Numerical simulation of thermal bridges in enclosure structures as an express-method for the expert assessment of thermal comfort in domestic premises

N D Korsun¹, D A Prostakishina¹, A S Novikova¹

¹ Department of Building structures, Industrial University of Tyumen, 625000, Volodarsky str., 38, Tyumen, Russian Federation

E-mail: korsun1@ya.ru

Abstract. The paper presents the solution to the problem of numerical simulation of thermal comfort in domestic premises. Three thermal bridges have been selected as the key parameters for enclosure structures. They have been calculated on the basis of thermographic studies of a group of typical brick blocks of flats which are located in the city of Tyumen. The considered thermal bridges are as follows: the insulation connections in the outer wall openings; insulation in the outer wall corners; insulation in the outer wall-floor structure connections. The functional connections of the thermal comfort level versus the values of the thermal bridge parameters have been determined. The study has resulted in an express-method of the expert assessment of thermal comfort in domestic premises based on the total assessment of thermal bridges in enclosure structures. The method can be used for a complete structural survey of residential buildings, and in examination of building operation and heat-protective properties of enclosure structures.

1. Introduction

The indoor climate has a direct effect on humans and their life and represents the indoor climatic conditions embracing temperature, humidity and air velocity [1]. Observance of the necessary measures focused on comfortable indoor climatic conditions is one of the main tasks when designing and constructing residential buildings. Equally, reduction of energy consumption is currently one of the priorities for national development, and it is directly related to improvement of energy efficiency of buildings and their thermal protection.

2. Thematic justification

Vlasov O.E. [2], Bogoslovsky V.N. [3], Ilinsky V.M. [4], et.al paid attention to thermal engineering for construction and thermal capacity of buildings. They developed fundamentals of the methodology of thermal engineering for construction.

At present, energy efficiency of buildings and thermal comfort at minimum energy costs dominate [5, 6, 7, 8, 9, 10, 11, 12, 13]. The authors [6, 14] consider models of thermal comfort in homogeneous and heterogeneous thermal media, their advantages, limitations and range of application. The influence of air permeability of enclosure structures on energy efficiency of buildings is studied in [7, 8, 13, 15, 16]. The study is based on the results of surveys of residential buildings erected in Canada and Sweden over the last decades. The effect of the thermal protection level of a building on the
amount of thermal energy losses is analyzed in [17]; operation and fuel-energy costs for a heating period of a block of flats are determined for a period of 5, 10 and 50 years of operation. The study on the influence of indoor air humidity on energy consumption of buildings, durability of building structures and human comfort, and a numerical method describing the moisture processes on the basis of experimental data are presented in [18].

Surveys of typical brick blocks of flats were conducted by experts of the Industrial University of Tyumen in the city of Tyumen from 2011 to 2017. They revealed a number of problems concerning thermal comfort of domestic premises in winter related to errors in design, construction and operation [19]. Based on the results of construction and technical expertise, when heat losses were measured by the thermal imaging control [20] using the FlirT335 thermal imager, conclusions were drawn on the most common defects related to the increased heat losses through the enclosure structures:

- defected insulation of connections in the outer wall openings as a result of poor air tightness of insulating glass units and poor junctions between window or door balcony blocks and the outer wall openings;
- defected insulation in the outer wall corners;
- defected insulation in the outer wall-floor structure connections; as a rule, this is due to the lack of thermal insulation in the end floor slab;
- empty vertical and horizontal mortar joints in brick outer walls; heterogeneous inclusions in outer walls.

These defects cause infiltration of outdoor air through the connections of outer and inner walls, connections of outer walls and floor structures or outer wall openings. This leads to a dramatic decrease of the thermal capacity of outer walls and condensate, fungi or mold formation, and hence, thermal comfort is disturbed.

3. Problem formulation and analysis

The revealed defects made it possible to formulate the problem in order to find the functional connections between the divergence of the parameters of thermal bridges in enclosure structures and the level of thermal comfort in domestic premises [21] on the basis of numerical simulation of heat flow processes in order to determine the acceptable limits.

The problem of numerical simulation consisted in a series of numerical experiments for each considered connection of the enclosure structure including thermal engineering irregularities which resulted in the values of the explanatory variable \( x_j (j = 1, k) \) and the response of the system \( y_i (i = 1, n) \), where \( k \) is the number of factors, \( n \) – the number of experiments. Next, the functional connections and optimal assessments of the parameters \( b_0, b_j, b_y, b_y \) were determined by the regression analysis.

Thermal bridges in the connections of enclosure structures were considered as the objects of simulation: insulation of connections in the outer wall openings (Fig. 1); insulation in the outer wall corners (Fig. 2); insulation in the outer wall-floor structure connection (Fig. 3). The actual structural diagram and structural performance were taken into account in simulation of every connection.

