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DETERMINING THE HEAT TRANSFER COEFFICIENT OF INSULATED LOG-CABIN WALLS BASED ON ONE-DIMENSIONAL HEAT CONDUCTION

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ABSTRACT

An accurate calculation of heat transfer coefficient (*U*-value) for the insulated log-cabin walls in the practice is carried out using a difficult method of two-dimensional heat conduction, or using experimental measurement. This is due to the various thicknes of the wall layers – log-cabin and thermal insulation. The calculations are demanding form the professional point of view, as well as from the time aspect. Furthermore, it requires the use of specific programmes. Experimantal measurements are demanding due to the same reasons.

The aim of the paper is to propose a simplified and accurate determinantion of the heat transfer coefficient of insulated log-cabin walls using the modification of the method according to the STN EN ISO 6946 following the one-dimenaional heat conduction. The basis for the method modification is to determine the exact substitution method for the substitution of the profile of insulated log-cabin walls to a constant thickness. The paper determines and analyses two substitution methods of wall layers – dimensional and areal. When using the areal substitution method the modified methodology according to the STN EN ISO 6946 is suitable for a simplified and accurate calculation of the *U*-value of insulated log-cabin wall or other similar wall constructions.

Key words: heat transfer coefficient, log-cabin walls, thermal resistance, *U*-value.

INTRODUCTION

In order to preserve the sustainable development of life it is the responsibility of civil engineering to design and build ecological buildings with very low energy consumption during the build up as well as during operation. Ecological buildings are wood based buildings built as: low-energy houses, passive houses, zero energy houses and active houses. The basic measures, aimed at achieving very low or even zero energy consumption, cover: envelope insulation of very high quality, i.e. meeting current required values of the heat transfer coefficient *U* (*U*-value), eliminating the thermal bridges, airtightness of the building envelope etc.

Log-cabin construction systems belong to active, ecological and low-energy buildings. Log-cabin walls are constructed using log-cabin elements, which can have various cross-section profiles, such as prisms, logs, half logs etc. From the point of view of meeting the current requirements for the *U*- values of constructions for the build up of low energy houses or passive houses, it is inevitable to insulate the log-cabin walls from the interior side using insulation of appropriate thickness and finish it with the layers of other materials.

Log-cabin walls with insulation are characterised by a non-constant thickness of the logs and thermal insulation in the wall cross section. It is more difficult to determine the *U*-value from the geometrical shape of the log-cabin elements and thermal insulation when compared to the wall construction with a constant thickness of individual layers.

Heat transfer coefficient *U* is one of the essential required thermal performance characteristics of building structures. It is important for the accuracy of calculating the thermal losses of buildings via heat transfer, which influences significantly the concordance with the obligatory criterion of energy efficiency of low energy houses and passive houses. Since the *U*-value of structures influences significantly the calculated result of the building thermall losses via heat transfer, it is inevitable to determine this value as accurately as possible. For calculations in practice it is appropriate to implement the application of simple, quick and reliable methods of calculation without further use of specialised software or further calculations.

The rules for calculating the thermal resistance and heat transfer coefficient of building structures are determined by the STN EN ISO 6946. The standard, however, does not mention any modified procedure for calculating the thermal resistance *R* or *U*-values based on one-dimensional heat conduction e.g. for insulated log-cabin walls, where the wall elements and insulation do not have a constant thickness.

Authors ROZINS, IEJAVS (2014) deal with the determination of heat transfer coefficient of building materials and constructions according to the EN 12667 and EN 6946 through experiments as well as calculations. The authors focus on the material Dendrolight with the application in the wall structures. Author GORGOLEWSKI (2007) deals with increasing the accuracy of the method for calculating the heat transfer coefficient *U* for light structure steel frames. Furthermore, the author RESCH (1999) deals with the calculation of the *U*-value of wood walls constructed from small logs cut from four sides. Authors QASASS *et al*. (2014) deal with the determination of thermal bridges of wood frame structures for a more real calculation of the thermal resistacne. The author SIVIOUR (1994) deals with the experimental measurement of *U*-values of various exterior walls and with the comparison with the calculated values.

