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New Calculation Technique for Assessment of Smoke Layer Interface in Large Buildings in Connection with the Design of Buildings in the Czech Republic

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Abstract: The sustainability of the indoor environment of buildings is also related to the conditions that arise in the case of fires. Fires in buildings are characterized by the formation of combustion products, which can significantly endanger the life and health of people. One of the major sources of danger is smoke. If there is no smoke exhaust into the outside environment during the development of the fire, the building is gradually filled with smoke. The important characteristic of the smoke layer is the level of the smoke layer, which changes over time. Several methods have been derived for determining the descent of the smoke layer in an enclosed area of space, which mainly differ in terms of the application area and limits of use. The methods used in the Czech Republic for the assessment of smoke layer descent in the case of fires do not have a clear rationale and in many cases lead to completely misleading results. For this reason, in connection with the standards for the assessment of the buildings in the Czech Republic, a new calculation technique (CSN) has been derived, which has been compared with the selected simple calculation techniques in large buildings. The deviations between the results have been evaluated by the percentage bias method (PBIAS), while the largest deviation, compared to the ISO standard technique, did not exceed 20%. The CSN calculation technique shows a favourable compliance with the technique presented by the ISO standard, where the deviation did not exceed 1.6%. In response to the proposed standards in the Czech Republic, the CSN calculation technique enables the assessment of safe evacuation in relation to the smoke layer interface and can be a considered perspective.

Keywords: fire; smoke; smoke layer interface; large buildings; evacuation time

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1. Introduction

Territorial safety and the protection of inhabitants are basic tasks of all countries. The safety of the territory and its inhabitants is also one of the primary interests of the European Union. It is conceived as the security policy of the European Union. The principles of the European Union security policy include an increase in the prosperity of inhabitants, ensuring sustainable territorial development or support for the robustness of democratic systems [1].

Sustainable territorial development is closely linked with the safety of buildings in each territory. Within the European Union, the requirements for ensuring the safety of buildings are based primarily on the Regulation of the European Parliament and of the Council (EU) No 305/2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC. The properties that buildings must have include fire safety requirements. The specified requirements include the preservation of the construction's load-bearing capacity in the event of a fire, as well as limiting the spread of fire within the building and outside of it, ensuring the evacuation and rescue of people, and ensuring the safety of rescue teams [2]. The sustainability of buildings is therefore closely connected to their security.

Ensuring the safe evacuation of people is one of the most significant building requirements from perspective of fire safety. As a rule, the safe evacuation of people is dealt with by designating the "required safe escape time RSET" and its comparison to the "available safe escape time ASET" [3,4]. The required safe escape time, RSET, consists of several basic steps, characterized by the interval from the ignition to the detection of the fire, the interval from the detection of the fire to the announcement of evacuation [5], the interval from the announcement of evacuation to the decision made by people to start evacuating, the interval from the decision made by people to start evacuating to the actual start of evacuation, and people's movement time through the building to an open area of space or another safe area [6–8]. The generation of smoke is one of the most significant threats that people are exposed to during evacuations in buildings. Smoke has a major negative impact on the sustainability of the indoor environment of buildings in the case of a fire. The basic characteristics of smoke in relation to the evacuation of people include its heat, toxicity, and optical density [6,9].

Smoke management methods are employed in order to ensure fire safety from the perspective of the negative impact of smoke [10,11]. These include smoke compartmentation, smoke dilution, the pressurization of protected areas of space, generation of airflow from protected areas of space, and the utilisation of smoke's buoyancy effect. The smoke buoyancy effect arises as a result of an increase in its temperature, which causes a reduction in smoke density thus resulting in a buoyancy effect. Smoke accumulates under a ceiling and gradually fills the area of space where a fire is developing [12,13].

One of the significant factors influencing ASET is the threat to people resulting from the descending smoke layer interface in the area of space. A level of 2.5 m above the floor is generally considered a "safe level" of the smoke-free height of space. However, in some cases, there are different recommendations for the smoke level, for example in public buildings, 3 m above the floor and in garages, 80% of the space's clear height. The height of the smoke layer being 2.5 m above the floor of the area of space can be considered representative [14,15]. The formation and the spread of smoke also affects the RSET. This is mainly the interval from the occurrence to the detection of fire (the quality and quantity of smoke affects the reaction speed of fire detectors). However, it also partially affects other RSET intervals.

The spread of smoke and the formation and deepening of the smoke layer in the area of space are influenced by many factors, including, for example, the difference between the interior and exterior temperature, wind speed and direction, the installed technical equipment of buildings, the design of the building from the perspective of fire safety, and the piston effect caused by elevators [12]. Another is the geometric shape of the space [16]. The characteristic construction of corridors (the predominant dimension is length) and construction of atria (the predominant dimension is height) are specific manifestations [17].

From the perspective of smoke management, it is fundamental to evaluate the forming smoke layer depending on time as well as its behaviour (preservation). In corridors and atria, there can be a disruption to the required integrity of the smoke layer for various reasons, as well as its layering, which may result in a significant part of the area of space filling with smoke. Preserving the integrity of the smoke layer is a significant factor influencing the safe evacuation of people. The spread of a fire in areas of space with a specific layout and geometry has a significantly different characteristic compared to regular areas of space [18–20].

The location of the fire source is fundamental from the perspective of the spread of smoke in a burning area of space [21]. The number of fire sources is also significant. Experimental work carried out shows significantly worse conditions for the formation of a smoke layer in fires with several sources than fires with just one source with the same value of released heat flux [22–24].

Another factor significantly influencing the movement of smoke and formation of an accumulated smoke layer in a burning area of space is the use of fixed fire extinguishing systems. Fixed water fire suppression systems have a fundamental significance from the perspective of smoke management. The mutual action of fire-extinguishing equipment and equipment for exhausting smoke and heat results in a change in the smoke's temperature, concentration of toxic substances, and level of the smoke layer. The layering of smoke in the area of space and disruption of the accumulated smoke layer is supported by the cooling of smoke [25–27].

Ensuring the safe evacuation of people in relation to the formation of a smoke layer in the area of space can be dealt with experimentally or through calculations. The calculation methods can be broken down into the simple calculations or simulations using fire models. Increasing use is being made of simulations using fire models, where single-zone models, two-zone models, and models based on computational fluid dynamics (CFD) are applied [28]. The choice of the type of model is closely associated to, primarily, the goal of the solution, scope and quality of the input data, scope and quality of the required output data, visualisation quality requirements, properties of the model, and its potential to resolve the designated goals [29–32].

Simple calculations for determining the smoke layer interface descent in the area of space are also currently widely used. Calculations have been derived by various authors based on theoretical or experimental solutions. The diversity of the authors and different conditions under which the calculation techniques were created have resulted in deviations during the evaluation of the smoke layer interface descent in the area of space [33].

