65), the pressure difference between the internal and external air is found using formula (21), $\Delta p = 3.44$ Pa. The results of the calculation regarding the influence of wind flow velocity on the air permeability of the multi-layer wall structure are presented in Table 3.

Table 3. Heat loss due to air permeability from a multi-layer wall structure at different airflow velocities

Air speed, *m/s.*	0	1	5	10	15	20
Pressure difference between the internal and external environment, *Pa.*	3.168	3.44	9.918	30.44	63.918	111.168
Air permeability coefficient for a multi-layer wall, *kg/(m³·h).*	0.000455	0.000515	0.00251	0.0135	0.0412	0.0947
Air permeability coefficient for the mounting foam layer, *kg/(m³·h).*	0.0048	0.00486	0.00686	0.0178	0.0455	0.099
Heat loss through the wall structure due to air permeability, *kW.*	$3.05\cdot10^{-6}$	$3.32\cdot10^{-6}$	$9.58\cdot10^{-6}$	$29.41\cdot10^{-6}$	$61.74\cdot10^{-6}$	$107.39\cdot10^{-6}$
Heat loss through the mounting foam layer due to air permeability, *kW.*	$4.68\cdot10^{-6}$	$5.08\cdot10^{-5}$	$14.68\cdot10^{-6}$	$45.05\cdot10^{-6}$	$94.6\cdot10^{-6}$	$164.53\cdot10^{-6}$
Total heat loss due to air permeability Q_{inf}, *W.*	1.0477	1.0484	1.0643	1.114	1.291	1.312

A comparative analysis of the results shows that the absence or presence of wind flow does not lead to significant heat losses. This is due to the very small values of the air permeability coefficient. Under conditions with or without wind flow in the range of 0-20 m/s, the air exchange rate in the room is within the range of 0.61 to 0.74, depending on the wind speed.

3. Results and Discussion

A comparison of the calculated indicators with the results of experimental studies showed that the air exchange rate in the experiments was close to 1.4 h^{-1}. This is due to the presence of non-airtight contact points between casement windows and their frames, as well as between the ceiling slabs and external wall structures, which were not taken into account when calculating ventilation losses.

However, the values obtained prove the previously stated assumption about the presence of hidden ventilation openings in the room, which were not considered in the ventilation loss calculations and are not accounted for by the current methodology.

Therefore, only the use of an improved heat loss calculation methodology for individual rooms of a multi-story building — one that accounts for wind flow speeds in conjunction with an airtightness test of the building envelope — will make it possible to realistically assess the actual level of energy consumption and establish the building's energy efficiency class, as the difference between the obtained values can reach 40 %.

The heat balance of total heat losses and heat gains in the room is obtained by the formula:

$$Q_{bat}=Q_{st}+Q_{vik}+Q_{dv}+Q_{pid}+Q_{st,sum}+Q_{ven}+Q_{inf}-Q_{os}-Q_{pryl}-Q_{lud}-Q_{vypr} \quad (26)$$

The presence of doors, floors, and walls that are adjacent to other rooms within the building does not affect the heat losses and heat gains of the room. Therefore, given the absence of a ventilation system, we can assume: Q_{dv}=0, Q_{pid}=0, $Q_{st,sum}$=0, Q_{ven}=0.

By calculating all components of the heat losses and heat gains, we obtain the required heating load for the room under no-wind conditions in the external environment, Q_{bat}=-2991.88 W. In the absence of people, Q_{bat}=132.62 W.

In the presence of a wind flow that has different speeds, the results of calculating the total heat loss in the room are given in Table 4.

Table 4. Total heat losses from the lecture room at different wind speeds

Airflow velocity, *m*/s.	0	1	5	10	15	20
Heat losses at different wind speeds, without considering heat gains Q_{bat}, *W*.	-2992.38	-2861.65	-2712.88	-2691.18	-2653.75	-2612.95
Heat losses at different wind speeds Q_{bat}, *W*.	132.62	263.35	412.12	433.82	465.25	512.45

An analysis of the obtained data on heat losses from the lecture room shows that the required heating power to heat this space and maintain a temperature of 20 °C, in the absence of occupants, is in the range of 132 W to 512 W, depending on the airflow velocity. Under conditions of people being present in the room and during the operation of a mechanical supply and exhaust ventilation system, this value can be increased by 1.5 times.

