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The Impact of the Heat Flux Density on Separation Distances from Flammable Surfaces of Exterior Walls

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Case study

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Abstract

The paper deals with the topic of determining the density of heat flow from combustible surface treatments of exterior walls, such as combustible insulation systems, combustible cladding of facades and from all-wood constructions of exterior walls. Heat flow density is an important indicator in determining the fire resistance rating of exterior walls and in determining safe separation distances. The article describes the ways in which exterior walls can be classified in terms of fire resistance. One of these methods is a numerical calculation (of the surface amount of released heat and heat flow density), which will be applied to various types of combustible surfaces of the perimeter walls of wooden buildings. The results showed that the numerical calculation is a suitable method for determining the classification of fire resistance rating of exterior walls with combustible coating. The Czech legislation defines the criteria for this classification better.

Keywords: flammable surface treatment; released heat per area; thermal flux density; Heat Release Rate; partly fire open area; fire separation distance

1 Introduction

At the present time, fire safety of the building is placing an emphasis on determining the fire separation distances from the exterior walls, which have an external surface treatment made of combustible materials in the form of wooden cladding or insulation made of plastic or wood fiber materials. This approach is relevant, especially for the frame or prefabricated panel timber buildings, which are often covered with wooden or other combustible cladding on the outside and for all-wood log wooden buildings or wooden buildings made of CLT panels. The listed combustible materials release a surface amount of heat in the event of a fire, which must be taken into account when determining the fire resistance of exterior walls and subsequently when calculating the fire separation distances in accordance with valid standards. In practice, this means that the distances determined in this way can be significantly increased, especially for wooden buildings, which is undesirable in view of the decreasing size of land plots for wooden buildings. Therefore, it is necessary to look for methods to determine the separation distances more precisely so that the distances are adequate and at the same time safe for neighboring buildings.

1.1 Fire closedness and fire openness of exterior walls

Fire-resistive-rated structures are those that are closed to the spread of fire. The term fire closedness is not defined by STN 92 0201-4/Z3 [1], but we can say that a fire-closed structure is one that has fire resistance and that prevents the spread of fire for a certain time. Fire-open structures are those that are vulnerable to the effects of fire, i.e., they do not have the required fire resistance. The concept of fire-open area is defined in STN 92 0201-4/Z3 [1], while two types of fire-open areas are defined as follows:

Completely fire-open area (CFOA) is the area of:
a) an exterior wall that does not provide for the stability of the building or its part, which does not meet the requirement for fire resistance according to STN 92 0201-2 [2];
b) an exterior wall of a one-story building that does not meet the requirement for fire resistance according to STN 92 0201-2 [2];
c) an opening in the exterior wall or an opening in the exterior wall filled with a filling that does not meet the requirements for fire resistance according to STN 92 0201-2 [2] which is, therefore, considered fore-open.
Partially fire-open area (PFOA) is the area of an exterior wall or its part that meets the requirement for fire resistance, but its outer side has a flammable surface, and it is able to release more than 100 $MJ.m^{-2}$ of heat from 1 m^2 during a fire.

This definition suggests that, in the case of a partially fire-open area, it is necessary to consider not only combustible construction products and components that are added from the outside to the construction of the exterior wall, but also combustible surfaces; if the entire exterior wall is made of combustible material, e.g., in case of a wooden log wall or a CLT exterior wall.

The size of the fire-hazardous space depends on the classification of the fire openness of the exterior wall. Whether it is a wall with a fire-closed or fire-open area can be determined in several ways [3]:
1. By calculation:
- numerical calculation (amount of released heat, heat flux density),
- mathematical model, e.g., CFD (Computational Fluid Dynamics) model;

2. By test:
- fire resistance test,
- test of the reaction-to-fire of facades,
- conical calorimetry.

1.2 Released heat per area

Numerical calculation is rather often used method for determination of fire openness of the surface by the amount of released heat from the combustible mass. The classification depends in this case on area weight and calorific value of used materials.

The released heat per area *Q* from the combustible materials of outer surface of the exterior walls can be determined according to the following equation [1]:

$$Q = \Sigma M_i \cdot H_i \qquad (1)$$

where:
Q - released heat (MJ/m^2),
M_i – area weight of the flammable material *i* placed on the outer surface of the exterior wall (kg/m^2),
H_i – calorific value of flammable material i on the outer surface of the exterior wall (MJ/kg) according to STN 73 0824 [4],
j – the number of types of flammable materials.

