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PROBABILISTIC ANALYSIS OF THERMAL PERFORMANCE OF THE WALL FROM LIGHT-GAUGE THIN-WALLED STEEL STRUCTURES

The article is devoted to determining of the thermal reliability rates of CFS wall panels based on three thermo-technical failure criteria - reduced heat transfer resistance, exceeding the values of the temperature difference between the reduced temperature of the inner surface of structure and internal air temperature above the permissible temperature values by the sanitary requirements and criteria of reduction of local values of the inner surface temperature to the temperature of vapor-liquid condensation.

With increasing coefficient of variation of thermal conductivity from 2.28% to 20%, the probability of refusal of wall panels of light steel thin-walled structures, under the criterion of the specified heat transfer resistance, is increasing from $9,85\times10^{-7}$ to 0,015 respectively.

***Keywords:** light-gauge thin-walled steel structures, wall, thermal conductivity, linear heat transfer coefficient, thermal resistance, thermal reliability.*

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ІМОВІРНІСНИЙ АНАЛІЗ ТЕПЛОТЕХНІЧНИХ ПОКАЗНИКІВ СТІНИ З ЛЕГКИХ СТАЛЕВИХ ТОНКОСТІННИХ КОНСТРУКЦІЙ

Розглянуто визначення показників теплової надійності стінової панелі із легких сталевих тонкостінних конструкцій (ЛСТК) при зміні фізичних характеристик за трьома теплотехнічними критеріями відмови – приведеним опором теплопередачі, перевищенням значень перепаду температур між приведеною температурою внутрішньої поверхні конструкції та температурою внутрішнього повітря над значеннями температури, допустимими за санітарно-гігієнічними вимогами, та за критерієм зниження локальних значень температур внутрішньої поверхні до температури конденсації пари повітря.

З'ясовано, що ймовірність відмови стінової панелі із ЛСТК за критерієм приведеного опору теплопередачі зі збільшенням коефіцієнта варіації теплопровідності від 2,28 до 20% підвищується від $9,85\times10^{-7}$ до 0,015 відповідно.

***Ключові слова:** легкі тонкостінні конструкції, стіна, теплопровідність, лінійний коефіцієнт теплопередачі, опір теплопередачі, теплова надійність.*

Introduction. One of the important factors of economic growth in Ukraine is the development of energy saving and energy efficiency in the construction. Reducing the costs of heating buildings is possible by using both renewable energy and increasing requirements for enclosing structures. One of the points of energy efficiency measures for the household sector is the improvement of building regulations and standards (including the provision of annual increase in the number of newly constructed buildings close to zero energy consumption). Considering that Ukraine has raised the standards for enclosing structures almost for two times [1, 2], while the number of temperature zones decreased from 4 to 2, there is quite acute problem of thermal reliability for buildings that are in the same temperature zone, but geographically located at great distances (from north to south).

Enclosing structures of frame buildings of light steel thin-walled structures have many heat-conducting inclusions, through which there are significant heat loss of the building as a whole. However, many designers in the deterministic calculations do not include these inclusion and offer only constructive solutions of eliminate the influence of thermal bypass to enhance of thermal reliability. At the same time Enclosing structures is calculated as thermally homogeneous. This may have a negative effect to frame buildings of light steel thin-walled structures.

Review of recent research and publications sources. The concept of thermal reliability in Ukraine was first introduced by G. Fareniuk. According to [3], thermal reliability is a property of the object (enclosing structure) to store in time within the established value of parameters which characterizing the ability to perform necessary functions in specified modes and conditions of use. In other words, it must maintain its thermal performance within permissible limits given in the lifetime of the building. To solve the problem of evaluation of thermal reliability of enclosing structures G. Fareniuk proposed four conditions of thermal failures [4].

In the future research area was continued by V. Pashynskyi [5]. By his participation was made DBN V.1.2.-14-2009: «System to ensure reliability and safety of building objects. General principles of ensure reliability and structural safety of buildings, building structures and foundations» [6]. In it noted that the reliability of construction object is a property of the object to perform specified functions within a specified period of time. Methods for numerical evaluation of the probability of failure of similar enclosing structures were proposed by V. Pashynskyi on the following criteria: failure to achieve a sufficient level of thermal resistance through the variability of geometric and thermal characteristics of materials enclosing structures; exceeding the maximum acceptable value of density of heat flow through the enclosing structure [7].

Further research in the area of thermal reliability of enclosing structures, in particular enclosing structures of light steel thin-walled profiles was performed by V. Semko and S. Pichugin [8 – 10].

Methods for determining the probability of thermal failures of enclosing structures of cold formed steel elements in three thermo-technical parameters were proposed and developed by V. Semko – the provided thermal resistance, exceeding the values of the temperature difference between the provided temperature of internal surface of the construction and the temperature of internal air above the permissible temperature values for the sanitary requirements and criteria for reducing local temperature values of internal surface to the temperature of vapor condensation air.

Selection the general problems are not resolved before. The results of previous studies of higher mentioned scientists and our own developments [11] show that at performance of deterministic calculations of wall panels of light steel thin-walled structures and its specific nodes, in most cases the three main thermal criteria are fully ensured, while indicators of its faultless operation may be low under these same criteria.

In cases where the design scheme provides enough qualitative insulation of heat-conducting inclusions and wall constructions calculations performed for ideal (theoretical) conditions of their production and operation, the faultless operation performance can be quite high in three main thermo-technical criteria. But as practice shows, in real conditions of building the defects of structures are often observed in the following way: thermal insulation of thermal bypass is not performed quite efficiently, especially in the joints of several metal elements, the accumulation of moisture in the insulation is also possible and others.

Therefore the aim of the article was offer to perform the probabilistic analysis of the main thermal indicators of the wall of light steel thin-walled structures under change of physical characteristics.

Main material and results. Construction of exterior wall panels of light steel thin-walled structures (Fig. 1) with its structural nodes (Fig. 2) was chosen for numerical experimental research.

