$$R = \frac{T_2 - T_1}{q};$$
$$\lambda = \frac{q \cdot d}{T_2 - T_1}, \tag{3}$$

where λ is coefficient of thermal conductivity, W/(m·K);

q is heat flow, W/m^2;

d is wall thickness, m;

T_1, T_2 are temperature of wall surfaces, °C

Table 4. Coefficient of thermal conductivity of surface.

Date Day/month/year	Time Hour/minute	Coefficient of thermal conductivity, W/(m·K)			
Date	Time	Point 1	Point 2	Point 3	Point 4
07.05.	4:57	0.376	0.41	0.257	0.255
07.05.	7:57	0.363	0.437	0.251	0.251
07.05.	10:57	0.328	0.415	0.271	0.252
07.05.	13:57	0.317	0.433	0.224	0.259
07.05.	16:57	0.342	0.421	0.229	0.247
07.05.	19:57	0.328	0.412	0.217	0.239
07.05.	22:57	0.321	0.446	0.236	0.246
08.05.	1:57	0.329	0.429	0.257	0.241
08.05.	4:57	0.343	0.425	0.23	0.236
08.05.	7:57	0.365	0.429	0.248	0.248
08.05.	10:57	0.341	0.438	0.252	0.253
08.05.	13:57	0.377	0.382	0.226	0.218
08.05.	16:57	0.348	0.407	0.222	0.231
Average value		0.344	0.422	0.24	0.244

Technical thermal resistance is calculated by formula (4) (For reinforced section is R_a, for unreinforced section is R_b).

$$R = \frac{d}{\lambda}, \tag{4}$$

where R is thermal resistance, (m^2·K)/W;

d is wall thickness, m;

λ is coefficient of thermal conductivity, W/(m·K)

$$R_a = \frac{0.3}{0.383} = 0.783 \frac{m^2 \cdot K}{W}; \quad R_b = \frac{0.3}{0.242} = 1.239 \frac{m^2 \cdot K}{W}.$$

Thermal resistance diagram for sample section is plotted to calculate thermal resistance for whole construction (Figure 2).

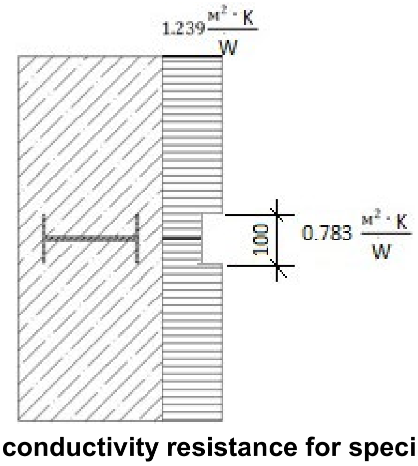

Figure 2. Thermal conductivity resistance for specimen cross section.

Average value of thermal resistance is calculated:

$$R = \frac{A_1 + A_2 + A_3 \ldots + A_n}{\frac{A_1}{R_1} + \frac{A_2}{R_2} + \frac{A_3}{R_3} + \ldots \frac{A_n}{R_n}} = 1.209 \frac{\text{m}^2 \cdot \text{K}}{\text{W}}. \tag{5}$$

Formula (6) is applied to obtain thermal conductivity:

$$R_o = \frac{1}{\alpha_e} + R + \frac{1}{\alpha_i}, \tag{6}$$

where α_i is heat exchange coefficient for interior surface of enclosure structure by Set of Rules 50.13330.2012 $(\alpha_i = 8.7 \frac{\text{m}^2 \cdot \text{K}}{\text{W}})$;

α_e is heat exchange coefficient for exterior surface of enclosure structure by Set of Rules 50.13330.2012 $(\alpha_e = 23 \frac{\text{m}^2 \cdot \text{K}}{\text{W}})$;

R is thermal resistance, (m²·K)/W.

$$R_o = \frac{1}{8.7} + 1.209 + \frac{1}{23} = 1.367 \frac{\text{m}^2 \cdot \text{K}}{\text{W}}.$$