1.3 Heat flux density

Heat flux density, called also heat flux density per area, is a heat flux which is transferred by the unit area perpendicular to the direction of heat transfer. The SI unit of thermal flux density is W/m^2.

According to STN 92 0201-4/Z3 [1], the fire hazardous space, surrounded by a defined separation distance, is safe towards the neighbouring buildings when the thermal flux density on its boundary stays below $q = 18{,}5\ kW/m^2$.

A lot of countries state thermal flux density value more strictly, e.g., England 12.5 kW/m^2, Sweden 15 kW/m^2 resulting in bigger separation distances. Namely, in Sweden, the separation distances are determined according to the Swedish procedure to architectural design

(Boverket's building regulations). The buildings must be placed at least 4.0 m from the boundary or at minimum 8.0 m from other buildings at the neighbouring lot. In case the separation distances are not met, it must be proven that potential fire shall not spread between the buildings [5].

Thermal flux density per area is determined according to [1] from the respective time of fire duration τ_e, or calculated fire load p_v, and from the gas temperature which is expressed by a standard time-temperature curve T_N for the respective duration of fire:

$$q = (T_N + 273)^4 \cdot 5{,}67 \cdot 10^{-11} \qquad (2)$$

$$T_N = 20 + 345 \log (8t + 1) \qquad (3)$$

where:
q – thermal fluc density per area (kW/m^2),
T_N – standard gas temperature in the burning space (°C),
t – respective fire duration τ_e or calculated fire load $p_{v,}$ (kg/m^2).

1.4 Fire openness of structural elements abroad

According to ČSN 73 0802 [6], the boundaries between fire-opened and fire-closed areas of exterior walls are determined by the threshold values of the amount of released heat Q and the area density of the heat flow I according to Tab. 1.

Tab. 1 Threshold values of heat flux density I and the amount of released heat Q [6]

Fire-closedness definition	I (kW/m^2)	Q (MJ/m^2)
Fire-closed area	$I \leq 15$	$Q \leq 150$
Partially fire-open area	$15 > I \leq 60$	$150 > Q \leq 350$
Completely fire-open area	$I > 60$	$Q > 350$

For exterior walls of type DP1 (D1) or DP2 (D2) both of the above-mentioned criteria (I and Q) can be applied, for walls of type DP3 only calculation of heat flow density I or fire test can be used.

According to Article 8.4.5 ČSN 73 0802 [6] for structural parts (structural elements) of type DP1 (D1) and DP2 (D2) are classified as fire-closed areas. The exception is in cases where the outer surface of products of fire-reaction class E or F with released heat $Q > 150$ MJ/m^2. The wall is then considered as a partially fire-open area. The type of structural part (structural element) has an influence on the classification of the fire openness of exterior walls according to the regulations of the Czech Republic. Constructions DP1 and DP2 (as long as no combustible material is added to their outer surface) can be classified as fire-closed surface by virtue of their definition (no heat is released from them). Constructions of type DP3 are mostly classified as fire-open areas. An important factor in these constructions is fire resistance. This means that even a structural part of the DP3 type can be classified as a fire-closed area, as long as its fire resistance is ensured by an effective fire coating on the outer side of the wall [3].

However, the technical standard in the Slovak Republic [1] does not state threshold values of the heat flux density per area and the amount of released heat to specify fire openness. Only the threshold amount of released heat is determined to include an exterior wall with an outer combustible surface into a partially fire-open area ($Q > 100$ MJ/m^2), which must be taken into account when calculating separation distances. However, this does not take into account the type and thickness of the combustible surface of the perimeter wall; it only classifies the combustible surface as a partially fire-open surface (PFOA), whereby the distance from the exterior wall remains the same, regardless of the type and thickness of the combustible material (see Table 2).