4. Conclusions

In the course of this study, infiltration and transmission heat losses of building structures were evaluated. Modern methods for assessing heat loss were considered, including numerical modeling and experimental studies using thermal imaging analysis. The obtained results allow for the following conclusions.

Infiltration heat losses depend on the building's airtightness level and external factors such as wind speed and pressure difference. The use of improved methodologies for calculating air permeability makes it possible to reduce the error in determining heat losses and to adjust energy-saving measures.

Transmission heat losses are largely determined by the thermal resistance of the building envelope. A comparative analysis of calculation methodologies showed that traditional regulatory approaches can overestimate actual heat losses by 17−51 %, which may lead to excessive energy consumption for heating.

The influence of wind flows on heat transfer coefficients confirms the need to account for mixed convection regimes when assessing heat losses through walls and window structures. Calculations showed that with an increase in wind speed up to 20 *m/s*, heat losses can rise by 20−30 %.

The study of heat loss through windows confirmed the need to improve regulatory approaches to evaluating their heat transfer. It was found that calculations based on current standards may contain an error of up to 25 %, which affects the accuracy of energy audits.

The air permeability of the building envelope significantly affects the energy efficiency of buildings. The analysis showed that heat loss through non-airtight structures can account for 10−15 % of a room's total heat loss, and hidden ventilation openings, which are not considered by traditional methods, can increase the air exchange rate.

The balance of heat losses and gains showed that the actual heating energy requirements for a room can vary depending on the presence of wind flows and internal heat sources. To maintain a temperature of 20 °C, in the absence of occupants, the required heating power varies within the range of 132−512 W depending on the airflow velocity.

The results obtained can be used for improving methods of building energy analysis, developing more effective strategies for thermal modernization, and clarifying regulatory documents on the evaluation of building heat loss.

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ОЦІНКА ІНФІЛЬТРАЦІЙНИХ ТА ТРАНСМІСІЙНИХ ТЕПЛОВТРАТ БУДІВЕЛЬ

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Анотація. *Зменшення тепловтрат у будівлях є критично важливим завданням у контексті підвищення енергоефективності та дотримання сучасних екологічних стандартів, особливо в умовах зростання вартості енергоресурсів. Метою дослідження є комплексна оцінка інфільтраційних та трансмісійних тепловтрат з урахуванням впливу зовнішніх факторів і конструктивних особливостей будівель. Для досягнення поставленої мети застосовано чисельне моделювання теплових процесів, аналітичні розрахунки та експериментальні методи, включаючи тепловізійний аналіз та аерометричні вимірювання герметичності. На основі аналізу отриманих геометричних параметрів та теплофізичних характеристик матеріалів проведено розрахунок тепловтрат через стінові, віконні та дверні конструкції, зокрема з урахуванням таких зовнішніх чинників як швидкість вітру, атмосферний тиск та температурні перепади. Результати дослідження показали, що інфільтраційні тепловтрати значно залежать від рівня герметичності огороджувальних конструкцій і можуть досягати 10–15 % від загальних втрат. Дослідження теплових втрат через вікна підтвердило необхідність вдосконалення нормативних підходів до оцінки їх теплопередачі. Встановлено, що розрахунки за чинними нормативами можуть містити похибку до 25 %, що впливає на точність енергоаудиту. Трансмісійні втрати також залежать від термічного опору огороджувальних конструкцій, а стандартні розрахункові підходи можуть завищувати їх на 17–51 %. Виявлено, що зі збільшенням швидкості вітру до 20 м/с тепловтрати зростають на 20–30 %, що підтверджує необхідність врахування змішаних режимів конвекції. Порівняння отриманих експериментальних даних з результатами розрахунків дозволило оцінити похибки існуючих нормативних методик та уточнити підходи до розрахунків при визначенні теплових втрат. Це дослідження підтверджує необхідність удосконалення підходів до оцінки теплових втрат будівель з врахуванням особливостей повітропроникності матеріалів. Результати цього дослідження можуть бути використані для вдосконалення методів енергетичного аналізу будівель, розробки більш ефективних стратегій термомодернізації будівельного фонду, а також створення науково обґрунтованих рекомендацій щодо зниження енергоспоживання.*

Ключові слова: повітропроникність, енергоефективність, герметичність, огороджувальні конструкції, інфільтраційні тепловтрати, трансмісійні тепловтрати, тепловізійне обстеження.

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