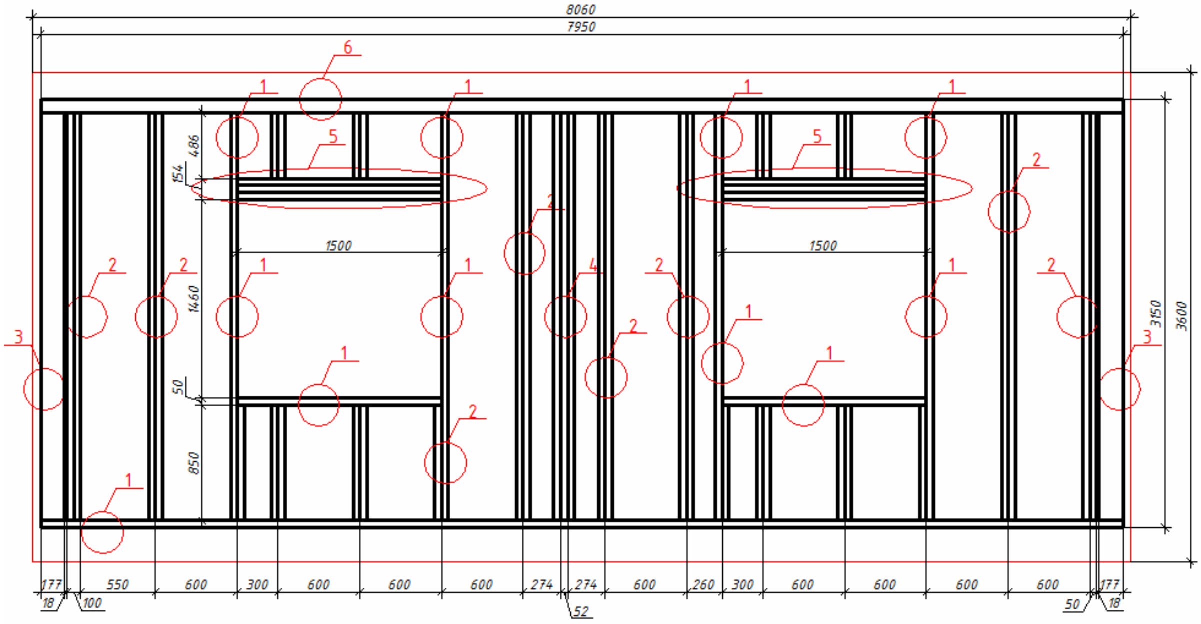


Figure 1 – Construction scheme of exterior wall of light steel thin-walled structures: 1-6 – numbering of structural nodes

Research of influencing factors on the value of the local temperature at the site of heat-conductive inclusion, for each of the experimental nodes, showed that the most influential indicator is the thermal conductivity of insulation in the construction of wall of light steel thin-walled structures. That is why was proposed to perform probabilistic analysis of the main thermal indicators of the wall with different coefficients of variation of heat conduction of thermal insulation material.

Experimental research in [12] has allowed to receive a coefficients of variation of heat conduction of mineral wool V=3,52%. According to previous research [13-16] this value ranged from V=2,28% to V=12,7%. These results enabled to estimate the probability of thermal failure of (by three main thermo-technical criteria's) a nodes and a whole panel wall of light steel thin-walled structures under changing the coefficient of variation of heat conductivity of mineral wool from V=2,28% to V=20%.

In determining the probability of faultless operation under the criterion of reducing local values of temperature of internal surface to the temperature of water vapor condensation (Table 1), calculations were made for the climate of Poltava and Kropyvnytskyi (1-st climatic area) with different values of relative humidity of internal air (the values of relative humidity of internal air are shown from below for each schedule in Table 1, %).