Neither the above mentioned authors, nor other ones, however, have dealt with the issue aimed at determining the *U*-value of insulated log-cabin walls based on the one-dimensional heat conduction.

The aim of the paper is to determine the heat transfer coefficient of insulated log-cabin walls using the modification of the method according to the STN EN ISO 6946 based on one-dimensional heat conduction. Further aim, connected to the method modification, is to determine and analyse the dimensional and areal substitution method for the substitution of the profile of logs and wall thermal insulation to a constant thickness.

METHODOLOGY

1. Specimens for the determination of the heat transfer coefficient

In order to achieve the aim an insulated log-cabin exterior wall from spruce logs and with interior panelling was selected. The construction is illustrated in Fig. 1.

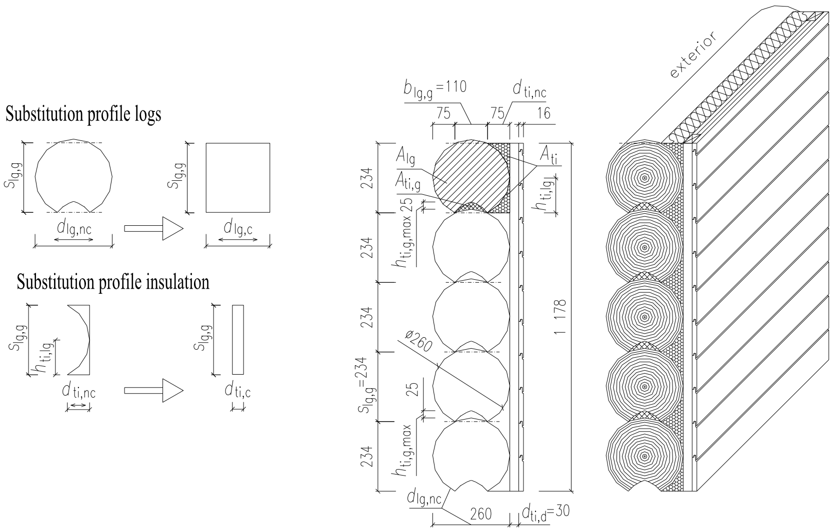

Fig. 1 Insulated log-cabin exterior walls ZG/260-Z1/V1 - constructions. Substitution of log profiles and insulation to constant thickness.

<u>Construction composition of the exterior wall ZG/260 – Z1/V1: from the exterior</u>

1. Log-cabin: spruce diamater 240 to 260 mm
2. Thermal insulation – mineral *) 30.0 mm
3. Vapour barrier – with alluminium layer
4. Wood paneling – spruce 16.0 mm

Note: *) thermal insulation fills in the gap between the lath and log

1. Boundary Conditions and Material Design Values

The boundary conditinos for calculation are in accordance with the STN 73 05040-2: 2012. For the theoretical analysis materials with the calculation values of thermal conductivity coefficient λ given in Tab. 1 were used.

Tab. 1 Materials and values of physical quantities of materials of proposed exterior walls.

No	Material	Volumetric weight in dry condition ρ_d [kg/m^3]	Thermal conductivity coefficient λ [W/(m.K)] for building structures		Specific heat capacity c [J/(kg·K)]	Difusion resistance factor μ [-]
			exterior	interior		
Wood values according to the STN EN ISO 10456/AC						
1.	Softwood perpendicular to fibres	500	0.13			50
Values according to the STN 73 0540-3.						
2.	Softwood perpendicular to fibres - spruce	400	0.18	0.15	2,510	157
3.	Insulation ISOVER DOMO	12	0.043	0.039	940	2.5
4.	Foil PE	170 g/m^2	0.35	0.35	1,470	9,380
Wood values according to the ČSN 73 0540-3						
5.	Spruce, fir – heat flow, perpendicular to fibres, moisture 15 %	450-500	0.14		2,000 to 2,400	

2. Determining the heat transfer coefficient *U* of insulated log-cabin walls using a modified method of one-dimensional heat conduction

The method of one-dimensional heat conduction – the calculation follows a simple procedure. Constant thickness and the calculation coefficient of thermal conductivity (layer) of the construction are important.