Another limitation placed on the use of simple calculation techniques is caused by the countries' national standards used to evaluate buildings in terms of fire safety. This primarily consists of the use of different input values when evaluating buildings and the safe evacuation of people in relation to the derived calculation techniques. In some cases, the calculation techniques for determining the smoke layer interface descent in the area of space have been "simplified in order to achieve a specific purpose". The benefit of this step is the simple use of calculation techniques; however, sometimes the simplification has no clear justification and, in certain situations, can lead to wholly distorted results. One typical example is the Czech Republic's current simple calculation techniques used for designating the smoke layer interface descent in the area of space [34,35].

The aim of the study was to assess the sustainability of the indoor environment of buildings in the case of fires in relation to the evaluation of the smoke layer interface. In this paper, the existing worldwide calculation techniques for designating the smoke layer interface descent in the area of space without its release into an external environment are compared to a newly derived calculation technique that would be useable during the evaluation of buildings from the perspective of fire safety under the conditions of the Czech Republic. The presented results are then generalized and recommendations for their use are proposed. The current manner of dealing with this issue in the Czech Republic is so misleading that it could lead to significant human loss during fires. By contrast, in some cases, it leads to an inadequate increase in the economic costs on buildings. The newly derived calculation technique, following the standards for building design from the perspective of fire safety in the Czech Republic, is a simple and effective technique that will significantly increase human safety during fires.

2. Materials and Methods

The dynamics of the fire and characteristics of smoke "behaviour" during its spread in the area of space have a fundamental influence for evaluating the smoke layer interface descent. To follow is a presentation of selected calculation techniques that can be considered, tried, and tested over the long-term and are, in this sense, also representative. The augmented technique for designating the smoke layer interface descent in the area of space was derived with linkage to calculation procedures for evaluating the fire safety of buildings in the Czech Republic. The deviations between the individual techniques will be evaluated.

2.1. Dynamics of Fire in Relation to the Matter in Question

The parameters accompanying the spread of a fire can be designated for a constant or growing fire [4,36]. The released heat flux can be described using the following equations:

Constant fire

$$Q = const. \tag{1}$$

Fire growing over time

$$Q = f(t) \tag{2}$$

As a rule, a fire is described in four phases, which are the initiation phase, the fire growth phase, the fully developed fire phase, and the burning out phase [3,4]. In terms of the evacuation of people, the most significant are the initial phase and fire growth phase. The initial phase is generally overlooked for practical applications. The fire growth phase is also called a "local fire", which means fire in a limited area where a limited number of flammable substances burn (fire load) [2,37,38].

For a designation of the released heat flux in the fire-growth phase, the authors used a t-quadratic fire, which can be described by the following equations [3,4,39]:

$$Q = 1000 \times \left(\frac{t}{t_g}\right)^2 \tag{3}$$

$$Q = \alpha \times t^2 \tag{4}$$

The dependency between the time needed to reach the reference rate t_g and fire growth rate α can be described using the following equation [37]:

$$\alpha = \frac{1000}{(t_g)^2} \tag{5}$$

Standard described qualities are used when describing the characteristic types of fire, which are slow, medium, fast, and ultra-fast fire growth [3,4]. The characteristic types of fires are described by the fire growth rate α and the time needed to reach the reference rate t_g.

2.2. Spread of Smoke in an Area without Discharge into an External Environment

One of the characteristic accompanying phenomena is the formation of a vertical plume of combustion products (fire plume). The fire plume is a representation of mass and energy transported from the fire into the enclosure. With the progressing fire growth, the temperature of smoky gases (combustion products) rises, resulting in increased buoyancy. When the temperature difference is sufficient, the fire plume reaches the ceiling of the enclosure and a ceiling jet (radial smoke spread) is formed.

Smoky gases spread radially under the ceiling in a relatively thin layer from the plume centreline until they reach the enclosure bounding constructions. Once the radially spreading thin smoke layer reaches the enclosure boundaries, the layer starts descending. This is known as smoke filling, when more hot smoky gases enter the layer through the plume, thereby increasing its volume and temperature. Due to the decrease in the smoke layer height, the distance between the fire source and the bottom of the layer is reduced, resulting in less ambient air entraining into the plume and a further increase in the smoke layer temperature [3,4]. The layer descends until it fills the enclosure completely or reaches an opening with sufficient discharge capacity. The process of smoke filling an enclosure is shown in Figure 1.

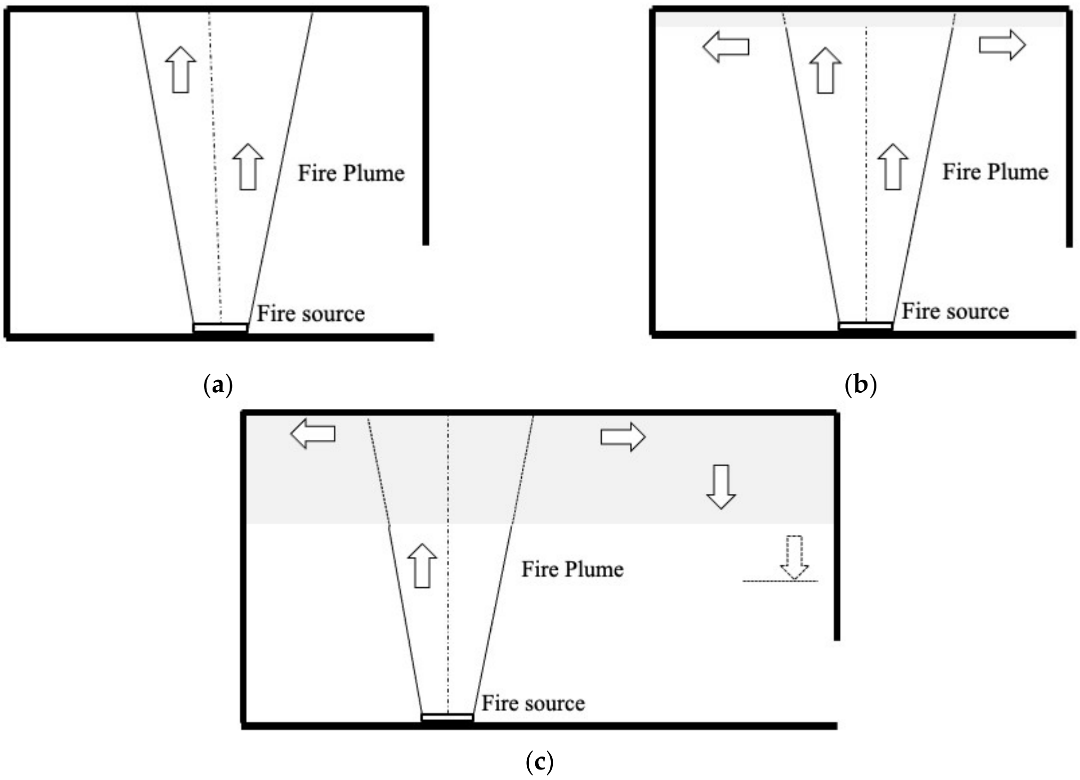

Figure 1. Schematic depiction of smoke filling an enclosure [29,36,40], where (**a**) is development of fire plume in enclosure, (**b**) is ceiling jet, and (**c**) is smoke layer descent in enclosure without smoke vents.