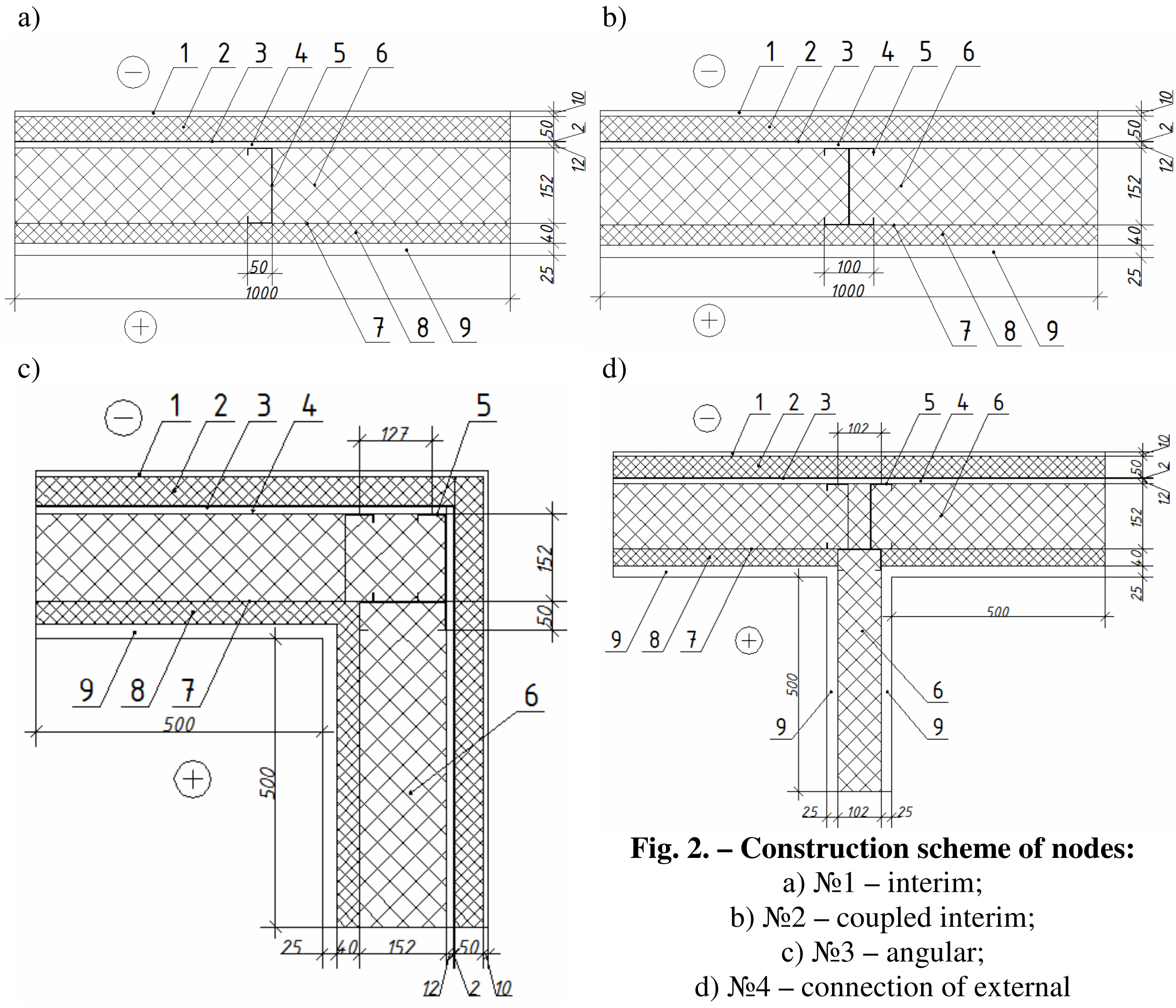


Fig. 2. – Construction scheme of nodes:
a) №1 – interim;
b) №2 – coupled interim;
c) №3 – angular;
d) №4 – connection of external wall with internal one

1 – plaster layer: 10 mm; 2 – insulation: 50 mm; ρ=135 kg/m³; λ(V)=0,042 W/m·K;
3 – polymer adhesive for thermal insulation: 2 mm; 4 – slab OSB-3: 12 mm;
5 – metal frame (profile C152,4×50,8×1,5; t=1,5 mm); 6 – insulation: 150 mm; ρ=45 kg/m³;
λ(V)=0,043 W/m·K; 7 – vapor insulation; 8 – insulation: 40 mm; ρ=135 kg/m³;
λ(V)=0,042 W/m·K); 9 – gypsum plasterboard: 25 mm; ρ=800 kg/m³; λ(V)=0,21 W/m·K.

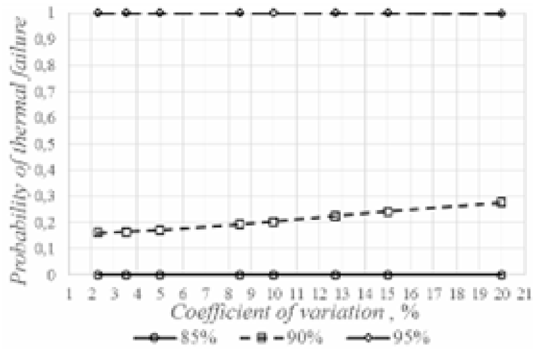
The probability of thermal failure of wall panels of light steel thin-walled structures is almost zero under the criterion of values exceeding of temperature difference between the specified temperature of internal surface of the construction and the temperature of internal air above the permissible temperature values by sanitary requirements at change of coefficient of variation of heat conductivity of mineral wool from V=2,28% to V=20%. This is according to obtained values of safety coefficient, which are rather large.

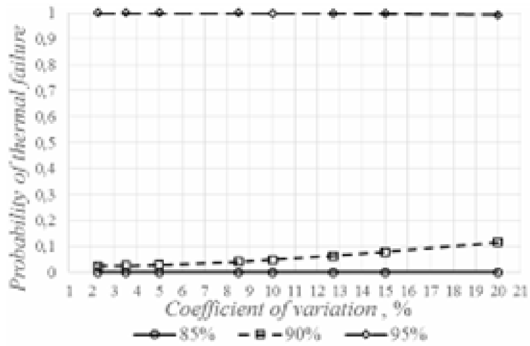
The probability of thermal failure of wall enclosing constructions under criteria of specified heat transfer resistance and overall resistance of heat transfer, shown in Figure 3, can be divided into three stages: 1) from V=2,28% to V=10% – probability of thermal failure remained almost zero; 2) from V=10% to V=15% – probability of thermal failure increased for 15.3 times; 3) from V=15% to V=20% – probability of thermal failure increased f or 4,8 times compared to the previous interval. At the same, the condition in terms of specified resistance of heat transfer is fully implemented under the deterministic approach.

Table 1 – The probability of thermal failure under changing coefficient of variation of heat conductivity