The method of determining the *U*-value according to the STN EN ISO 6946 for insulted log-cabin walls based on one-dimensional heat conduction is not suitable for a direct use due to the fact that the wall elements – logs and thermal insulation terminated by the logs and panelling do not have a constant thickness.

The basic procedure to determine the *U*-value (according to the mentioned standard) **needs to be modified by supplementing the substitution method of the log and thermal insulation profiles** using the following principle (Fig. 1):

- profile of logs $\phi = d_{lg,nc}$ = non-constant thickness to be substituted to $d_{lg,c}$ = constant thickness,
- profile of the thermal insulation $d_{ti,nc}$ = non-constant thickness to be substituted to $d_{ti,c}$ = constant thickness

The theoretical background for determining the constant thickness of logs and thermal insulation: the whole shape of the log profile and of the thermal insulation substitueted to the constant thickness is used to determine the exact *U*-value of the insulated log-cabin wall based on one-dimensional heat conduction.

Methods of substitution of the log profile and of the thermal insulation to the constant thickness

Tab. 3 illustrates the construction parameters of insulated log-cabin exterior wall according to Fig. 1

Tab. 2 Exterior log-cabin walls with insulation - construction data.

No.	Parameters	Symbol	Dimension	Unit
1.	diameter of logs	$\phi = d_{lg,nc}$	260	mm
2.	width of logs in the gap	$b_{lg,g}$	110	mm
3.	max. insulation height in the gap	$h_{ti,g,max}$	25	mm
4.	maximum not constant thickness of insulation (between the logs and the lath)	$d_{ti,nc,max}$	75	mm
5.	designed constant insulation thickness:	$d_{ti,d}$	30	mm
6.	spacing gaps between logs	$s_{lg,g}$	234	mm

Solution 1: Dimensional substitution method

1a) Substitution of the log profile – is based on the log diameter and the width of the contact in the cross section direction of the wall. The method is simplified and approximate for the substitution of the log profile to the constant thickness. The formula for determining the constant thickness of the log (Tab. 3) is derived from the construction solution according to Fig. 1.

Tab. 3 Dimensional substitution method - substitution of log profile.

No.	Determined value - description	Formula	Result	Unit
1.	Substitution of log profile to constant thickness	$d_{lg,c} = (d_{lg,nc} + b_{lg,g})/2$	185	mm
where: d_{lg} - diameter of logs [mm] $b_{lg,g}$ - width of logs in the gap [mm]				

1b) Substitution of the thermal insulation profile – is based on the width of the thermal insulation between the log surface and the lath. The method is simpliefied and approximate for the substitution of the thermal insulation profile to a constant thickness. The formula for determining the constant thickness of the thermal insulation (Tab. 4) is derived from the construction solution according to Fig. 1.

Tab. 4 Dimensional substitution method - substitution of thermal insulation profile.

No	Determined value - description	Formula	Result	Unit
1.	Substitution of the profile for thermal insulation to constant thickness	$d_{ti,c} = (d_{ti,nc,max} + d_{ti,d})/2$	52.5	mm
where: $d_{ti,nc,max}$ - maximum non-constant insulation thickness [mm] $d_{ti,d}$ - designed constant insulation thickness [mm]				

Solution 2: Areal substitution method

2a) Substitution of the log profile – is based on the log profile. The method is accurate for the substitution of wall log profiles to the constant thickness. The procedure and calculation formulas for determining the constant thickness of a log (Tab. 5) are derived from the construction solution according to Fig. 1.

Tab. 5 Areal substitution method – substitution of log profile.