**Figure 1** Connection in the outer wall opening: 1 – face layer, 2 – thermal insulation, 3 – bearing layer, 6 – assembly foam, 7 – insulation tape.
The temperature on the inner surface of the enclosure structure in the joint zone $\tau_v$, °C was taken as a target parameter in the whole of experiments. The level of thermal comfort was assessed in the following ranges:

- optimal level at $\tau_v > 16$°C;
- permissible level at $16$°C $\leq \tau_v < 14$°C;
- unacceptable level at $14$°C $\leq \tau_v < 10.6$°C;
- critical level at $\tau_v \leq 10.6$°C.

The thermal physical properties of materials and geometric dimensions of the structural sections joined in the connections were taken as the variable parameters of the experiment; the range of the variable parameters was taken from the constructive considerations in accordance with the regulations and norms.

The considered variable parameters for the connection in the outer wall opening: the coefficient of thermal conductivity of the assembly foam $x_1$, $W/(m \cdot ^{\circ}C) ^{-1}$ (in availability), $x_1 \in \{0; 0.7\}$; layer thickness of the assembly foam $x_2$, mm (in availability), $x_2 \in \{0; 60\}$ and the coefficient of thermal conductivity of the insulating self-expanding tape or mastic compound $x_3$, $W/(m \cdot ^{\circ}C) ^{-1}$ (in availability), $x_3 \in \{0; 0.058\}$. The significance of the factor model parameters was determined by means of rough estimates using the Plackett-Berman method [22].

The considered variable parameters for the outer walls connection: the coefficient of thermal conductivity of the wall insulator, $x_1$, $W/(m \cdot ^{\circ}C) ^{-1}$, $x_1 \in \{0.031; 0.110\}$; the length of the extra thermal insulation $x_2$, mm (in availability), $x_2 \in \{0; 500\}$ and the coefficient of thermal conductivity of the wall bearing layer, $x_3$, $W/(m \cdot ^{\circ}C) ^{-1}$, $x_3 \in \{0.20; 0.81\}$.

The considered variable parameters for the outer wall - floor structure connection: the coefficient of thermal conductivity of the wall insulator, $x_1$, $W/(m \cdot ^{\circ}C) ^{-1}$, $x_1 \in \{0.031; 0.110\}$; the length of the extra thermal insulation $x_2$, mm, $x_2 \in \{120; 450\}$ and the coefficient of thermal conductivity of the insulator in the end floor slab, $x_3$, $W/(m \cdot ^{\circ}C) ^{-1}$ (in availability), $x_3 \in \{0; 0.062\}$.

In order to describe the model, a second-degree polynomial-type function was taken, where the regression coefficients $\beta_0$, $\beta_j$, $\beta_{ji}$, $\beta_{ji}$ were replaced by the estimated coefficients $b_0$, $b_j$, $b_{ji}$, $b_{ji}$:

$$y = b_0 + \sum_{j=1}^{k} b_j x_j + \sum_{j=1}^{k} \sum_{i=j+1}^{k} b_{ji} x_i x_j + \sum_{j=1}^{k} b_{ji} x_j^2.$$  \hspace{1cm} (1)
In order to solve this problem, an active experiment was conducted using methods of the theory of planning of extreme experiments and saturated continuous D-optimal plans [22]. The ELCUT 6.1 software program was used to implement the experimental results [23].

4. Results

The experimental studies resulted in graphic presentations of the temperature fields with isotherms and heat flow vectors (Fig. 4, 5, 6), temperature values on the inner surface of the outer enclosure structure in the connection obtained for each experiment, and analytical dependencies of the objective function.

The analytical dependencies obtained are as follows:

- for the connection in the outer wall opening
  \[ y = 12,58 + 1,59 \cdot X_1 + 3,26 \cdot X_2 + 0,73 \cdot X_3; \]  

- for the outer walls connection
  \[ y = 14,45 + 1,49 \cdot X_1 + 1,45 \cdot X_2 + 0,84 \cdot X_3; \]  

- for the outer wall - floor structure connection
  \[ y = 15,12 + 3,70 \cdot X_1 + 0,94 \cdot X_2 + 0,93 \cdot X_3. \]

The analysis of the data obtained after the experimental plans (from 13 experiments of the saturated D-optimal plan for each connection) and the regression equations made it possible to draw the following conclusions:

1) for the connection in the outer wall opening, the whole of the studied parameters are significant; the best options for optimization of the connection are as follows: errors of closure insulated with the assembly foam with the coefficient of thermal conductivity to be 0.035 \( W/(m \cdot ^\circ C) \); minimum error of closure - 20 mm and availability of the insulating self-expanding tape or mastic compound with the coefficient of thermal conductivity to be 0.029 \( W/(m \cdot ^\circ C) \);.