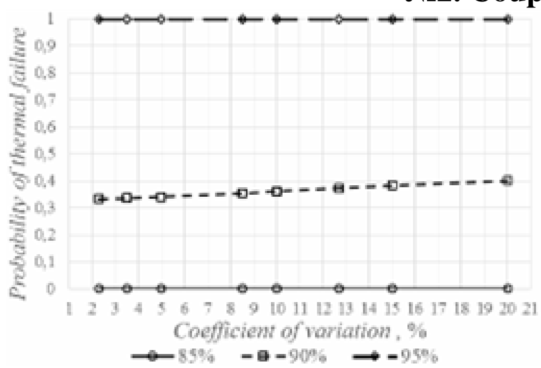
City	
Poltava	Kropyvnytskyi

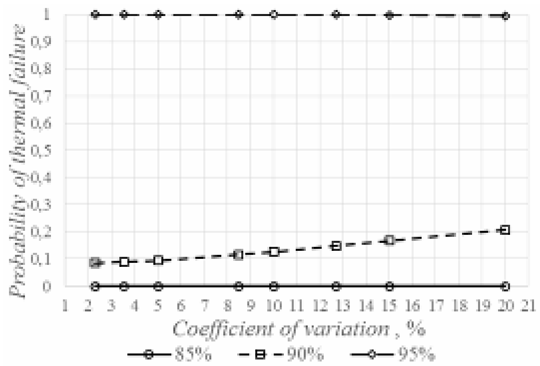
№1. Interim node



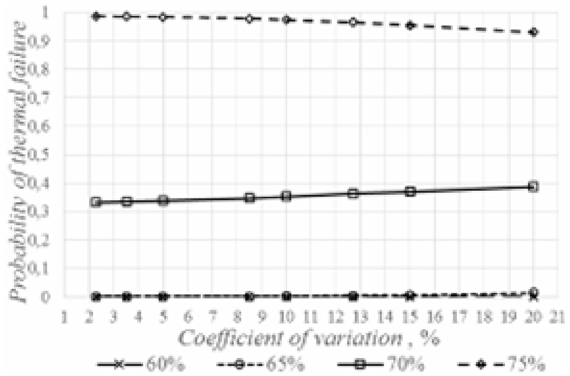


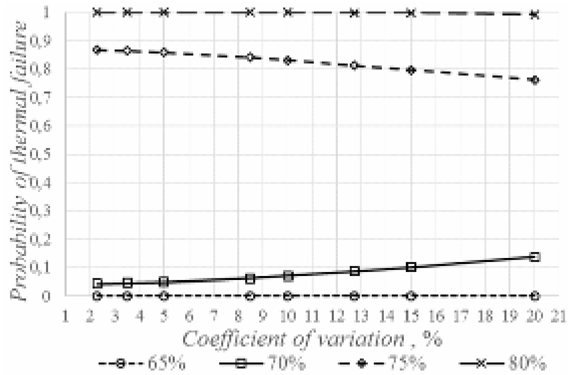
№2. Coupled interim node



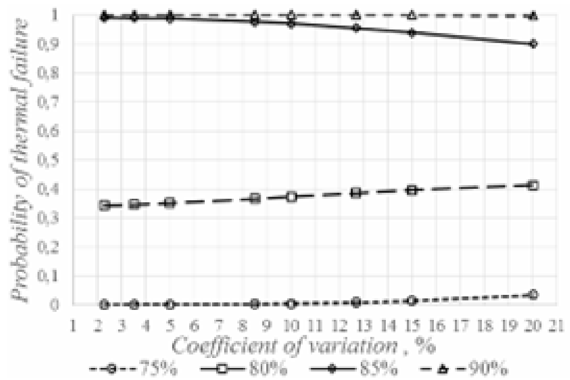


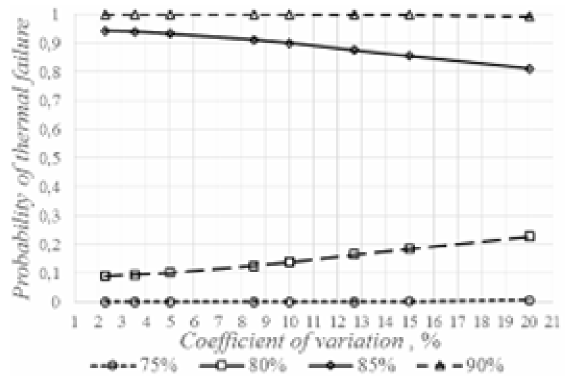
№3. Angular node





№4. Node of connection of external wall with internal one





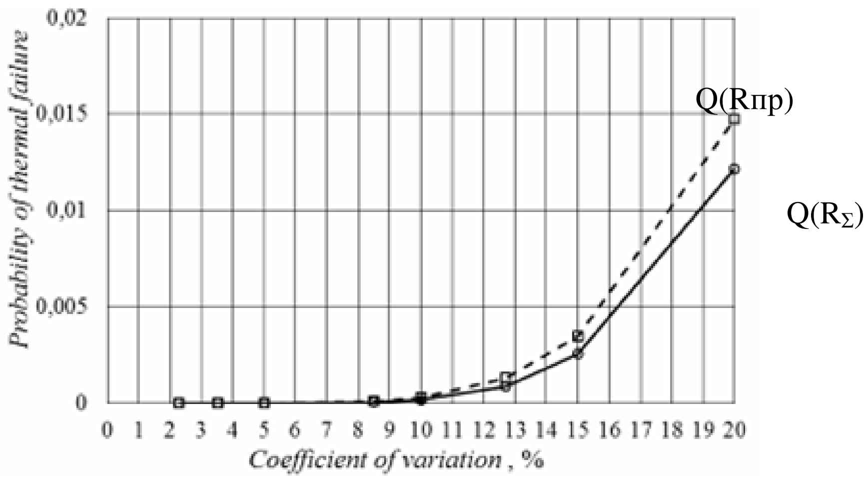


Figure 3 – Graph of changing probability of thermal failure depending on the coefficient of variation of heat conductivity of mineral wool

The following condition in the research of thermal reliability of wall of light steel thin-walled structures: coefficient of thermal conductivity of insulation material was taken as a constant λ=0,0423 (W/m·K) with providing 0,95 (Table 2). The coefficient of variation of thermal conductivity of mineral wool is ranged from V=2,28% to V=20%.

Table 2 – The coefficient of thermal conductivity under changing coefficient of variation

V, %	2,28	3,52	5	8,5	10	12,7	15	20
λ, (W/m·K)	0,0439	0,0448	0,0457	0,0482	0,0492	0,0511	0,0526	0,0561

Table 3 – Indicators of reliability of thermal conductivity functions with providing 0,95

	R_{Σ}	$R_{пр}$
M	5,035	4,128
S	0,391	0,219
β	4,438	3,790
Q	$4{,}54 x 10^{-6}$	$7{,}53 x 10^{-5}$

The data in Table 3 prove that the probability of failure under the criterion of specified heat transfer resistance is increased for 2.2 times when using value of thermal conductivity of mineral wool with providing 0.95 in the experimental wall constructions of light steel thin-walled profiles.

Another physical characteristic that influences on probabilistic analysis of the main thermal indicators of the wall of light steel thin-walled structures is a linear heat transfer coefficient.

The probability of faultless operation of wall panels of light steel thin-walled structures (under criterion of specified heat transfer resistance) was defined by specified conditions, in particular, that linear heat transfer coefficient for each of the structural nodes changes depending on thermal conductivity of insulation material (Fig. 3). The coefficient of variation of thermal conductivity of mineral wool is ranged from V=2,28% to V=20%.

The graph in Figure 4 shows that the probability of failure-free operation under criterion of decreasing of local values of temperature of internal surface to the temperature of vapor condensation is reduced with increasing of variability of linear heat transfer coefficient for each of the structural nodes. At the same, the probability of thermal failure (Fig. 5) (under criterion of specified heat transfer resistance) of wall panels of light steel thin-walled structures for the 1-st temperature area is increased comparatively to the variability of linear heat transfer coefficients: for V=5% –0,6 times; foe V=10% – 4,4 times; for V=15% –25,7 times; for V=20% – 93,6 times.