No	Determined value - description	Formula	Result	Unit
1.	calculation of loga area	$A_{lg} = (\pi.d_{lg,nc}^2)4 - A_{ti,g}$	50,310	mm²
2.	Substitution of the log profile to constant thickness	$d_{c,lg} = A_{lg}/s_{lg,g}$	215	mm
where: $A_{ti,g}$ - is surface of insulation in the gap [mm²] $s_{lg,g}$ - spacing of gaps between logs [mm]				

2b) Substitution of the thermal insulation profile – is based on the surface of the thermal insulation. The method is accurate for the substitution of the thermal insulation profile to the constant thickness. The procedure and calculation formulas for determining the constant thickness of insulation (Tab. 6) are derived from the construction solution according to Fig. 1.

Tab. 6 Areal substitution method – substitution of thermal insulation profile.

No	Determined value - description	Formula	Result	Physical unit
1.	Maximum non-constant insulation thickness from the interior side	$d_{ti,g,max} = (d_{lg,nc} - b_{lg,g})/2$	75	mm
2.	Height of the insulation space from the interior side	$h_{ti,lg} = s_{lg,g} / 2$	117	mm
3.	Surface of insulation in the gap from the interior side	$A_{ti} = d_{ti,nc,max} . h_{ti,lg}$	8,775	mm²
4.	Substitution of insulation profile to constant thickness	$d_{ti,c} = A_{ti}/s_{lg,g}$	37.5	mm
5.	Designed constant insulation thickness	$d_{ti,d}$	30.0	mm
6.	The total constant thickness of the insulation	$d_{ti,t} = d_{ti,c} + d_{ti,d}$	67.5	mm

After substituting the log profile i.e. $d_{lg,nc}$ = non-constant thickness in the x-axe direction to $d_{lg,c}$ = constant thickness and thermal insulation $d_{ti,nc}$ = non-constant thickness to $d_{ti,c}$ = constant thickness the basic procedure according to the EN ISO 6946 can be used to determine the *U*-values of insulated log-cabin walls.

Simmulation software PHPP, which uses the method of steady thermal state and simplified calculation formulas according to the mentioned standard, was used for determining the *U*-value of the insulated log-cabin wall, including the thermal bridges.

3. The methods for verifying the results of determining the heat transfer coefficient

a) Method of two-dimensional thermal field – is used for theoretically more accurate determination of the *U*-value of structures, which are geometrically coplex and inhomogenous or include thermal bridges.
The programme Therm was used to determine the *U*-value using the mentioned method. The simmulation software is based on the Fourier partial differential equation of heat conduction; it uses the solution via the finite element method. In order to obtain graphical illustration and processing of the log-cabin wall the compatibile CAD software was used.
b) Experimental determinantion of heat transfer coefficient *U*- via the method of a climate chamber using the heat flow meter. The measurements were carried out in a large climate chamber at the Faculty of Civil Engineering, Slovak University of Technology, Bratislava. A fragment of the exterior log-cabin wall (Fig. 1) with the dimensions of 1,180 × 1,180 mm was used. Three measurements were carried out and the average value was determined.
Equipment and measurement principle – the measuring equipment for this specific measurement consists of four basic parts and its scheme is illustrated in Fig. 2:
A – fixed climate chamber,
B – mobile climate chamber,
C – smaller mobile climate chamber, so called "HOT – BOX" for an exact measurement of the basic thermal performance characteristics of the envelope.
D – additional panel of known thermal performance characteristics with an opening of 1,190 × 1,190 mm.

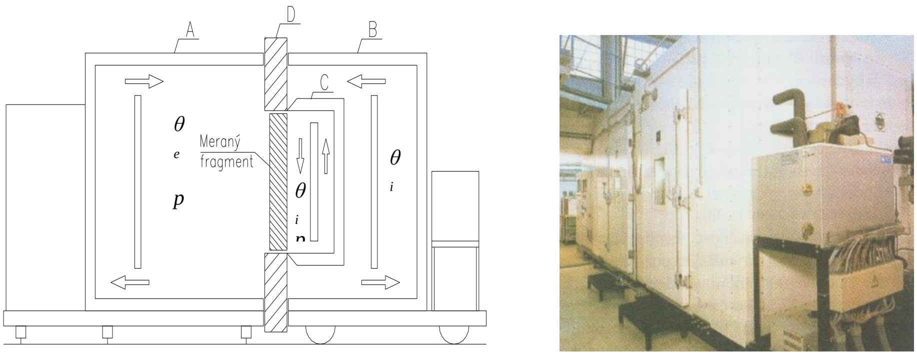

Fig. 2 Scheme of laboratory equipment of the large climate chamber.