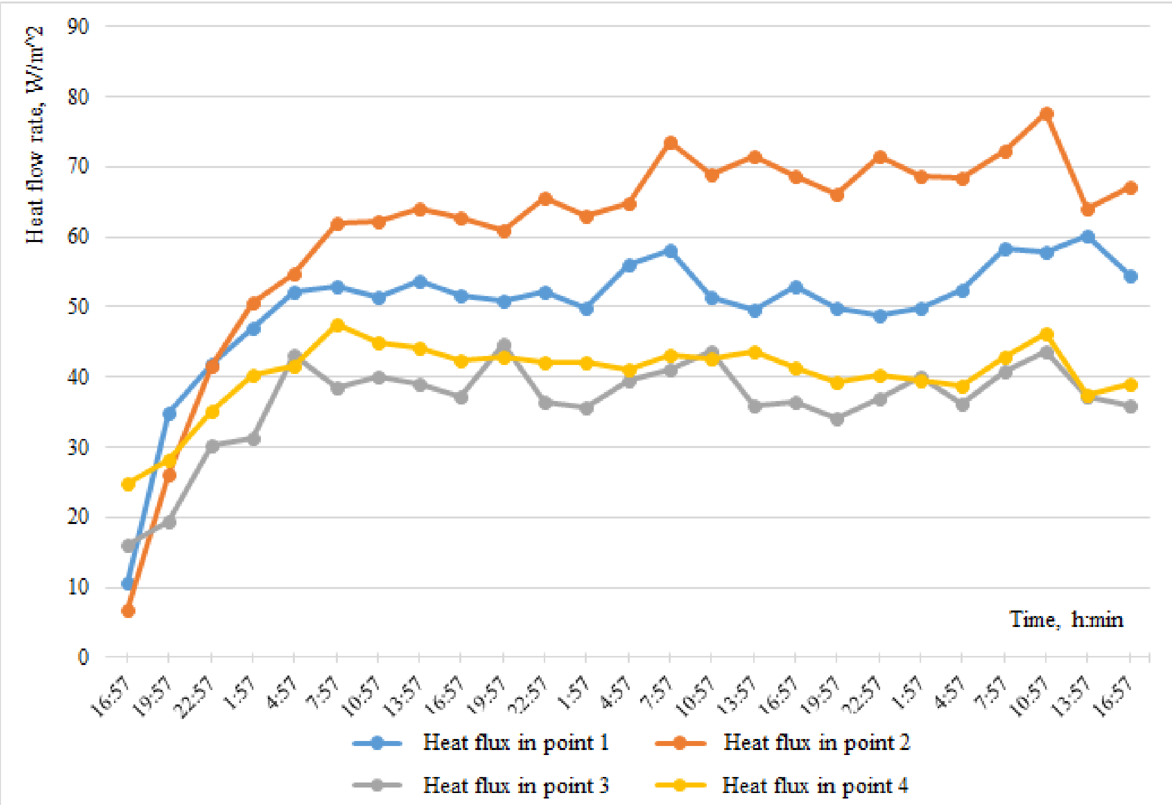

Figure 3. Heat flow chart.

3. *Results and Discussion*

Technologies of cast in situ non-autoclave foamed concrete buildings construction are lack in Russian industry in 2020. Thus, Business association “SOVBI” is a unique manufacturer of bearing enclosing structures, based on thin-wall profile metal framing and cast in situ foamed concrete. Therefore, research from this article does not have any analogue, and consideration of comparison of obtained results with others is premature. Researches of thermal-saving properties of this kind of structures are also lack abroad.

However, in order to evaluate adequacy of obtained results, method from ISO_06946–2007 can be applied.

3.1. Theoretical calculation of thermal conductivity resistance for non-uniform enclosing structure

Calculation of thermal conductivity resistance for non-uniform enclosing structure is performed according to following rules ISO_06946–2007.

The total thermal resistance R_o, of a component consisting of thermally homogeneous and thermally inhomogeneous layers parallel to the surface is calculated as the arithmetic mean of the upper and lower limits of the resistance:

$$R_o = \frac{R'_T + R''_T}{2}, \tag{7}$$

where R'_T is the upper limit of the total thermal resistance, is determined by formula:

$$\frac{1}{R'_T} = \frac{f_a}{R_{Ta}} + \frac{f_b}{R_{Tb}} + \frac{f_c}{R_{Tc}} + \frac{f_d}{R_{Td}} + \frac{f_e}{R_{Te}}. \tag{8}$$

f_a; f_b; f_c; f_d; f_e are fractional area of each section (Figure 5).