2.3. Selected Techniques for Evaluating the Smoke Layer Interface

The smoke layer interface in room z, where the fire is developing, can be described as a function of fire growth dynamism and the geometry of the area of space.

$$z = f\left(t_g/\alpha, A, H\right) \tag{6}$$

The smoke layer interface in the room where the fire is developing can be described for two basic model situations, i.e., the situation where smoke is not exhausted out of this room, or a situation where the smoke is exhausted out of this area of space (generally by equipment for the exhaust of smoke and heat). The article will also describe calculation techniques with a fire developing over time and the area of space where the smoke is not exhausted into an external environment.

One of the techniques for designating the smoke layer interface in the area of space is the procedure designated by ISO [41]:

$$z = \left(\frac{0.076}{\rho_s}\frac{(1-\chi)^{1/3}\times\alpha^{1/3}}{A}\frac{2}{n+3}t^{\left(1+\frac{n}{3}\right)} + \frac{1}{H^{2/3}}\right)^{-3/2} \tag{7}$$

The size of the radiation fraction of the fire χ is generally assumed to be 20 to 30% of the total value of the released heat flux Q. One can assume a smoke density of 1 kg.m^{-3} for the attainment of conservative results. The calculation technique was derived from the Zukoski equation [32,42], which can be used for the fire plume [33,41]. The usual rule for the application of Equation (7) is the limit criterion of the mean flame height L_f. The height of the smoke-free layer must be greater or equal to the mean flame height, i.e., $L_f \leq z$. The fire growth phase is described by a so-called t-quadratic fire with value n = 2 [41]. Under these assumptions, it is possible to correct Equation (7) to the following form [43]:

$$z = \left(0.0304 \times A^{-1} \times \alpha^{1/3} \times t^{5/3} + H^{-2/3}\right)^{-3/2} \quad (8)$$

The standard NFPA describes the technique for designating the smoke layer interface in large-volume areas of space [10,44]:

$$z = 0.91 \times \left(\frac{t}{t_g^{2/5} \times H^{4/5} \times (A/H^2)^{3/5}}\right)^{-1.45} \times H \quad (9)$$

The calculation technique can be used for the ratio of the area and height of space $\frac{A}{H^2} = 0.9 - 23$, while also respecting the ratio of the smoke-free height of space and clear height of space $\frac{z}{H} > 0.2$.

Another simple technique is the equation used by the zone model available safe egress time (ASET, or ASET-B) [45]. The fire model was created by the National Institute of Standards and Technology in the United States of America [46] and focuses on a designation of the smoke layer interface parameters that change over time. Although the ASET model is not currently being developed, it provides simple and verified procedures for the designation of the smoke layer interface [46]:

$$z = \left(1 + \frac{\frac{20 \times k_v \times t^{5/3}}{H^{-4/3}}}{t_g^{2/3} \times \frac{A}{H^2}}\right)^{-\frac{3}{2}} \times H \quad (10)$$

Although Equation (10) is part of the ASET fire model, it can also be used for simple calculations. The limits for its use are not given by the authors. Equations (7) and (9) are the most used simple techniques for designating the smoke layer interface descent in an enclosed area of space.

2.4. Existing Technique for Evaluating the Smoke Layer Interface in the Czech Republic

In the Czech Republic, the smoke layer interface is designated by technicians for buildings intended for production and storage and for non-production buildings. The starting point for designating the safe escape time is the time for the smoke level to reach 2.5 m above the floor in the area of space. The time to reach this level can be designated using the following equations [34,35]:

Non-production buildings

$$t_{(z)} = \frac{1.25 \times H^{1/2}}{a} \times 60 \quad (11)$$

Buildings intended for production and storage

$$t_{(z)} = 1.25 \times \left(\frac{H}{p_1}\right)^{1/2} \times 60 \quad (12)$$

The basic problem of Equations (11) and (12) is that, from the perspective of the geometry of space, they only take height into account. They do not consider its area and the description of fire dynamism is also performed differently than given in the preceding equations. There is no linkage here to the characteristics of the type of fire, to the fire growth rate α, and the time required to reach the reference rate t_g.

2.5. Relationship of Foreign Characteristics for Evaluation of fire Dynamism and Characteristics in the Czech Republic

The basic quantities for evaluating fire dynamism in the Czech Republic are primarily the fire loading p, which is used for non-production buildings, or average fire loading $\overline{p}$, which is used for buildings intended for production and storage. An additional value for non-production buildings is the coefficient a, which expresses the combustion rate from the perspective of the character of flammable materials. With linkage to standards in the Czech Republic, the released heat flux can be designated using the following equations [47]:

Non-production buildings

$$Q = \frac{p \times a^2 \times t^2}{2560} \tag{13}$$

Buildings intended for production and storage

$$Q = \frac{\overline{p} \times t^2}{2560} \tag{14}$$

The fire growth rate α can be determined using the following equations [47]:

Non-production buildings

$$\alpha = \frac{a^2 \times p}{2560} \tag{15}$$

Buildings intended for production and storage

$$\alpha = \frac{\overline{p}}{2560} \tag{16}$$

The time needed to reach the reference rate t_g can be designated using the following equations [47]:

Non-production buildings

$$t_g = \frac{1600}{a \times p^{1/2}} \tag{17}$$

Buildings intended for production and storage

$$t_g = \frac{1600}{\overline{p}^{\,1/2}} \tag{18}$$

The mathematical expression of the mutual relations between the time needed to reach the reference rate t_g, fire growth rate α, and aforementioned basic quantities for evaluating the dynamism of fire in the Czech Republic constituted the basis for drafting a new technique for evaluating the level of the smoke layer interface without its release into an external environment.