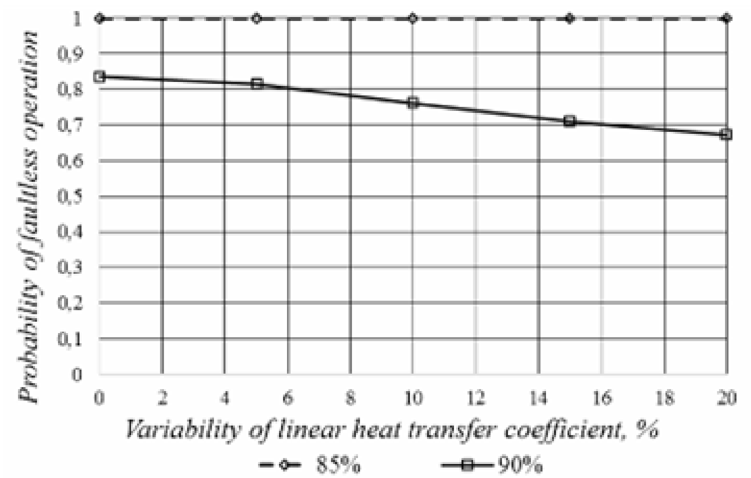


Figure 4 – Probability of faultless operation of constructive node №1 with variability of linear heat transfer coefficient at various humidity of internal air for Poltava

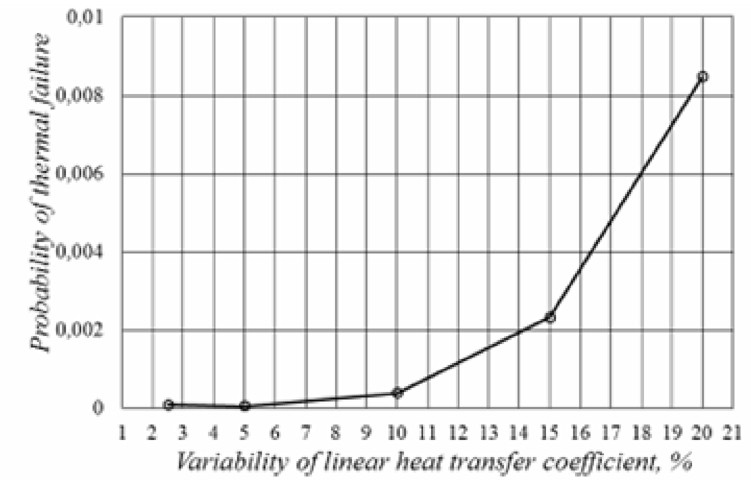


Figure 5 – Graph of changes the probability of thermal failure under criteria of specified heat transfer resistance with variability of linear heat transfer coefficient

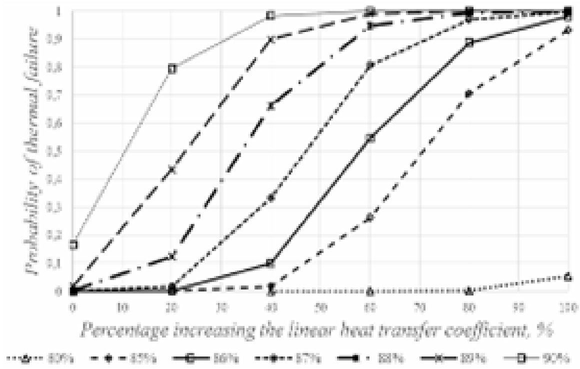
Conductive inclusions have a great impact on the thermal reliability of walls of light steel thin-walled structures. Theoretically determined values of linear heat transfer coefficient in place of heat-conductive inclusion can be greater in practice because of defects and errors during installation. That is why necessary to consider a possible increase value of the linear heat transfer coefficient.

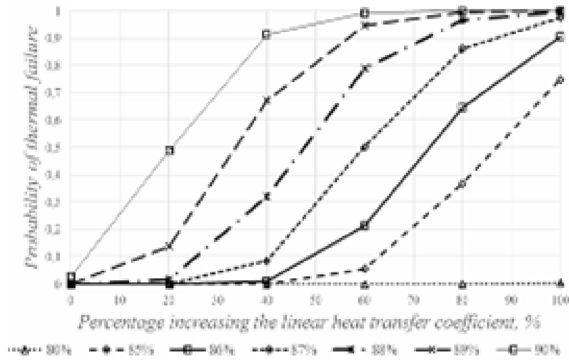
During the probabilistic analysis of basic thermal indicators of the walls of light steel thin-walled structures, the conditions for calculation remained unchanged under criterion of reduction of local temperature values of internal surface to the temperature of condensation of water vapor – for city: Poltava and Kropyvnytskyi, which are in the same climatic area with different values of relative humidity of indoor air (Table 4).

Table 4 – Probability of thermal rejection under changing the linear coefficient of thermal conductivity