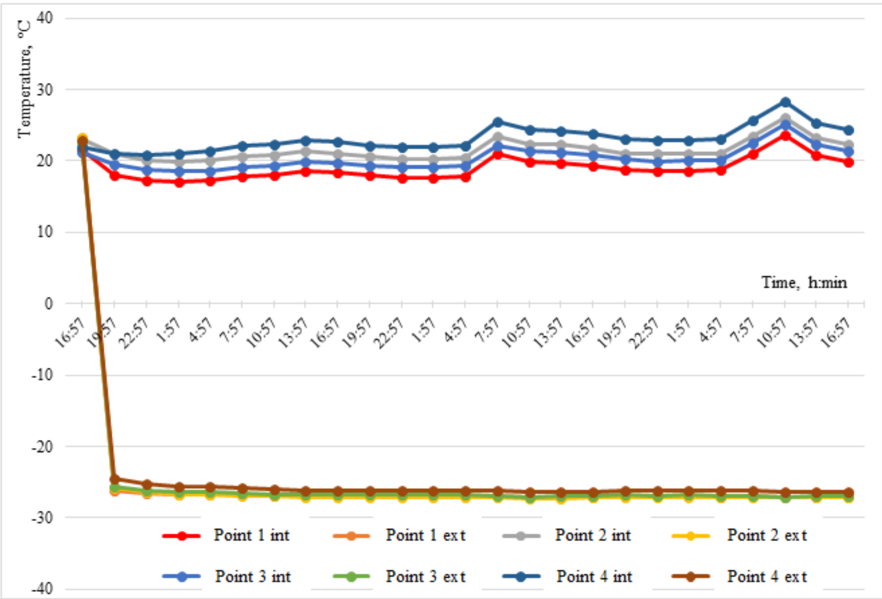

Figure 4. Surface temperature chart.

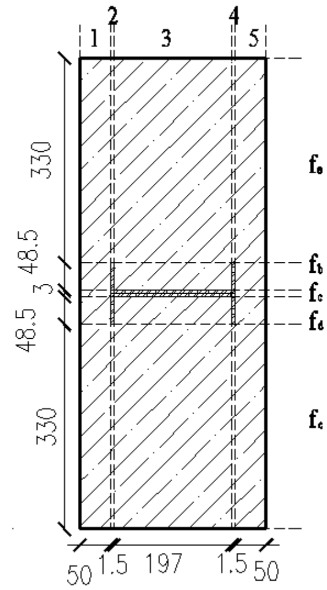

Figure. 5 Division to planes.

R_{Ta}; R_{Tb}; R_{Tc}; R_{Te} are the total thermal resistances from environment to environment for each section, calculated using Equation (4).

$$\frac{1}{R'_T} = 2\cdot\frac{0.33}{\frac{0.3}{0.08}} + 2\cdot\frac{0.0485}{2\cdot\frac{0.05}{0.08} + 2\cdot\frac{0.0015}{47} + \frac{0.197}{0.08}} + \frac{0.003}{2\cdot\frac{0.05}{0.08} + \frac{0.2}{47}} = \frac{1}{0.44}\,\frac{m^2\cdot K}{W}.$$

R''_T is the lower limit of the total thermal resistance:

Calculate an equivalent thermal resistance, R_j, for each thermally inhomogeneous layer using Equation (9):

$$\frac{1}{R_j} = \frac{f_a}{R_{aj}} + \frac{f_b}{R_{bj}} + \frac{f_c}{R_{cj}} + \frac{f_d}{R_{dj}} + \frac{f_e}{R_{ej}}. \tag{9}$$