2.6. New Technique for Evaluating the Smoke Layer Interface in the Czech Republic

The new technique for designating the smoke layer interface in the area of space was derived by the substitution of Equations (15) and (16) in Equation (7). The result is the following equations, which will be designated as the future Czech CSN standard:

Non-production buildings

$$z = \left(0.002 \times \left(\frac{a^2 \times p \times t^5}{A^3} \right)^{\frac{1}{3}} + H^{-\frac{2}{3}} \right)^{-\frac{3}{2}} \tag{19}$$

Buildings intended for production and storage

$$z = \left(0.002 \times \left(\frac{\overline{p} \times t^5}{A^3} \right)^{\frac{1}{3}} + H^{-\frac{2}{3}} \right)^{-\frac{3}{2}} \tag{20}$$

The presented equations for designating the interface descent in the area of space without its release into an external environment will be included in the following evaluation.

2.7. Evaluation of Designated Deviations

Deviations between the values designated by the individual techniques were evaluated using the percent bias (*PBIAS*) method and root mean square error (*RMSE*) method.

The *PBIAS* method evaluates the deviations between the etalon (comparative) value and evaluated value [48]:

$$PBIAS = \frac{MBE}{\overline{E}} = \frac{\frac{1}{m}\sum_{j=1}^{m}(P_j - E_j)}{\frac{1}{m}\sum_{j=1}^{m}E_j} = \frac{\sum_{j=1}^{m}(P_j - E_j)}{\sum_{j=1}^{m}E_j} \tag{21}$$

The method uses mean bias error (*MBE*), which is the difference between the evaluated values and the etalon values [48]:

$$MBE = \frac{1}{m}\sum_{j=1}^{m}(P_j - E_j) \tag{22}$$

The *MBE* value is a statistical indicator. A positive value indicates an evaluated value as overestimating and a negative one as underestimating.

The *RMSE* value indicates the average size of errors between the etalon and evaluated value [48]:

$$RMSE = \sqrt{\frac{1}{m}\sum_{j=1}^{m}(P_j - E_j)^2} \tag{23}$$

The results are always greater than zero, which eliminates situations with positive and negative values of deviations. In the case of the *PBIAS* and *RMSE* methods, it applies that a decreasing value indicates a smaller deviation between the etalon and evaluated value. Equation (7) was selected as the etalon. This is because the equation has long been considered relevant for designating the smoke level in the area of space and has a wide scope of application. Equation (9) was derived experimentally, particularly for large areas of space. At the same time, it has relatively significant limitations in terms of use. Equation (10) found its greatest application in the past in the developed zone models of a fire. It is no longer developed. These facts were the reason that technique (7) has been chosen as the standard (etalon). This choice of standard (etalon) is also supported by the fact that the CSN technique was derived from the ISO technique. All outputs were processed using Microsoft Excel software.

3. Results

The equations presented in the preceding part of the article were compared under preselected conditions. The ISO (7), NFPA (9), ASET (10) and CSN (19) equations were compared.

3.1. Input Values

The input values for comparing the individual calculation techniques are given in Table 1.

Table 1. Input values for comparing the presented equations.

Designation of Input Values	Symbol	Value	Physical Unit
fire loading	p	6, 24, 96, 383	$kg.m^{-2}$
combustion rate coefficient	a	1.09	-
maximum heat release rate	RHR_f	300	$kW.m^{-2}$
intake constant	k_v	0.064	$m^{4/3}.s^{-1}.kW^{-1/3}$
height of space	H	30	m
fire growth time	t	900	s
time needed to reach reference rate	t_g	600, 300, 150 and 75	s
time interval of calculations		30	s
smoke density	ρ_s	1	$kg.m^{-3}$
radiation fraction of heat flux	χ	0.2	-
fire growth rate	α	0.003, 0.012, 0.047, 0.19	$kW.s^{-2}$

3.2. Output Values

The individual calculation techniques were compared considering four characteristic types of fire, i.e., slow, medium, fast and ultra-fast fire growth. For each type of fire, four outputs have been prepared, characterized by the ratio of the area of space A to the square of the clear height of the space H^2 (A/H^2). The specified dependency was selected on the basis of limitations of the NFPA calculation technique, and the floor area of the evaluated area of space was chosen so that the ratio A/H^2 is 1 (900 m^2), 5 (4500 m^2), 10 (9000 m^2), and 20 (18,000 m^2). The output values are presented as the ratio of the smoke free layer in the area of space z to the clear height of space H (z/H).

The comparison of the calculation techniques for the characteristic types of fire and for the ratio of the geometry of space A/H^2 = 1 is described in Figure 2, the ratio of the geometry of space A/H^2 = 5 is described in Figure 3, the ratio of the geometry of space A/H^2 = 10 is described in Figure 4, the ratio of the geometry of space A/H^2 = 20 is described in Figure 5.