2) for the outer walls connection, the key parameters are as follows: the coefficient of thermal conductivity of the wall insulator \( x_1, W/(m \cdot ^\circ C) \) and the length of the extra thermal insulation \( x_2, \text{mm} \); the best options for optimization of the connection are as follows: thermal insulation of the outer wall with the coefficient of thermal conductivity to be 0.031 \( W/(m \cdot ^\circ C) \), the length of the extra thermal insulation min. 500 mm and efficient brickwork with the coefficient of thermal conductivity to be 0.2 \( W/(m \cdot ^\circ C) \).

3) for the outer wall - floor structure connection, the coefficient of thermal conductivity of the wall insulator \( x_1, W/(m \cdot ^\circ C) \) is the most significant parameter; the best options for optimization of the connection are as follows: thermal insulation of the outer wall with the coefficient of thermal conductivity to be 0.031 \( W/(m \cdot ^\circ C) \), the depth of the floor slab support max 120 mm (min depth in...
terms of design requirements), and availability of the insulator in the slab end with the coefficient of thermal conductivity to be 0.031 W·(m °C)-1.

5. Conclusions
Thus, it can be concluded that temperature conditions in domestic premises are the key factor for the winter period; in here, the key parameters are air temperature in the rooms and surface temperature of the enclosure structure in the zone of thermally-conductive inclusions. The challenges concerning thermal protection of buildings include: insulation in the outer wall - floor structure connection, insulation in the corners of the outer walls, insulation of connections in the outer wall openings.

A series of numerical experiments was performed for the thermal bridges which resulted in the obtained values of the target parameters and the given factors of the temperature conditions of the connections. Models of the selected indoor climate parameters were constructed using the regression analysis.

Based on the models built, the significant parameters influencing the indoor climate were determined:

- for the outer wall - floor structure connection - the coefficient of thermal conductivity of the wall insulator ($x_1$, W·(m °C)-1);
- for the outer walls connection - the coefficient of thermal conductivity of the wall insulator ($x_1$, W·(m °C)-1) and the length of the thermal insulation section ($x_2$, mm);
- for the connection in the outer wall opening - layer thickness of the assembly foam and the size of the error closure ($x_2$, mm).

The data obtained can be used to simplify the work of specialists and experts in a complete structural survey of residential buildings or in examination of building operation and heat-protective properties of enclosure structures in individual domestic premises, in particular, in the city of Tyumen.

Since the regression equations are based on calculations of the temperature fields for particular brick walls that are widely used in residential construction in the city of Tyumen, their use will make it possible to exclude calculations of the temperature fields and conduct thermovision quality control of these structures in their expert assessment.

References
[1] Tekhnicheskij reglament o bezopasnosti zdanij i sooruzhenij [Technical regulations on safety of buildings and structures] (rus)
[2] Vlasov O E. Osnovy stroitel'noj teplotekhniki (k kursu otopleniya ventilyacii)/ O.E.Vlasov. M: Tip. VIA RKKA, 1938. - 94 s. [Vlasov O E. Basics of thermal engineering for construction (to the course of heating and ventilation)] (rus)
[3] Bogoslovskij V N. Teplovoj rezhim zdaniya. – M:Strojjizdat, 1979. - 248s. [Bogoslovskij V N. Building thermal conditions] (rus)
[4] Il'inskij V M. stroitel'naya teplofizika. - M:Vysshaya shkola, 1974. – 320 s. [II'inskij V M. Building Thermophysics ] (rus)
[5] Kuvshinov Yu Ya. Osnovy obespecheniya mikroklimata zdani/ucheb.dlya vuzov. – M: Izdatel'stvo Associacii stroitel'nyh vuzov 2012. – 200 s. [Kuvshinov Yu Ya. Basics of indoor climate for buildings / Manual for building universities] (rus)
[6] Cheng Y, Nin J and Gao N. Thermal comfort models: A review and numerical investigation Building and Environment 2012 vol 47 pp 13-22
[7] Orr H, Wang J, Fetsch D and Dumont R.Technical note: Airtightness of older-generation energy-efficient houses in Saskatoon Journal of Building Physics 2013 vol 36 pp 294-307
[8] Rohdin P, Molin A and Moshfegh B. Experiences from nine passive houses in Sweden – indoor thermal environment and energy useBuilding and Environment 2014 vol 71 pp 176-185
[9] Dodoo A, Gustavsson L and Sathe R. Building energy-efficiency standards in a life cycle primary energy perspective Energy and Buildings 2011 vol 43 Issue 7 pp 1589-1597
[10] Mlakar J and Štrancar J. Temperature and Humidity Profiles in Passive-house Building Blocks. *Building and Environment* 2013 vol 60 pp 185-193