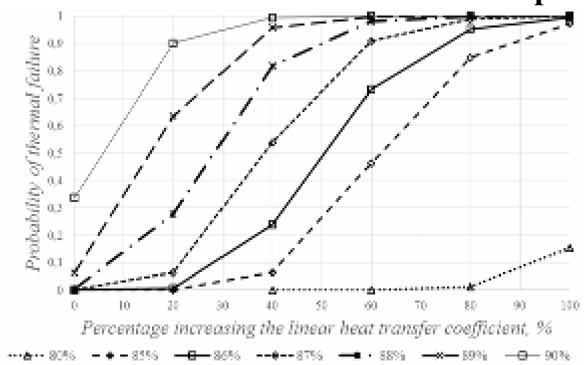
City	
Poltava	Kropyvnytskyi

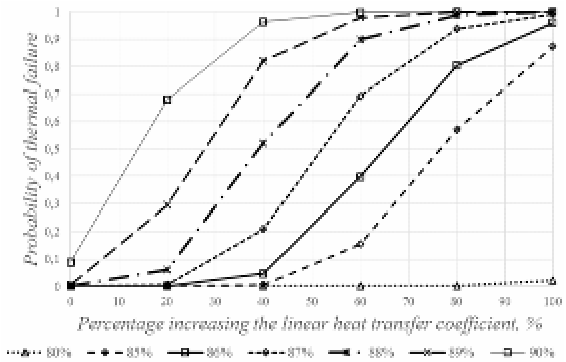
№1. Interim node



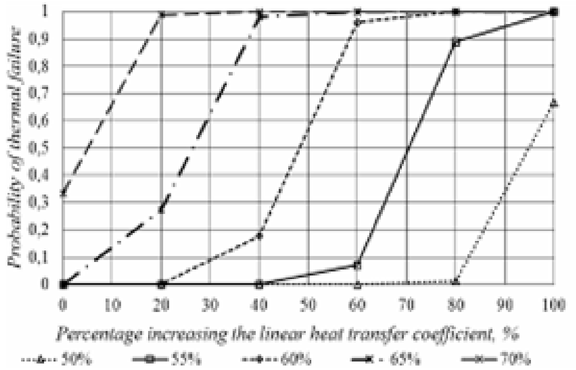


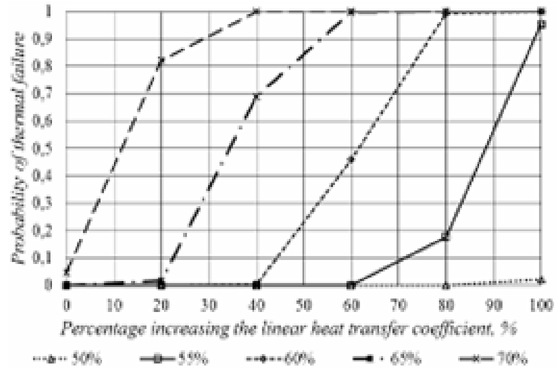
№2. Coupled interim node



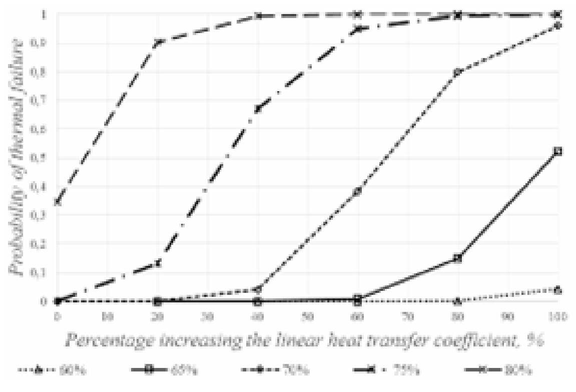


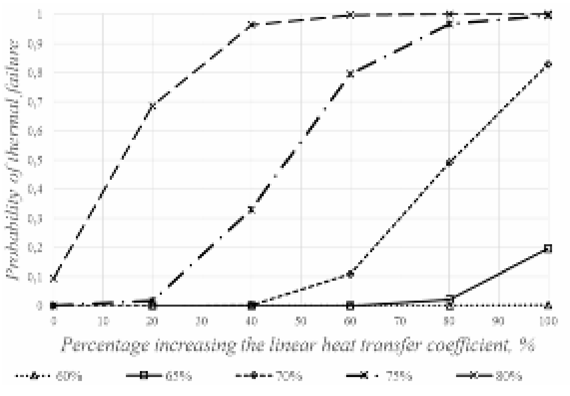
№3. Angular node





№4. Node of connection of external wall with internal one





At increase of value of the linear heat transfer coefficient for 20% 40%, 60%, 80% and 100%, the probability of thermal rejection for each of considered nodes№1-№4 (Fig. 2) of wall of light steel thin-walled structures (Fig. 1) increases with increase of humidity of indoor air. The probability of thermal failure presented in the form of vapor condensation in place of heat-conductive inclusion on the wall.

Probability of thermal failure for nodes №1 and №2 for Poltava is possible only when the humidity of internal air is 85% and higher, for Kropyvnytskyi – 86% and higher. At increase of linear heat coefficient for 20%, the probability of thermal failure (under internal air humidity – 90%) will increase for 4.8 times for Poltava and for 18,7 times for Kropyvnytskyi. At increase of value of the linear heat transfer coefficient for 40%, 60%, 80% and 100%, the probability of thermal rejection is almost 100%.

For example, Probability of thermal failure for angular node №3 is possible when the humidity of internal air is 60% and higher for Poltava (Table 4) and for Kropyvnytskyi – 65% and higher. At increase of value of the linear heat transfer coefficient for 20%, the probability of thermal failure (under internal air humidity – 65%) will increase from 0,0005 to 0,27 for Poltava and from $1{,}1\times10^{-6}$ to 0,017 for Kropyvnytskyi; for 40% – it will increase plus for 6.3 times for Poltava and for Kropyvnytskyi – for 41 times. At increase of value of the linear heat transfer coefficient for 60% and higher, the probability of thermal failure (under internal air humidity – 65%) is almost 100%. The values of relative humidity of internal air are shown from below for each schedule in Table 4, %.

Thermal reliability (faultless operation) of wall panel of light steel thin-walled structures under criterion of specified heat transfer resistance is reduced depending on a linear coefficient of thermal conductivity. By its increasing for 20% the faultless operation of wall panel is 99,8%, for 40% – 97,2%, for 60% – 85,1%, for 80% – 60,0%, for 100% – 32,2%. This is evidenced by the graph on Figure 6.

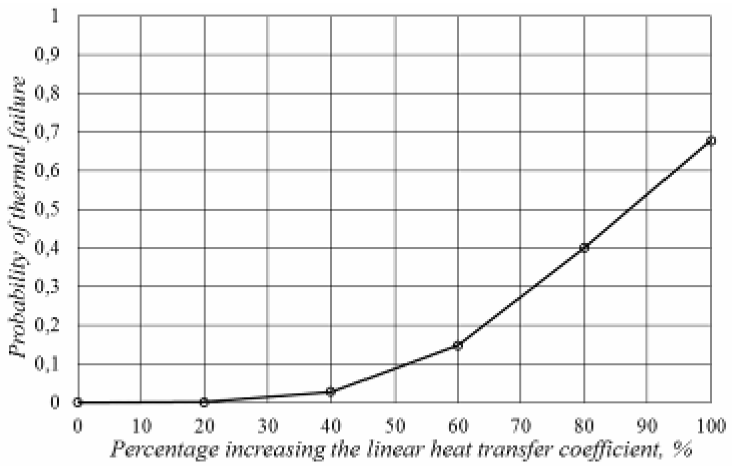


Figure 6 – Probability of thermal failure under criterion of specified heat transfer resistance depending on the a linear coefficient of thermal conductivity

The results of probabilistic calculations have shown that the effect of the variability of heat conduction of insulation and linear heat transfer coefficient of heat-conductive inclusion significantly affect the thermal reliability of walls. That is why it is necessary to recommend determining the thermal conductivity of insulation on large series of samples to establish the values of coefficient of thermal conductivity variation. It is appropriate to use a value of thermal conductivity with providing 0.95 for samples with a high thermal conductivity variability (V>10%) for theoretical calculations. Also the control of conformity theoretical values of linear coefficient of thermal conductivity to actual values is recommended for serial constructions. It is necessary to prevent increasing losses of heat in areas of linear temperature inclusions because of installations defects by increasing the controls on the construction plant or steel production plant.