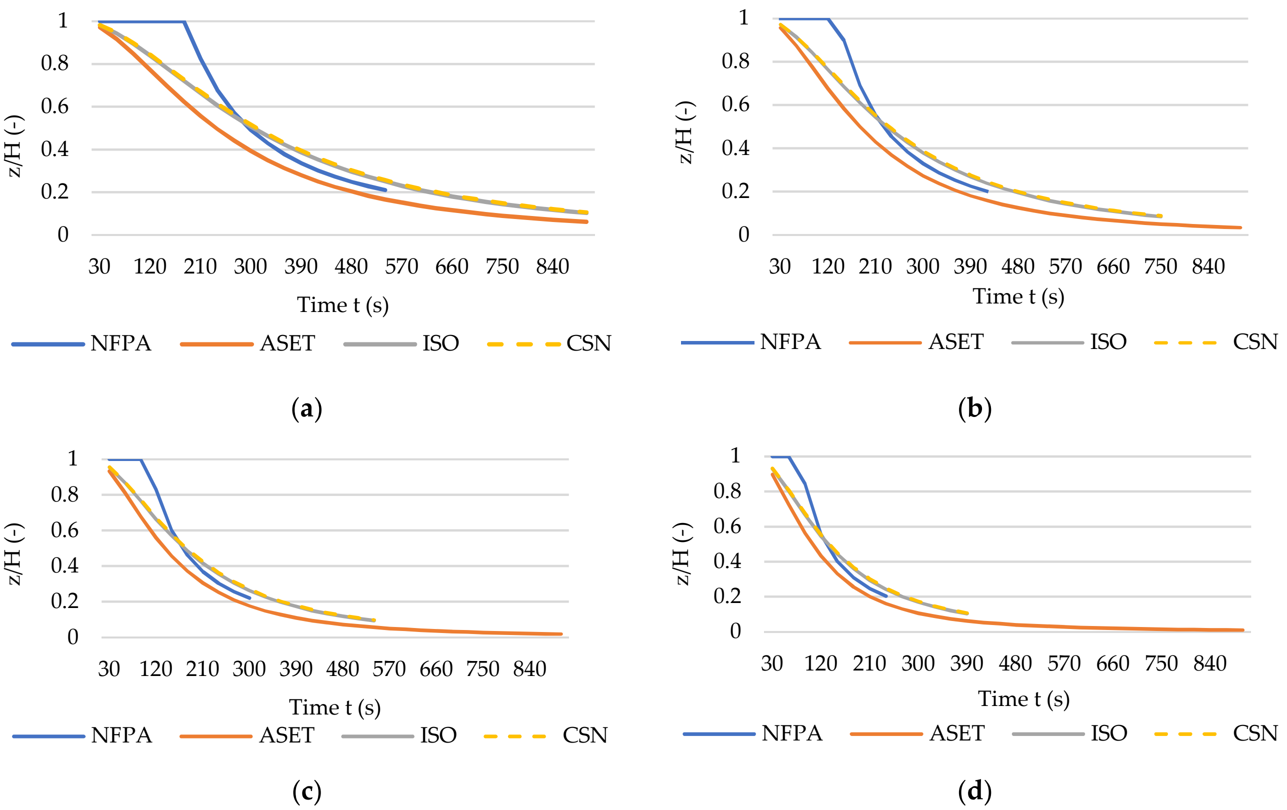

Figure 2. Comparison of the simple calculation techniques for the ratio of the geometry of space A/H^2 = 1, where (**a**) is slow fire growth, (**b**) is medium fire growth, (**c**) is fast fire growth, and (**d**) is ultra-fast fire growth.

The outputs described in Figures 2–5 will be briefly commented on in the following paragraphs and then discussed in Section 4. The results of the comparison of the individual calculation techniques show that the more dynamic the growth of a fire becomes, the faster the smoke layer interface descends.

As the area of space increases, the speed at which the smoke layer interface decreases. The results indicate a significant limitation for the use of the NFPA calculation technique. In some cases, the technique could not be applied. The limitation is caused by the limits of the calculation technique. The results of the obtained NFPA equation also indicate that, for a certain time, the smoke layer interface in the area of space does not descend. It is evident that this assumption is unrealistically optimistic in certain cases. The ISO and CSN calculation techniques also have their limits. However, this limit was not reached in the comparative calculations. The mean flame height L_f was always lower than the level of the smoke-free layer z. The results obtained through the ASET and ISO techniques agree with each other quite well. The deviations increase with increasing fire growth time. The results obtained using the ISO and CSN techniques are virtually identical.

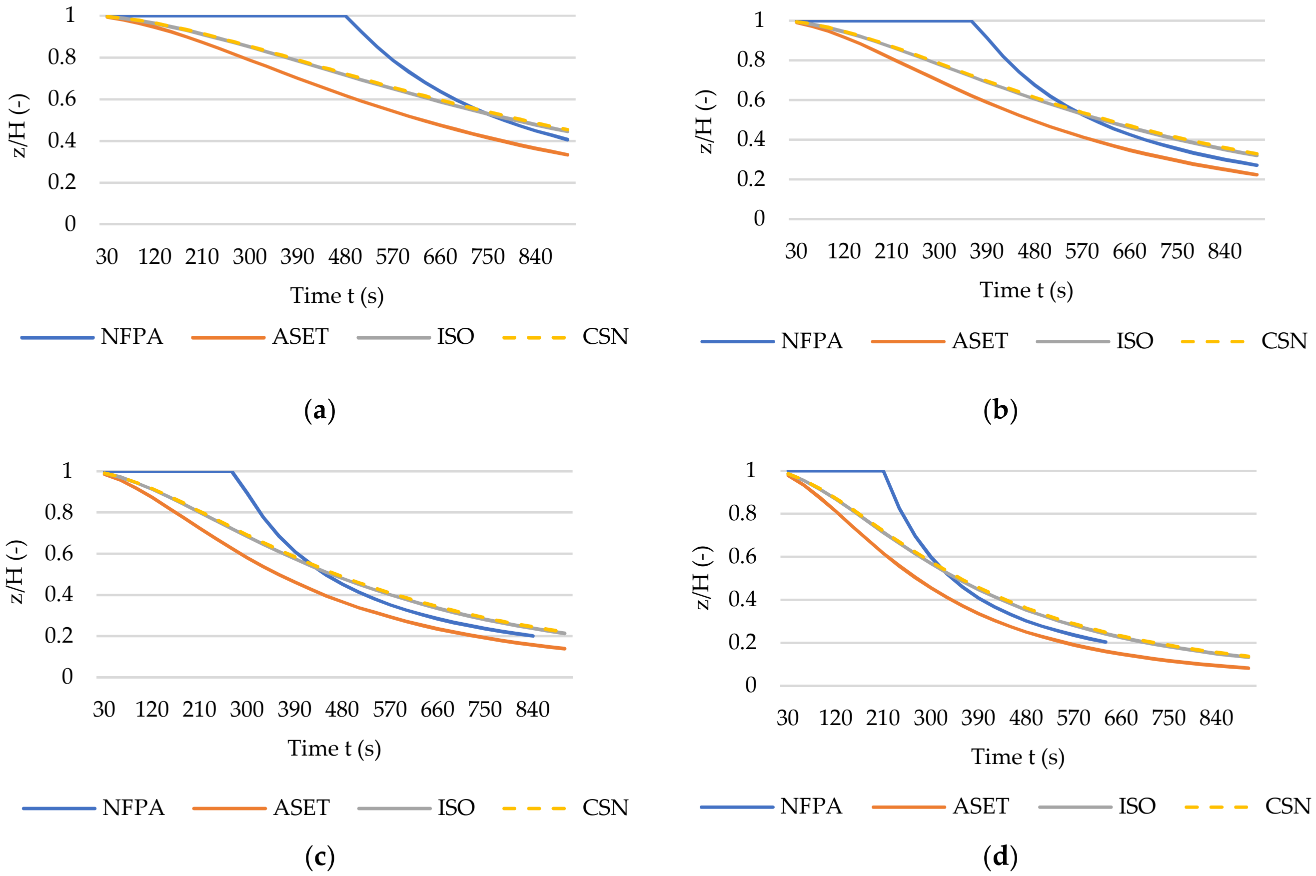

Figure 3. Comparison of the simple calculation techniques and the CFAST model for the ratio of the geometry of space $A/H^2 = 5$, where (**a**) is slow fire growth, (**b**) is medium fire growth, (**c**) is fast fire growth, and (**d**) is ultra-fast fire growth.