The lower limit is then determined using Equation (10):

$$R''_T = R_1 + R_2 + R_3 + R_4 + R_5. \tag{10}$$

Determine $\frac{1}{R_j}$ for every layer with Equation (9):

$$\frac{1}{R_1}=\frac{0.33+0.0485+0.003+0.00485+0.33}{\frac{0.05}{0.08}}=1.216\frac{W}{m^2\cdot K};$$

$$\frac{1}{R_2}=2\cdot\frac{0.33}{\frac{0.0015}{0.08}}+\frac{0.0485+0.003+0.0485}{\frac{0.0015}{47}}=3168.2\frac{W}{m^2\cdot K};$$

$$\frac{1}{R_3}=2\cdot\frac{0.3785}{\frac{0.197}{0.08}}+\frac{0.003}{\frac{0.197}{47}}=1.023\frac{W}{m^2\cdot K}.$$

$\frac{1}{R_1}=\frac{1}{R_5}$ and $\frac{1}{R_2}=\frac{1}{R_4}$ as the layers are similar, thus:

$$R''_T=2.62\frac{m^2\cdot K}{W};$$

$$R_o=\frac{2.27+2.62}{2}=2.44\frac{m^2\cdot K}{W}.$$

4. Conclusions

1. Research shows that strength properties of material do not allow to evaluate concrete with axial compression strength class, thus impact of foamed concrete on composite mechanical strength is negligibly. Major function of foamed concrete is thermal insulation.

2. Identified thermal protective properties of composite structure made of foamed concrete and steel thin-wall profiles have been determined experimentally in sections with/without reinforcement: reinforced sections – 0.783 (m^2·K)/W; unreinforced sections – 1.239 (m^2·K)/W

3. It's established that the heat resistance of the enclosing structure in reinforced section is 63 % of resistance in unreinforced one.

4. Shown comparison of thermal conductivity resistance of non-uniform enclosing structure has been performed by experimental and theoretical methodic :thermal conductivity resistance of enclosure, obtained experimentally – 1.367(m^2·K)/W; thermal conductivity resistance of enclosure, obtained by calculation – 2.44(м²·K)/W.

5. It's established that the heat resistance of the thermal conductivity of non-uniform enclosure, obtained experimentally is two times less than resistance, calculated theoretically.

6. It is recommended to modify enclosure made of steel thin-wall profiles and foamed concrete with layer of mineral wool for optimal heating performance according to requirements for Province of Leningrad.

7. Explanation of the discrepancies between the practical and theoretical values of the heat transmission resistance:

7.1 As we used monolithic foamed concrete on the site in the winter time, high probability that during the process of pouring of the sample, water or snow penetrated into the pores of sample and decrease heat transmission resistance.

7.2 Experimental accuracy.

5. Acknowledgment

Acknowledgment is expressed to Igor I. Pestryakov, CEO of «Vysota» certification center, for provided equipment, used for tests and to Anatoly V. Seliverstov, CEO of «Sovbi», Ltd, for structure specimens, provided for tests.

References

1. Leshchenko, M.V., Semko, V. Thermal characteristics of the external walling made of cold-formed steel studs and polystyrene concrete. Magazine of Civil Engineering. 2015. 60(8). Pp. 44–55. (rus). DOI: 10.5862/MCE.60.6.
2. Korniyenko, S.V., Vatin, N.I., Gorshkov, A.S. Thermophysical field testing of residential buildings made of autoclaved aerated concrete blocks. Magazine of Civil Engineering. 2016. 64(4). Pp. 10–25. DOI: 10.5862/MCE.64.2
3. Gorshkov, A.S., Pestryakov, I.I., Korniyenko, S.V., Vatin, N.I., Olshevskiy, V.Ya. Actual thermal insulation properties of cellular autoclave curing concretes, Construction of Unique Buildings and Structures. 2018. 68(5). Pp. 75–104. (rus) DOI: 10.18720/CUBS.68.7
4. Korniyenko, S. Complex analysis of energy efficiency in operated high-rise residential building: case study. E3S Web of Conferences. 2018. No. 33. Pp. 02005.