So, as a result of the research, we can make the following **conclusions**:

1. The probability of thermal failure is calculated in three thermo-technical criteria for frame buildings, enclosing structures of which have many temperature inclusions. Thermo-technical criteria are following: the specified thermal resistance, exceeding the values of the temperature difference between the specified temperature of internal surface of the construction and the temperature of internal air above the permissible temperature values for the sanitary requirements and criteria for reducing local temperature values of internal surface to the temperature of vapor condensation air.

2. Determination of probability of failure of enclosing structures under the criterion of local values decrease of temperature of internal surface to the temperature of vapor condensation showed that the probability of thermal failure can vary from 2 to 7 times for different structural nodes of walls of light steel thin-walled structures, which were designed in different places of the same temperature zone.

3. Changing the coefficient of thermal conductivity variation of insulation material leads to changes in the level of thermal reliability of wall constructions. The probability of failure of wall panels of light steel thin-walled structures under the criterion of specified heat resistance increases from 0,015 to $9{,}85 \times 10^{-7}$while increasing the coefficient of variation from 2.28% to 20% respectively.

4. Changing the linear heat transfer coefficient of heat-conductive inclusion leads to changes in the level of thermal reliability of wall construction in general. The probability of thermal failure for the angular node (projected in Poltava) under the criterion of specified heat resistance increases from 0,05% to 27% while increasing the linear heat transfer coefficient from 20% to 40% respectively.

5. This approach can be used not only to assessment the thermal reliability for an enclosing structures of cold formed steel profiles but also for any other enclosing structures with heat conductive inclusions.

References

1. *ДБН В.2.6-31:2006. Конструкції будинків і споруд. Теплова ізоляція будівель [Чинний з 2007-04-01. – К. : Мінрегіонбуд України, 2006. – 65 с.*
   DBN V.2.6-31:2006. Konstruktsiyi budinkiv i sporud. Teplova izolyatsiya budivel [Chinniy z 2007-04-01. – K. : Minregionbud Ukrayini, 2006. – 65 s.
2. *ДБН В.2.6-31:2006. Теплова ізоляція будівель. Зміна №1 // Інформаційний бюлетень МРУ. – 2013. – № 5. – С. 3 – 11.*
   DBN V.2.6-31:2006. Teplova izolyatsiya budivel. Zmina №1 // Informatsiyniy byuleten MRU. – 2013. – № 5. – S. 3 – 11.
3. *Фаренюк Г. Г. Методологічні аспекти забезпечення енергоефективності та теплової надійності будинків / Г. Г. Фаренюк // Строительство, материаловедение, машиностроение : сб. науч. тр. – Вып. 50. – Д. : ГВУЗ ПГАСА, 2009. – С. 593 – 597.*
   Farenyuk G. G. Metodologichni aspekti zabezpechennya energoefektivnosti ta teplovoyi nadiynosti budinkiv / G. G. Farenyuk // Stroitelstvo, materialovedenie, mashinostroenie : sb. nauch. tr. – Vyp. 50. – D. : GVUZ PGASA, 2009. – S. 593 – 597.
4. *Фаренюк Г. Г. Основи забезпечення енергоефективності будинків та теплової надійності огороджувальних конструкцій / Г. Г. Фаренюк. – К. : Гама-Принт, 2009. – 216 с.*
   Farenyuk G. G. Osnovi zabezpechennya energoefektivnosti budinkiv ta teplovoyi nadiynosti ogorodzhuvalnih konstruktsiy / G. G. Farenyuk. – K. : Gama-Print, 2009. – 216 s.