Measurement principle
In the chamber A the exterior climate with following parameters is simulated: temperature –15°C, pressure between the exterior and interior = 0Pa, surface coefficient of heat transfer at external h_e = 23 W/(m^2.K) *(STN 73 0540-3: 2012).*

The chamber B is the compensation chamber for the HOT-BOX and simulates the interior climate with the parameters: temperature +20°C, humidity 50%.

HOT-BOX is used to measure the heat flow through the measured elements while the interior conditions are being simulated: temperature +20°C, humidity 50%, surface coefficient of heat transfer at internal h_i = 8 W/(m^2.K) *(STN 73 0540-3: 2012).*

After reaching the steady state temperature regime for the measured elements, based on the control technology of the climate chamber, all mentioned physical quantities are measured during at least two hours. The measurement and the recording the measured values are repeated every two minutes.

The heat resistance of the measured element is determined according to the formula:

$$R = A \,.\, (\theta_{ai} - \theta_{ae}) \,/\, Q \quad [(\mathrm{m^2K})/\mathrm{W}]$$

All mentioned physical quantities are average values measured during the last two hours of the measurement. The value of the heat resistance *R* (*R*-value) and the standard conditions for R_{si} and R_{se} the heat transfer coefficient *U* of building construction is determined: $U = 1/(R_{si}+R+R_{se})$ [W/(m²K)] *(Puškár a kol. 2002)*.

where: R_{si} = 0.13 [m²K/ W], R_{se} = 0.04 [m²K/ W] *(STN 73 0540-3: 2012)*

RESULTS

1. The results of the *U*-values determined by the modified method of one-dimensional heat conduction

Tab. 2 Insulated log-cabin wall ZG/260 – Z1/V1: according to the calculation thicknesses

no	Calculation value of the spruce wood λ [W/(m·K)]	Final *U*- value [W/(m²·K)]		Note: Source of the value λ for spruce
		Dimensional substitution method Log thickness =185 mm Insulation thickness = 52.5 mm	Areal substitution method Log thickness = 215 mm Insulation thickness = 67.5 mm	
1	2	3	4	5
1.	0.13	0.35	0.29	STN EN ISO 10456/AC:2010
2.	0.14	0.37	0.30	ČSN 73 0540-3:2005
3.	0.18	0.41	0.34	STN 73 0540-3:2012
Note: Program PHPP was used to determine the *U* - value.				

2. The results of the *U*-values: two-dimensional heat conduction and experimental determination

Tab. 3 Verification of *U*-values of log-cabin walls: comparison of results.

no	Way of determining the *U*-value	Heat transfer coefficient λ of spruce [W/(m·K)]	Final *U*-value of the wall [W/(m²·K)]	Note: Source of the value λ for spruce
1	2	3	4	5
1.	One-dimensional heat conduction [1)] Direct use of layer thicknesses: - Log thickness = 260 mm - Insulation thickness = 30 mm	0.13	0.35	STN EN ISO 10456/AC:2010
		0.14	0.37	ČSN 73 0540-3:2005
		0.18	0.43	STN 73 0540-3:2012
2.	Two-dimensional heat conduction [2)]	0.13	0.33	STN EN ISO 10456/AC:2010
		0.14	0.34	ČSN 73 0540-3:2005
		0.18	0.39	STN 73 0540-3:2012
3.	Experiment – average value		0.31 [3)]	

Note: 1) Program PHPP was used to determine the *U* - value. 2) Program Therm was used to determine the *U* - value.
3) The average value is calculated from results provided by three measurements, which are the following: 0.31; 0.30; 0.32. W/(m²·K).