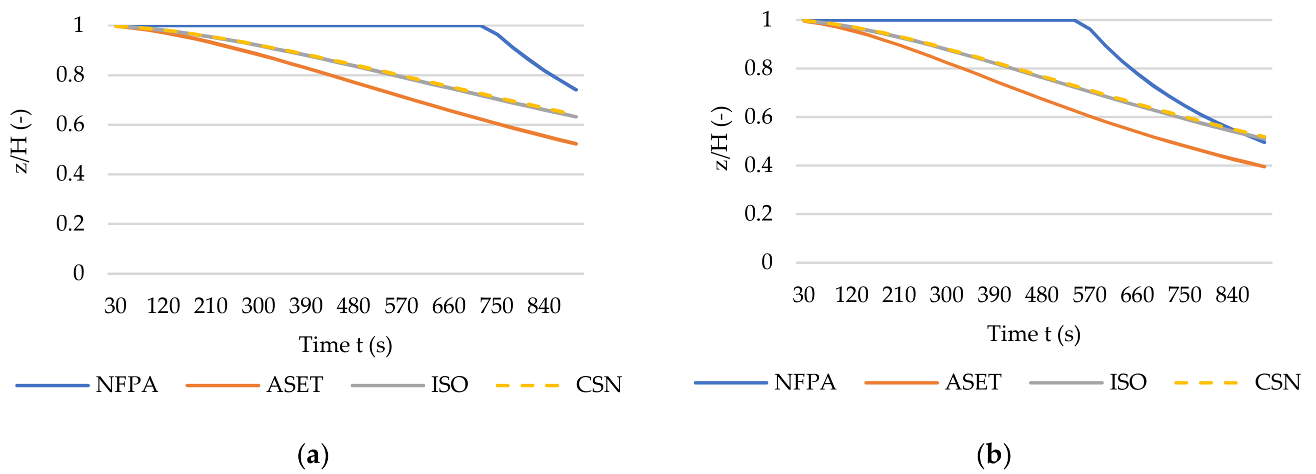

Figure 4. *Cont.*

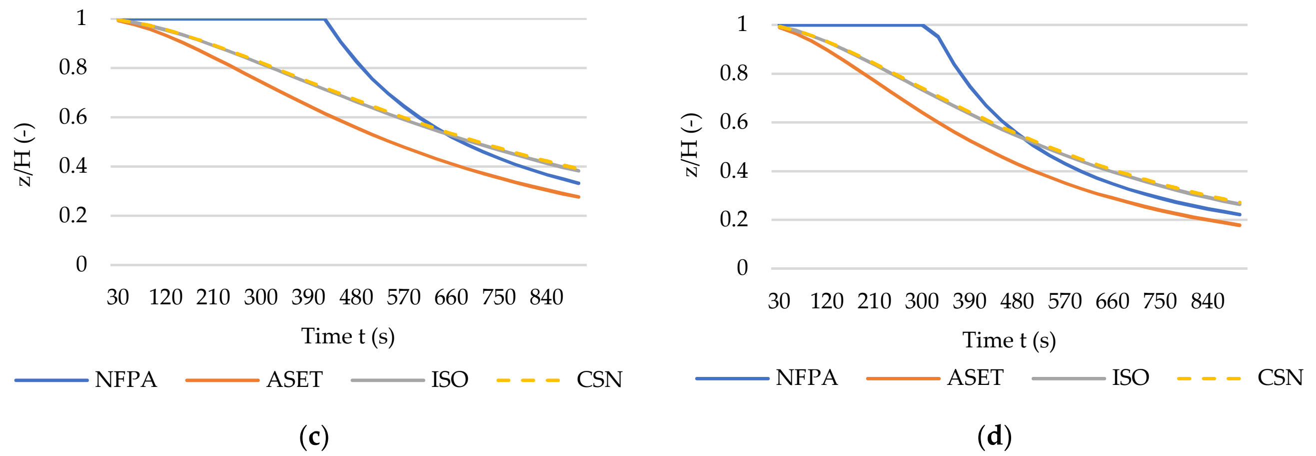

Figure 4. Comparison of the simple calculation techniques and the CFAST model for the ratio of the geometry of space A/H^2 = 10, where (**a**) is slow fire growth, (**b**) is medium fire growth, (**c**) is fast fire growth, and (**d**) is ultra-fast fire growth.