Tab. 2 Determination of separation distance depending on various combustible surfaces of the exterior wall according to STN [7]

	Flammable surface	Thickness (m)	Density (kg/m^3)	Area weight (kg/m^2)	Standard calorific value *H* (MJ/kg) STN73 0824	Heat per area *Q* (MJ/m$^{2)}$	PFOA	$Spo_2 \cdot k_{10}$ (m^2)	p_o (%)	*d* (m)
1	Facade EPS 70 F	0.15	17	2.55	39	99.45 ≈100	yes	22.27	46.89	8.1
	STEICO Protect	0.06	265	15.9	18	286.2	yes	22.27	46.89	8.1
	Wood cladding (spruce)	0.022	460	10.12	17	172.04	yes	22.27	46.89	8.1
2	Log house wall	0.2	420	84	17	1428	yes	22.27	46.89	8.1
3	CLT wall	0.08	470	37.6	17	639.2	yes	22.27	46.89	8.1

2 Material and Methods

In order to determine the fire openness of the considered exterior wall more accurately, we will proceed according to the methodology of Czech standards. The separation distance for the same materials considered in Tab. 2 shall be determined, while the facade cladding materials EPS 70 F, STEICO Protect - wood fiber board and wood (spruce) cladding will be applied from the outside of the column structure of the perimeter wall of type D2, and the log wall and the wall made of CLT panels are made of solely spruce wood, that means it is structural elements of type D3. There are two window openings measuring 1.10 × 1.25 m in the considered exterior wall. The dimensions of the perimeter wall are 12.41 × 4.3 m and it is a single-family house building, which forms one fire compartment.

According to Czech legislation, the calculation of the amount of released heat according to equation (1) can only be used for structural elements of type D1 and D2. This calculation cannot be used for structures of type D3 because we cannot neglect the combustible load-bearing structure in the calculation. For structural elements of type D3, the heat flux density calculation or fire test [3] is used.

Calculation of heat flux density can be used for all types of structural elements D1, D2, D3. We can use the following simplified equation [3] to determine the fire resistance of exterior walls:

$$I = \varepsilon \cdot \sigma \cdot (T_N + 273)^4 \quad (4)$$

where:
I – heat flux density (kW/m^2),
ε – emissivity with the estimated value $\varepsilon = 1.0$ (-),
σ – Stefan-Boltzmann constant equal to the value of $5.67 \cdot 10^{-8}$ W/m$^2 \cdot$K^4,
T_N – temperature of the burning surface (°C).

The gas temperature value is variable. The formula of the external fire curve or the hydrocarbon curve (for flammable gases and vapours) is inserted into the equation. All the mentioned curves depend on the duration of the fire.

In the case of timber structures made of structural elements of type D3, it is also possible to use a more effective assessment of the fire openness, or closedness of the exterior walls depending on the calorific value and burning rate. This method is used, for example, in software for fire CFD simulations [3]:

$$I = \frac{\upsilon \cdot H}{60} \quad (5)$$

where:
I – heat flux density (kW/m^2),
υ – burning rate (kg/m^2·min),
H – calorific value of the flammable material on the outer surface of the exterior wall (MJ/kg).

When calculating, it is possible to take into account the fact that a larger part of the total released heat is usually released in the form of air flow and combustion products, and a smaller part by heat radiation, heat transfer through conduction is neglected. From the safety point of view, it is possible to consider a value of the radiation equal to 50 % of the total released heat. In mathematical models, the radiation is assumed to be even smaller [3].

2.1 Methodology of calculation of heat flux density for chosen flammable materials on the outer side of the exterior wall

In order to take into account the type and thickness of the material from the outer side of the considered exterior walls (post-frame construction D2 construction, log construction D3 and CLT panel construction D3), according to relation (5), the heat flux density I is calculated for each type of combustible surface material. As mentioned before, this calculation can be used for all types of structural elements D1, D2, D3. The input data for the calculation are listed in Tab. 3. The calculation results are shown in Tab. 4. The burning rate of individual combustible materials is determined according to Annex C, Tab. C2 of STN 92 0201-1 [8]. The calorific value of these materials is determined according to STN 73 0824 [4].