[11] Fountain M E, Xu T, Arens E and Oguro M. An investigation of thermal comfort at high humidities. *ASHRAE Transactions* 1999 vol 105 Part 2 pp 94-103

[12] Zhang L Y, Jin L W, Wang N Z et. al. Effects of wall configuration on building energy performance subject to different climatic zones of Chia. *Applied Energy* 2017 vol 185 part 2 pp 1565-1573

[13] Sassine E, Younsi Z, Cherif Y and Antczak E. Frequency domain regression method to predict thermal behavior of brick wall of existing buildings. *Applied Thermal Engineering* 2017 vol 114 pp 24-35

[14] Friess W A, Rakhshan K and Davis M P. A global survey of adverse energetic effect of increased wall insulation in office buildings: degree day and climate zone indicator. *Energy Efficiency* 2017 vol 10 Issue 1 pp 97-116

[15] Sobhy I, Brakez A and Benhamou B. Analysis for thermal behavior and energy savings of a semi-detached house with different insulation strategies in a hot semi-arid climate. *Journal of Green Building* 2017 vol 12 Issue 1 pp 78-106

[16] Dos Santos G H and Mendes N. Heat, Air and Moisture Transfer through Hollow Porous Blocks. *International Journal of Heat and Mass Transfer* 2009 vol 52(9-10) pp 2390-2398

[17] Vatin N I, Nemova D V, Rymkevich P P and Gorskhov A S. Vliyanie urovnya teplovoj zashchity ograzhdayushchih konstrukcij na velichinu poter' teplovoj ehnergii v zdanii. *Inzhenerno-stroiteln'nyj zhurnal*. 2012. № 8 (34). S. 4—14. [Vatin N I, Nemova D V, Rymkevich P P and Gorskhov A S. Influence of a thermal protection level of enclosure structures on amount of thermal energy losses in buildings. *Engineering and Construction Journal* (rus)]

[18] Teodosiu R. Integrated Moisture (Including Condensation)-Energy-Airflow Model within Enclosures. *Building and Environment* 2013 vol 61 pp 197-209

[19] Novikova A S and Korsun N D. Obzor narushenij teplovoj zashchity na primere zhilyh ob'ektov goroda Tyumeni. *Energosberezhenie i innovacionnye tekhnologii v toplivno-ehnergeticheskom komplekke: materialy Mezhdunarodnoj nauchno-prakticheskoy konf. T 1 – Tyumen*: TIU, 2016. – 438 s. - S. 237-241. [Novikova A S and Korsun N D. Survey of thermal protection defects as exemplified by residential buildings in the city of Tyumen. *Energy saving and innovative technologies in the fuel and energy complex*: Collected papers of the International Scientific and Practical Conference. - Tyumen: IUT, 2016] (rus)

[20] GOST R 54852-2011. Metod teplovizionnogo kontrolya kachestva teploizolyacii ograzhdayushchih konstrukcij. - M.: Standartinform. – 19 s. [GOST R 54852-2011. Method of thermovision quality control of thermal insulation of enclosure structures] (rus)

[21] Novikova A S and Korsun N D. Ocena teplovych poter' na primere zhilyh ob'ektov goroda Tyumeni. *Voprosy nauki i obrazovaniya: teoreticheskie i prakticheskie aspekty: materialy Mezhdunarodnoj nauchno-prakticheskoy konferenции (CHEkhiya, Praga, 16 мая 2017). – Vydavatel “Osviceni”, Prague, ChechRepublic, 2017. - S. 127-131. [Novikova A S and Korsun N D. Assessment of heat losses as exemplified by residential buildings in the city of Tyumen. *Issues of Science and Education: Theoretical and Practical Aspects*: Collected papers of the International Scientific and Practical Conference. – Prague, Czech Republic, 2017] (rus)

[22] Hartman K. *Planirovanie eksperimenta v isssledovanii tekhnologicheskikh processov* / K. Hartman, EH. Leckij, V. SHEfeir i dr.; pod obschch. red. EH. K. Leckogo. – M.: Mir, 1987. – 522 s. [Hartman, K. Planning an experiment in studying technological processes] (rus)

[23] ELCUT [Elektronnyj resurs].URL: http://elcut.ru/index.htm (data obrashcheniya: 13.11.2015) [ELCUT [Electronic resource].URL: http://elcut.ru/index.htm (reference date: November 13, 2015) (rus)