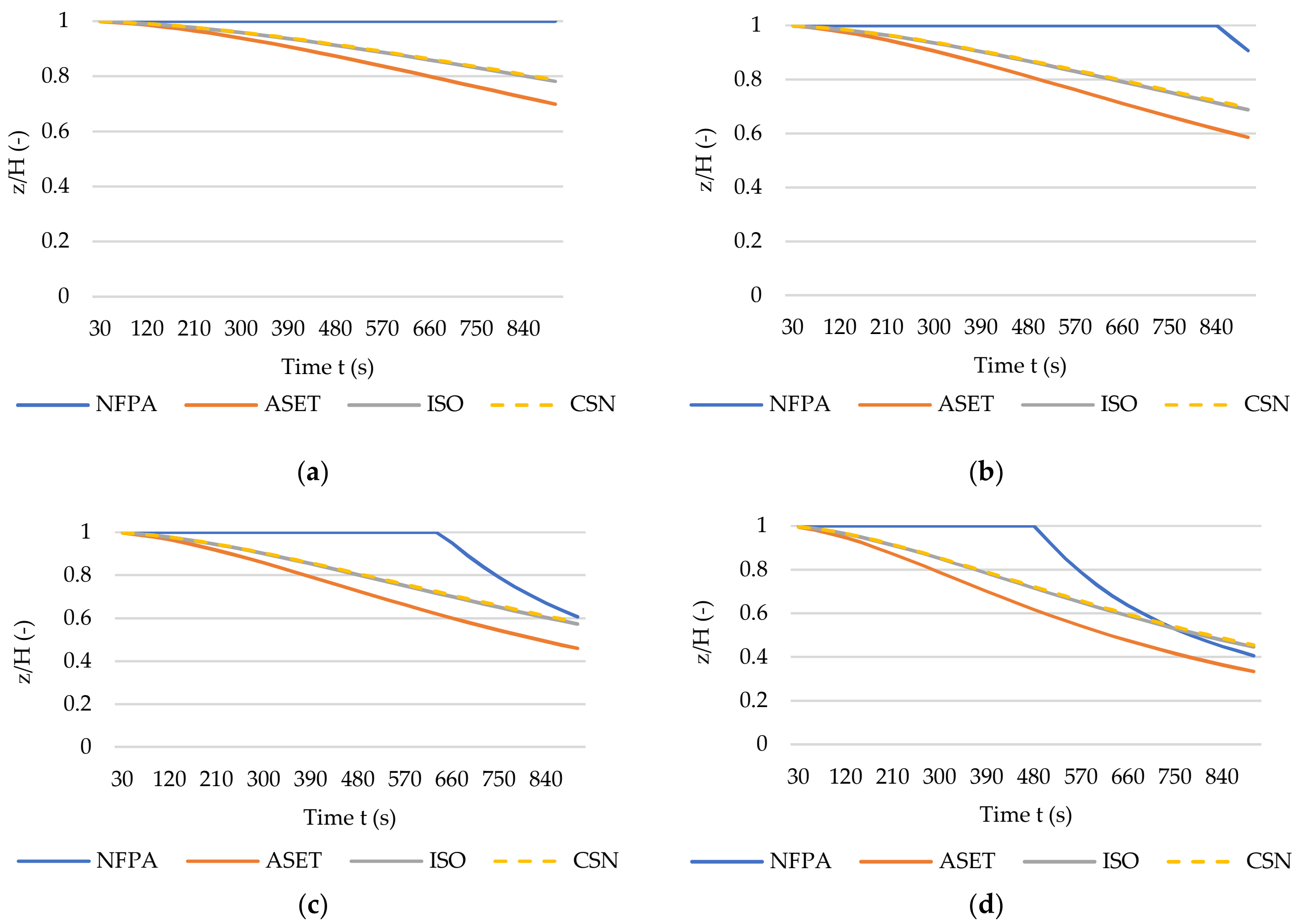

Figure 5. Comparison of the simple calculation techniques for the ratio of the geometry of space A/H^2 = 20, where (**a**) is slow fire growth, (**b**) is medium fire growth, (**c**) is fast fire growth, and (**d**) is ultra-fast fire growth.

When using the existing calculation technique according to Equation (11), the time it takes for the smoke layer interface level to reach 2.5 m above the floor is 377 s (smoke layer interface level 2.5 above the floor corresponds to the ratio z/H = 0.083). The presented NFPA, ASET, ISO, and CSN calculation techniques achieve, in most cases, more positive results (higher levels of the smoke layer interface) than the existing calculation technique according to Equation (11). The only exceptions are the results for the smallest evaluated areas, i.e., at the ratio of the geometry of space $A/H^2 = 1$ and for ultra-fast fire growth, when Equation (11) achieves approximately identical results. Equation (11) is therefore more conservative than other calculation techniques. Due to the fact that Equation (11) does not take into account the effect of the floor area, it can be concluded that Equation (11) has been derived for a smaller floor area than the floor areas being compared. The constraints of Equation (11) are not currently presented anywhere. The fact that the results of Equation (11) can be misleading for the objects with a larger area is evidenced by the relatively small deviations between the values provided by all other equations, including the newly derived CSN calculation technique.

3.3. Evaluation of Designated Deviations

The deviations between the etalon Equation (7) and other equations designated by the PBIAS method are shown in Figure 6.

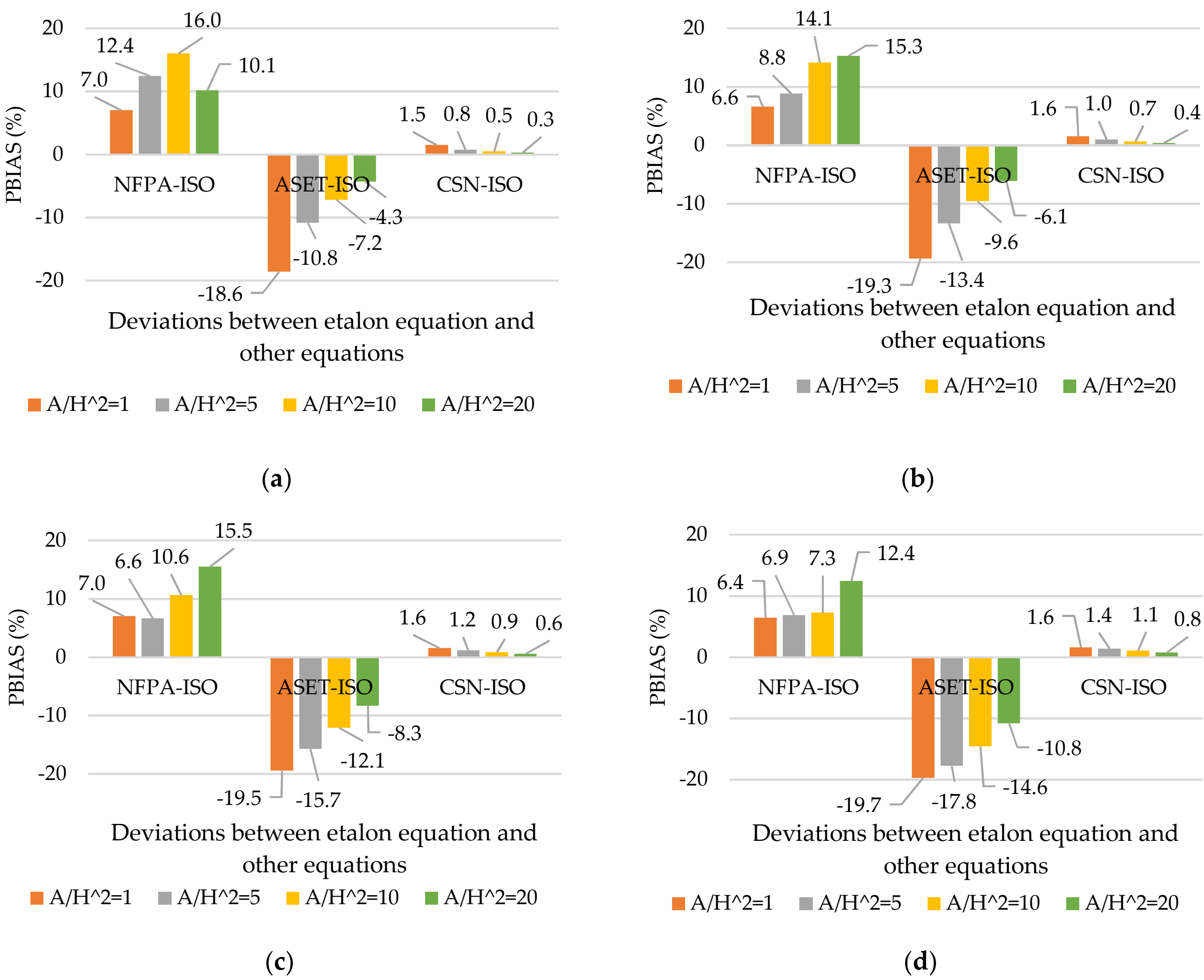

Figure 6. Deviations between the etalon equation and other equations designated by the PBIAS, where there is (**a**) slow fire growth, (**b**) medium fire growth, (**c**) fast fire growth, and (**d**) ultra-fast fire growth.

The evaluated values in Figure 6 obtain positive and negative values. Positive values indicate that, in relation to the etalon Equation (7), the compared equation obtains greater heights of the smoke-free height of space *z* (NFPA-ISO, CSN-ISO), whereas negative values indicate that, in relation to the etalon Equation (7), the compared equation obtains lower heights of the smoke-free height of space z (ASET-ISO). It is also evident that the deviations between the etalon Equation (7) and equation according to CSN are small.