Tab. 3 Input data for the calculation

Item No.	Combustible surface	Thickness (m)	Density ς (kg/m^3)	Surface weight M_i (kg/m^2)	Standard calorific value H (MJ/kg) STN 73 0824	Heat per area Q (MJ/m^2)	Burning rate υ (kg/m^2·min)
1	Facade EPS 70 F	0.15	17	2.55	39	99.5	1.50
	STEICO Protect	0.06	265	15.9	18	286.2	0.22
	Wooden cladding (spruce)	0.022	460	10.12	17	172.04	0.45
2	Log house wall	0.2	420	84	17	1428	0.45
3	CLT wall	0.08	470	37.6	17	639.2	0.45

2.2 Methodology of separation distance calculation

The separation distance shall be calculated according to the technical standard [1] and [9]. First, the separation distance from the completely fire-open areas shall be determined for the specified reference exterior wall construction.

The total fire-open area S_{po} is determined from the ratio of heat flux density according to individual areas of the equation:

$$S_{po} = S_{po1} + k_{10} \cdot S_{po2} + k_{11} \cdot S_{po3} \quad (m^2) \tag{6}$$

where:
S_{po1} – completely fire-open area (m^2),
S_{po2} – partially fire-open area (m^2),
S_{po3} – fire-open area of roof cover (m^2),
k_{10} – coefficient of partlially fire-open area (-),
k_{11} – coefficient of fire-open area of roof cover (-).

Coefficients k_{10}, k_{11} are determined according to Tab. 2 STN 920201-4 [9]. Further, the percentage of fire-open area p_o and the total area of exterior wall according to the equation:

$$p_o = \frac{S_{po}}{S_p} \cdot 100 \leq 100\ (\%) \tag{7}$$

where:
p_o – percent of fire-open areas (%).
S_{po} – total fire-open area (m^2),
S_p – area of exterior wall (m^2).

The separation distance *d* (m) is deteremined according to Tab. 3 STN 92 0201-4 [9] depending on the length and height of the exterior wall *l* and h_u and percent of fire-open areas p_o and fire risk by calculated fire load p_v. According to Tab. K1 STN 92 0201-1 [8], the fire risk value for the construction of a family house is p_v = 50 kg/m^2. In case of a combustible structural assembly of the building, the calculated fire load in the fire section must be increased by 25 kg/m^2 in accordance with [1]. To determine the separation distance, we will, therefore, consider the value p_v = 75 kg/m^2.

3 Results and Discussion

Part 1.4 mentions that both criteria *I* and *Q* can be used to assess the fire openness (closedness) for exterior walls of type D1 or D2. As for walls of type D3, only the calculation of heat flow density *I* can be used. For post-frame exterior wall of type D2 with combustible cladding materials (EPS, STEICO, wooden cladding) are the values of the amount of heat per area *Q* already calculated (see Tab. 2 and Table 3) according to Tereňová (2021) [7]. To classify the post-frame exterior wall from the point of view of fire openness (closedness), Tab. 1 according to ČSN 73 0802 [6] was used. For log and CLT exterior wall type D3, the heat flux density *I* was calculated according to relation (5), while a 50 % radiation share according to [3] was taken into account and was classified also according to Tab. 1. The separation distance was determined for all types of combustible surfaces according to the methodology given in part 2. 2. The results of the calculations are shown in Tab. 4.

Tab. 4 Calculation results according to the Czech Technical Standard (ČSN)

Number	Combustible surface	Heat per Area *Q* (MJ/m^2)	Heat flux density *I* (kW/m^2)	Fire openness of exterior wall	Percentage of fire open area p_o (%)	Separation distance *d* (m)
1	Facade EPS 70 F	99.5	-	Partially fire-closed area	5.15	2.7
	STEICO Protect	286.2	-	Partially fire-open area	46.89	8.1

Continuation of Tab. 4

1	Wooden cladding (spruce)	172.04	-	Partially fire-open area	46.89	8.1
2	Log house wall	-	63.75	Completely fire-open area	100	11.4
3	CLT wall	-	63.75	Completely fire-open area	100	11.4

When the results of determined fire openness (closedness) and separation distance according to Czech legislation (Table 4) and Slovak legislation (Table 2) are compared, significant differences can be seen. With a combustible EPS surface, the exterior wall was classified as a fire-closed area according to Tab. 4 and thus the separation distance changed from the value of 8.1 m to 2.7 m as it was determined only from the size of openings in the exterior wall. With a greater thickness of EPS insulation, an increase in the amount of released heat Q can be assumed which would classify the exterior wall as a partially fire-exposed area.