5. Korniyenko, S.V. The experimental analysis and calculative assessment of building energy efficiency. Applied Mechanics and Materials. 2014. Vol. 618. Pp. 509–513.
6. Barabanshchikov, Y., Fedorenko, I., Kostyrya, S., Usanova, K. Cold-Bonded Fly Ash Lightweight Aggregate Concretes with Low Thermal Transmittance. Advances in Intelligent Systems and Computing. 2019. 983. Pp. 858–866.
7. Lundyshev, I.A. Karkasnyye sistemy, primenyayemyye v ograzhdayushchikh konstruktsiyakh pri stroitel'stve iz monolitnogo penobetona [Frame systems used in enclosure structure in construction from monolithic autoclaved aerated concrete]. Magazine of Civil Engineering. 2009. 3(1). Pp. 13–16. (rus)
8. Vasilyev, V.D. Monolitnyy penobeton po tekhnologii «SOVBI» [Monolithic foam concrete according to the "Svbi" technology]. Stroitelnyye materialy. 2005. No. 12. Pp. 39–40. (rus)
9. Struchkova, A.Y., Barabanshchikov, Yu.G., Semenov, K.S., Shaibakova, A.A. Heat dissipation of cement and calculation of crack resistance of concrete massifs. Magazine of Civil Engineering. 2018. No. 78(2). Pp. 128–135. doi: 10.18720/MCE.78.10
10. Krivaltsevich, T.V., Gurova, Ye.V. Sravneniye neavtoklavnogo penobetona s drugimi teploizolyatsionnymi materialami [comparison of non-autoclave foam concrete with other heat-insulating materials]. Arkhitektura, stroitelstvo, transport. 2015. Pp. 508–512. (rus)
11. Bespalov, V.V., Ucer, D., Salmanov, I.D., Kurbanov, I.N., Kupavykh, S.V. Deformation compatibility of masonry and composite materials. Magazine of Civil Engineering. 2018. No. 78(2). Pp. 136–150. doi: 10.18720/MCE.78.11
12. Plotnikov, V.V., Botagovskiy, M.V. Povysheniye dolgovechnosti monolitnogo penobetona nizkoy plotnosti putem modifitsirovaniya tsementa aktivirovannymi kristallogidratami [Improving the durability of monolithic low-density foam concrete by modifying cement with activated crystalline hydrates]. Promyshlennoye i grazhdanskoye stroitelstvo. 2015. No. 10. Pp. 33–39. (rus)
13. Pertseva, O., Nikolskiy, S. Dependence of relative decreasing in strength by rate of strain for the new rapid method for determination of concrete frost resistance. Applied mechanics and materials. 2015. Pp. 505–510.
14. Korsun, V., Korsun, A. The influence of precompression on strength and strain properties of concrete under the effect of elevated temperatures. Applied mechanics and materials. 2015. Pp. 469–474.
15. Korsun, V., Vatin, N., Korsun, A., Nemova, D. Physical-mechanical properties of the modified fine-grained concrete subjected to thermal effects up to 200°s. Applied mechanics and materials. 2014. Pp. 1013–1017.
16. Usanova, K., Barabanshchikov, Yu., Fedorenko Yu., Kostyrya S. Cold-bonded fly ash aggregate as a coarse aggregate of concrete. Construction of Unique Buildings and Structures. 2018. 9(72). Pp. 31–45. DOI: 10.18720/CUBS.72.2
17. Bayev, M.N., Shchukina, Yu.V. Teploizolyatsionnyy neavtoklavnyy penobeton s povyshennymi kharakteristikami [Heat-insulating non-autoclave foam concrete with enhanced characteristics]. Polzunovskiy vestnik. 2011. No. 1. Pp. 35–37. (rus)
18. Orlovich, R.B., Bespalov, V.V., Derkach, V.N. Compressed-bent masonry walls reinforced with composite materials. Magazine of Civil Engineering. 2018. No. 79(3). Pp. 112–119. doi: 10.18720/MCE.79.12
19. Sovetnikov, D.O., Videnkov, N.V., Trubina, D.A. Light gauge steel framing in constructionof multi-storey buildings. Construction of Unique Buildings and Structures. 2015. 30(3). Pp. 152–165. (rus). DOI: 10.18720/CUBS.30.11