5. *Пашинський В. А. Температурні впливи на огороджувальні конструкції будівель / В. А. Пашинський, Н. В. Пушкар, А. М. Карюк. – Одеса : ОДАБА, 2012. –180 с.*
Pashinskiy V. A. Temperaturni vplivi na ogorodzhuvalni konstruktsiyi budivel / V. A. Pashinskiy, N. V. Pushkar, A. M. Karyuk. – Odesa : ODABA, 2012. –180 s.
6. *ДБН В.1.2.-14-2009. Система забезпечення надійності та безпеки будівельних об'єктів. Загальні принципи забезпечення надійності та конструктивної безпеки будівель, споруд, будівельних конструкцій та основ [Чинний з 2009-12-01]. – К. : Мінрегіонбуд України, 2009. – 56 с.*
DBN V.1.2.-14-2009. Sistema zabezpechennya nadiynosti ta bezpeki budivelnih ob'ektiv. Zagalni printsipi zabezpechennya nadiynosti ta konstruktivnoyi bezpeki budivel, sporud, budivelnih konstruktsiy ta osnov [Chinniy z 2009-12-01]. – K. : Minregionbud Ukrayini, 2009. – 56 s.
7. *Пашинський В. А. Методика оцінювання теплової надійності стін за критерієм тепловитрат / В. А. Пашинський, О. А. Плотніков, А. М. Карюк // Міжвузівський збірник «Наукові нотатки».– Луцьк, 2014. – Вип. 45. – С. 417 – 423.*
Pashinskiy V. A. Metodika otsinyuvannya teplovoyi nadiynosti stin za kriteriem teplovitrat / V. A. Pashinskiy, O. A. Plotnikov, A. M. Karyuk // Mizhvuzivskiy zbirnik «Naukovi notatki». – Lutsk, 2014. – Vip. 45.– S. 417 – 423.
http://www.irbis-nbuv.gov.ua/cgi-bin/irbis_nbuv/cgiirbis_64.exe?C21COM=2&I21DBN=UJRN&P21DBN=UJRN&IMAGE_FILE_DOWNLOAD=1&Image_file_name=PDF/Nn_2014_45_67.pdf
8. *Пічугін С. Ф. Імовірність теплової відмови огороджувальних конструкцій із сталевих холодноформованих елементів за критерієм зниження локальних значень температур / С. Ф. Пічугін, В. О. Семко // Збірник наукових праць Української державної академії залізничного транспорту.– Х. : УкрДАЗТ, 2016. – Вип. 160. – С. 25 – 34.*
Pichugin S. F. Imovirnist teplovoyi vidmovi ogorodzhuvalnih konstruktsiy iz stalevih holodnoformovanih elementiv za kriteriem znizhennya lokalnih znachen temperatur / S. F. Pichugin, V. O. Semko // Zbirnik naukovih prats Ukrayinskoyi derzhavnoyi akademiyi zaliznichnogo transportu.– H. : UkrDAZT, 2016. – Vip. 160. – S. 25 – 34.
http://csw.kart.edu.ua/article/view/69985
9. *Семко В. О. Методика визначення ймовірності теплової відмови огороджувальних конструкцій із сталевих холодноформованих елементів за теплотехнічними показниками / В. О. Семко // Строительство, материаловедение, машиностроение : сб. науч. тр. – Днепр : ПГАСА, 2016. – Вып. 91. – С. 140 – 147.*
Semko V. O. Metodika viznachennya ymovirnosti teplovoyi vidmovi ogorodzhuvalnih konstruktsiy iz stalevih holodnoformovanih elementiv za teplotehnichnimi pokaznikami / V. O. Semko // Stroitelstvo, materialovedenie, mashinostroenie : sb. nauch. tr. – Dnepr : PGASA, 2016. – Vyp. 91. – S. 140 – 147.
http://smm.pgasa.dp.ua/article/view/80503
10. *Semko V. Linear heat-transfer coefficient equation for a wall structure made of steel profiles / V. Semko, B. Gorb, A. Akamsin // Строительство, материаловедение, машиностроение : сб. науч. тр. – Вып. 75. – Д. : ГВУЗ ПГАСА, 2014. – С. 227 – 230.*
http://smm.pgasa.dp.ua/article/view/89629
11. *Лещенко М. В. Теплова надійність стін із легких сталевих тонкостінних конструкцій: автореф. дис. на здобуття наук. ступеня канд. техн. наук. : спец. 05.23.01 / Лещенко Марина Валентинівна; ПолтНТУ. – Полтава, 2016. – 24 с.*
Leshchenko M. V. Teplova nadiynist stin iz legkih stalevih tonkostinnih konstruktsiy: avtoref. dis. na zdobuttya nauk. stupenya kand. tehn. nauk. : spets. 05.23.01 / Leshchenko Marina Valentinivna; PoltNTU. – Poltava, 2016. – 24 s.
12. *Semko V. O. Experimental Study of Variability of Thermal Conductivity of Insulation Materials / V. O. Semko, M. V. Leshchenko, A. G. Rud // Збірник наукових праць. Серія: Галузеве машинобудування, будівництво. – Полтава : ПолтНТУ, 2016. − Вип. 1 (46). − С. 60 – 67.*
http://journals.pntu.edu.ua/index.php/znp/article/view/12

13. *Шульгін В. В. Імовірнісне подання технічних характеристик теплоізоляційних матеріалів / В. В. Шульгін, А. М. Карюк // Збірник наукових праць. Серія: Галузеве машинобудування, будівництво. – Полтава : ПолтНТУ, 2013. – Вип. 4 (39), Т.2. – С. 257 – 262.*
Shulgin V. V. Imovirnisne podannya tehnichnih harakteristik teploizolyatsiynih materialiv / V. V. Shulgin, A. M. Karyuk // Zbirnik naukovih prats. Seriya: Galuzeve mashinobuduvannya, budivnitstvo. – Poltava : PoltNTU, 2013. – Vip. 4 (39), T.2. – S. 257 – 262.
https://scholar.google.com.ua/scholar?hl=ru&as_sdt=0,5&cluster=10809368302259311710
14. *Stankevičius V. The Effect of Stochastically Dependent Physical Parameters on the Materials' Thermal Receptivity Coefficient / Vytautas Stankevičius, Liutauras Kairys // Materials science (Medžiagotyra). – 2005. – Vol. 11. – No. 2. – P.188 – 192.*
http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.544.6183&rep=rep1&type=pdf
15. *Uncertainty in the Thermal Conductivity of Insulation Materials / F. Domínguez-Muñoz, B. Anderson, J.M. Cejudo-López, A. Carrillo-Andrés // Eleventh Intern. IBPSA Conf., July 27–30, 2009. – Glasgow, Scotland. – 2009. – P. 1008 – 1013.*
16. *Uncertainty in the thermal conductivity of insulation materials / Fernando Domínguez-Muñoz, Brian Anderson, José M. Cejudo-López, Antonio Carrillo-Andrés // Energy and Buildings. – November 2010. – Vol. 42. – Is. 11. – P. 2159 – 2168.*
http://www.sciencedirect.com/science/article/pii/S0378778810002227
17. *Santos P. Thermal performance of lightweight steel framed wall: the importance of flanking thermal losses / P. Santos, C. Martins, L. Simo es da Silva // Journal of Building Physics. – 2014. – № 38 (1). – P. 81 – 98.*
http://journals.sagepub.com/doi/abs/10.1177/1744259113499212
18. *Garay R. Performance assessment of thermal bridge elements into a full scale experimental study of a building façade / R. Garay, A. Uriarte, I. Apraiz // Energy and buildings. – 2014. – № 85. – P. 579 – 591.*
http://www.sciencedirect.com/science/article/pii/S0378778814007178
19. *Structure, energy and cost efficiency evaluation of three different lightweight construction systems used in low-rise residential buildings / S. Naji, O. C. Çelik, U. J. Alengaram [and other] // Energy and buildings. – 2014. – № 84. – P. 727 – 739.*
http://www.sciencedirect.com/science/article/pii/S0378778814006513

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