The results for the combustible surface of the exterior wall cladded with STEICO Protect wood fiber board. Wooden cladding remained unchanged after comparison with Tab. 2 as the amount of released heat Q in both cases exceeded the value of 150 MJ/m^2 which meets the conditions for inclusion in a partially fire-exposed area according to STN and ČSN.

In the case of a log wall and a wall made of CLT panels, the value of the calculated heat flow density I (Tab. 4) exceeded 60 KW/m^2 and placed the structures in a completely fire-open area whereby the separation distance increased to a value of 11.4 m.

Based on the results, the following conclusion can be drawn, the type of structural element has an impact on the results of the evaluation of the fire openness of exterior walls with a combustible surface. Whether the given structure of type D1 or D2 will be classified as a closed or partially open area depends on the value of the amount of released heat Q, mainly on the type and thickness of the combustible surface. However, it is questionable what value of Q should be taken as a threshold; whether 100 MJ/m^2 according to STN or 150 MJ/m^2 according to ČSN.

The results confirmed that in the case of all-wood D3 constructions, it is appropriate to base the determination of the fire openness (closedness) of the exterior walls on the value of the heat flow density I. This is evidenced by the high calculated values of released heat Q = 1428 MJ/m^2 for the log wall and Q = 639.2 MJ/m^2 for a wall made of CLT panels (see Tab. 2) which are considerably higher than in other cases. Therefore, the established separation distance of 11.4 m according to ČSN is adequate.

Similar results were achieved by Pokorný (2014) [3] who numerically evaluated a log cabin with a massive wooden exterior wall which accounted for the required fire resistance. He considered the speed of wood burning υ = 0.45 kg/m^2·min and the calorific value of coniferous wood H = 17 MJ/kg with a 50 % radiation share, he calculated the heat flux density I = 63.8 KW/m^2 which classified the solid wooden exterior wall as a completely fire-open area. This result complies with our calculations (see Tab. 4).

Pokorný (2014) [3] also evaluated a building with the exterior wall of type D2 construction with wooden cladding thickness 20 mm, density 500 kg/m^3, calorific value 17 MJ/kg. Based on the given input data, he calculated the amount of released heat Q = 170 MJ/m^2 and the exterior wall was classified as a partially fire-open area. The result is identical to the result in Tab. 4.

To evaluate the degree of fire openness, it is possible to use a small-scale test with a conical calorimeter. Based on tests performed at the Technical Institute of Fire Protection in Prague (TUPO), presented by Kašová (2017) [10], samples of fiber board plastered with cement plaster (as designed for D3 type construction with fire resistance) showed heat release rate greater than 15 kW/m^2 and less than 60 kW/m^2. Therefore, the composition was classified as a partially fire-open area. In our case, the

STEICO fiber board was classified in the same way. Heat Release Rate is currently one of the most important fire engineering characteristics. The heat release rate does not only indicate the total amount of heat released, but it also expresses its time performance during the development of the fire. Therefore, it is not completely suitable for determining fire openness [10, 11].

Kašová (2017) [10] presents the results of a non-standardized large-scale test, during which construction D1 with combustible OSB cladding in which there was a window opening was tested. During the test, the fire was set according to the standard temperature curve inside the furnace to which the fire scenario of an external fire in the lintel was added. By numerically calculating the amount of released heat, the tested wall was classified as a partially fire-open area. The determination of fire openness (closedness) on the basis of the proposed non-standardized large-scale test turned out to be not very suitable because the classification of fire openness (closedness) is determined using the heat flux density on the burning surface. There is currently no procedure for measuring this parameter. At the same time, the methodology for testing this parameter has not been established yet.

4 Conclusions

According to the obtained results using numerical calculations, it was shown that it is a suitable way of determining the fire openness (closedness) of exterior walls with a combustible surface. The criteria for this classification are defined more precisely in the Czech legislation. Slovak legislation lacks threshold values of heat flux density I and the amount of released heat Q. The results of calculations of fire openness of the assessed exterior walls with a combustible surface according to ČSN and STN were different. Bigger separation distances were detected by Czech legislation. It would be appropriate to supplement the obtained calculation results with the results of mathematical modelling. However, the test methodology is still not clear.

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