20. Rybakov, V.A., Molchanova, N., Laptev, V., Suslova, A., Sivokhin, A. The effect of conjunction flexibility on the local stability of steel thin-walled slab beams. MATEC Web of Conferences. 2016. Pp. 01017.
21. Trubina, D., Abdulaev, D.A., Pichugin, E., Rybakov, V., Garifullin, M., Sokolova, O. Comprasion of the bearing capacity of lst-profile depending on the thickness of its elements. Applied mechanics and materials. 2015. Pp. 752–757.
22. Trubina, D., Abdulaev, D., Pichugin, E., Rybakov, V. Geometric nonlinearity of the thin-walled profile under transverse bending. Applied mechanics and materials. 2014. Pp. 1133–1139.
23. Ariyanayagam, A.D., Poologanathan, K., Mahendran, M. Thermal modelling of load bearing cold-formed steel frame walls under realistic design fire conditions. Advanced Steel Construction. 2017. No. 2. Pp. 160–189.
24. Kuz'menko, D.V., Vatin, N.I. Ograzhdayushchaya konstruktsiya «nulevoy tolshchiny» – termopanel' [Zero-thickness building envelope - thermopanel]. Magazine of Civil Engineering. 2008. 1(1). Pp. 13–21. (rus)
25. Bronzova, M.K., Vatin, N.I., Garifullin, M.R. Frame buildings construction using monolithic foamed concrete. Construction of Unique Buildings and Structures. 2015. 28(1). Pp. 74-90. (rus)
26. Vatin, N.I., Grinfeld, G.I., Okladnikova, O.N., Tulko, S.I. Soprotivleniye teploperedache ograzhdayushchikh konstruktsiy iz gazobetona s oblitsovkoy iz silikatnogo kirpicha [Resistance to heat transfer of aerated concrete enclosures with silicate brick cladding]. StroyPROFIl. 2007. No. 5(59). Pp. 28–32. (rus)
27. Rybakov, V.A., Gamayunova, O.S. The stress-strain state of frame constructions' elements from thin-walled cores. Construction of Unique Buildings and Structures. 2013. 12(7). Pp. 79-123. (rus). DOI: 10.18720/CUBS.12.10
28. Lalin, V., Rybakov, V., Sergey, A. The finite elements for design of frame of thin-walled beams. Applied mechanics and materials. 2014. Pp. 858–863.
29. Stamatovic, B., Korsun, A. Local data flow principles in porosity of materials. Applied mechanics and materials. 2015. Pp. 371–376.
30. Korsun, V., Korsun, A. The influence of precompression on strength and strain properties of concrete under the effect of elevated temperatures. Applied mechanics and materials. 2015. Pp. 469–474.
31. Akimov, L.I., Ilenko, N., Mizharev, R., Cherkashin, A., Vatin, N.I., Chumadova, L.I. Composite concrete modifier cm 02-10 and its IMPA. Matec web of conferences. 2016. Pp. 01022.
32. Frolov, A., Chumadova, L., Cherkashin, A., Akimov, L. Prospects of use and impact of nanoparticles on the properties of high-strength concrete. Applied mechanics and materials. 2014. Pp. 1416–1424.
33. Kornilov, T.A., Gerasimov, G.N. Naruzhnyye steny maloetazhnykh domov iz legkikh stalnykh tonkostennykh konstruktsiy dlya usloviy kraynego severa [External walls of low-rise buildings made of light steel thin-walled structures for conditions of the far north]. Zhilishchnoye stroitelstvo. 2016. No. 7. Pp. 20–24. (rus)
34. Danilov, N.D., Doktorov, I.A., Ambrosyev, V.V., Fedotov, P.A., Semenov, A.A. Issledovaniye teplozashchitnykh svoystv fragmenta steny v klimaticheskoy kamere [Study of the heat-shielding properties of a wall fragment in a climate chamber]. Promyshlennoye i grazhdanskoye stroitelstvo. 2013. No. 8. Pp. 17–19. (rus)

Contacts:

Vladimir Rybakov, fishermanoff@mail.ru

Irina Ananeva, irina.ananeva94@yandex.ru

Egor Pichugin, pichugin_egor93@mail.ru

Marsel Garifullin, marsel.garifullin@tuni.fi