DISCUSSION

If the log diameter of 260mm and insulation thickness of only 30mm are substituted directly in the process of calculating the *U*-value of insulated log-cabin wall using the one-dimensional heat conduction, we get the values illustrated in Tab. 3 according to line 1 and column 3. The accuracy of determining the *U*-value of the wall depends on the constant thickness of its layers and is influenced by the used heat transfer coefficient λ of the material. From the point of view of the directly used log thickness (its diameter) and regardless the insulation thickness in the space between the log-cabin surface and the lath, the calculation and final *U*-value of the wall is not accurate and thus unsuitable for the practice.

The direct use of the thicknesses of log wall layers with insulation is not suitable for an accurate determinantion of the *U*-value with the method according to the STN EN ISO 6946. For such cases it is necessary to modify the method. Solving the given issue follows the work of S. JOCHIM (2016). The work deals with the modification of method used for determining the *U*-value of a log-cabin wall without insulation. In this case the principle of method modification is the same, but it considers log-cabin wall with insulation and final wood panelling of the interior.

If constant thicknesses of the layers according to the dimensional substitution method are used for the calculation of the *U*-value of the insulated log-cabin wall, we get the results illustrated in Tab. 2, column 3, which are as follows:

- higher by 6.67% on average in comparison with the results of method of two-dimensional heat conduction illustrated in Tab. 3, line 2, column 4;
- higher by 12.9% - 32.2% in comparison with experimental results illustrated in Tab. 3, line 3, column 4.

If constant thicknesses of the layers according to the areal substitution method are used for the calculation of the *U*-value of the insulated log-cabin wall, we get the results illustrated in Tab. 2, column 4, which are as follows:

- lower by 12.24% on average in comparison with the results of method of two-dimensional heat conduction illustrated in Tab. 3, line 2, column 4.

In comparison with the experimental results ($U = 0.31$ W/($m^2 \cdot K$) in Tab. 3, line 3, column 4, the results are different, as follows:

- with the value $\lambda = 0.13$ W/($m^2 \cdot K$) the *U*-value is 0.29 W/($m^2 \cdot K$), lower by 6.45%
- with the value $\lambda = 0.14$ W/($m^2 \cdot K$) the *U*-value is 0.30 W/($m^2 \cdot K$), lower by 3.23%
- with the value $\lambda = 0.18$ W/($m^2 \cdot K$) the *U*-value is 0.34 W/($m^2 \cdot K$), higher by 3.23%

The accuracy of determining the *U*-value of the insulated log-cabin wall depends on the accuracy of the calculation of the constant thickness of the log and insulation profiles using the mentioned substitution methods. A certain concordance of the *U*-values with the use of layer thicknesses from the dimensional substitution method in Tab. 2, column 3 and result with the direct use of layer thicknesses in Tab. 3, line 1, column 4 is ineteresting. The simplified procedure of calculation influences the result in both cases in the same way, i.e. the differences are not signiticant.

Another interesting fact of using the substitution methods of wall layer profiles is the difference in the accuracy of *U*-values results (Tab. 2, columns 3,4) in comparison with the results of the two-dimensional heat conduction (Tab. 3, line 2, column 4). The methodology using the dimensional substitution method seems to be more accurate – the results are higher by 6.67% on average, while the results using the areal substitution method are lower by 12.24%. However, the practical reliability of the reuslts using the method of two-dimensional heat conduction is important, as well. The method cannot consider the real values of materials and construction.

For a more precise analysis in order to evaluate the accuracy and reliability of substitution methods it is important to consider also the comparison of results with the average results from the experimental measurements, where $U = 0.31$ W/(m^2·K). The results from the dimensional substitution method are higher by 21.51%. The results from the areal substitution method are different by 0.00%. The results from the experimental measurements – the avergae value can be considered representative due to the fact that in the experimental measurements the real quality of materials and construction in the steady climate conditions are verified.

Naturally, the final *U*-value of the construction is influenced also by the calculation value λ of materials, however, it does not influence the substitution methods of log profile to the constant thickness; it does not interfere with the calculation formulas. The highest concordance in the accuracy is shown by the determination of the *U*-value of insulated log-cabin wall while using the above mentioned methods with the spruce calculation value $\lambda = 0.14$ W/(m·K). The calculation values λ of materials are, however, the concern of corresponding and valid standards.

GORGOLEWSKI (2007) deals with the simplified and more accurate determination of the *U*-value of light steel structures based on one-dimensional heat conduction. This procedure is derived from the basic methodology BS EN ISO 6946 and the corresponding methodology for calculation of the *U*-value of inhomogenous structures. When compared to the methodology for determining the *U*-value of log-cabin structures, the basis for the calculation is the same, according to the basic formula in EN ISO 6946. Modified methodology procedures are, however, different, due to the construction of walls, inhomogenous steel construction and insulated log-cabin wall. Concordance in the modified methods lies in the fact that both cases have to consider the area of materials in order to obtain an accurate calculation of the *U*-value.

The author SIVIOUR (1994) and works of other authors confirm some deviations among experimentally measured and calculation results of *U*-values. Experimentally measured values can be higher or lower than the calculation results. There are several factor influencing the measured values, e.g. the real thermal conductivity of materials, air movement in cavities, construction thermal bridges, factor connected to measurement as reaching the steady heat flow, steadiness of the temperature difference during several days etc.

Higher *U*-value (0.31 W/(m^2·K) of an insulated log-cabin wall measured experimentally was confirmend also in our study, when it is compared with the results in Tab. 2, column 2, lines 1 and 2. However, the results are not significantly different. With other results, the calculated *U*-values of the wall are higher than those measured. One of the reasons is the inaccurate dimensional substitution method (Tab. 2, column 1). Another reason is overrated coefficient of heat conduction for spruce $\lambda = 0.18$ W/(m·K).

The overall analysis, as well as the experimental measurement proved the accuracy of the use of areal substitution method for the modification of the method of one-dimensional heat conduction for the calculation of the *U*-value of insulated log-cabin walls.

CONCLUSION

The submitted study deals with the issue of determining the coefficient of heat transfer of insulated log-cabin walls using the modified method of one-dimensional heat conduction according to STN EN ISO 6946. For the modification of the method two methods for substitution of the log profile and shape of the thermal insulation to the constant wall thickness were proposed and verified.

The dimensional substitution method of the log and insulation profiles to the constant thickness of layers was proven as very inaccurate. The use of constant thicknesses of layers from the dimensional method in order to determine the coefficient of heat transfer shows higher values. It is suitable only for approximate calculation of the thermal performance of the construction.

The areal substitution method of the log and insulation profiles to the constant thickness proved to be the correct and more accurate one. The use of constant thicknesses of wall layers from the areal method in order to determine the coefficient of heat transfer shows low and generally valid deviations from the results of experimental measurements.

The presented results show that the modified method in accordance with the STN EN ISO 6949 based on one-dimensional heat conduction using the areal substitution method is suitable for a simple and practically accurate determination of the *U*-value of insulated log-cabin walls. There is no need to use specific calculation softwares; it is based only on the dimension of the wall construction and uses known and simple calculation formulas.

Scientific and practical contribution of the modified method of one-dimensional heat conduction in accordance with the STN EN ISO 6949 for the insulated log-cabin walls:

1. It considers the different geometry of log-cabin profile and thermal insulation for determination of the constant thickness of the wall layers influencing the determination of *U*-value.
2. It uses basic formulas according to the STN EN ISO 6949 for determining the *U*-value based on one-dimensional heat conduction.
3. Determination of the constant thickness of wall layers according to the areal substitution method for the log and insulation profiles is simple and accurate for the determination of the *U*-value of the wall.
4. The areal substitution method of the log and insulation profiles to the constant thickness does not depend on the calculation value of the coefficient of heat conductivity λ of the material.

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