The deviations between the etalon equation and other equations designated by the RMSE method are shown in Figure 7.

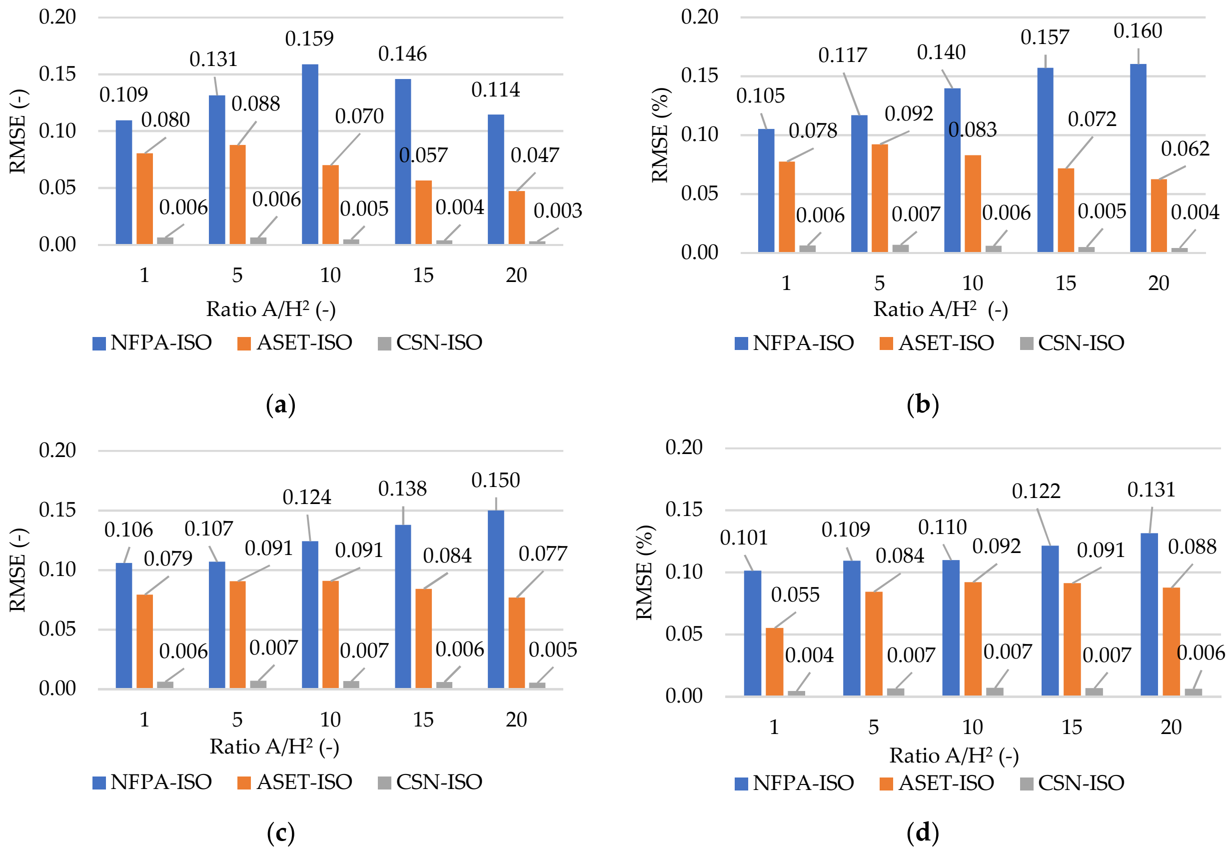

Figure 7. Deviations between the etalon equation and other equations designated by the RMSE, where there is (**a**) slow fire growth, (**b**) medium fire growth, (**c**) fast fire growth, and (**d**) ultra-fast fire growth.

The evaluated values in Figure 7 show that the deviations between the etalon Equation (7) and NFPA (NFPA-ISO) equation are the greatest for slow, medium, and fast fire growth. As a rule, the deviations between the etalon Equation (7) and ASET (ASET-ISO) equation reach the highest values for fast and ultra-fast fire growth. As a rule, deviations between the etalon Equation (7) and CSN (CSN-ISO) equation reach values an order lower. The similarity to the ISO equation is very favourable.

4. Discussion

The sustainability of the indoor environment of buildings is also related to the occurrence of emergency situations. Substantial changes occur inside buildings during the occurrence and development of a fire. If the smoke from the fire is not removed from the building, the building is gradually filled with smoke, which significantly affects the safety of people. In these cases, it is desirable to evaluate the decreasing level of the smoke layer. This article presented and compared some techniques for designating the descent in the smoke layer interface in the area of space without discharge into an external environment. Simple calculation techniques that are currently applied in practice have been selected. The calculations consider the geometry of space and dynamism of the fire.

The presented techniques have been derived by various authors and under different conditions. They are experimentally (NFPA) and analytically (ISO, ASET) derived techniques. As a rule, the calculation techniques have limits that specify the scope of their possible use. Limits for using the technique were presented in Section 2. The newly derived CSN calculation technique was derived from the ISO calculation technique, which is based on the Zukoski equation for determining the mass amount of smoke. The Zukoski equation holds only if the mean flame height L_f is less than or equal to the smoke interface above the base of fire source z. Therefore, this limit also applies to the CSN calculation technique.

The designated limits have been respected during the comparison of the individual calculation techniques. As is evident from the figures shown in Section 3 of the article, in some cases, there are significant limitations for the technique according to NFPA. The specified technique can be used, but only to a limited extent. This is due to the inherent limits of the techniques, presented for Equation (9), which significantly restrict its use.

The calculation technique that is currently used in the Czech Republic for determining the smoke layer interface descent in an enclosed area of space without discharge into an external environment is unsuitable. This is because the calculation technique does not consider the floor area of space.

The use of the presented techniques (ISO, NFPA, ASET) in the Czech Republic is problematic. The reason for this is that the required input values, primarily the values concerning the dynamism of a fire, are not common in the Czech Republic. The description of the fire dynamic is primarily based on the "fire loading" or "average fire loading", not on the released heat flux or individual values that can be used to determine the heat flux (fire growth rate α and time needed to reach reference rate t_g).

In the preceding articles [49], there has been a derivation of the fire growth rate α and time needed to reach reference rate t_g from fire loading for non-production buildings (15) and average fire loading for buildings intended for production and storage (16). Thus, the Czech national standard for evaluating fire dynamism can be linked to the characteristic types of fires, and also to the NFPA, ASET, and ISO techniques. By substitution of the specified equations in the ISO calculation, the equations for designating the smoke layer interface descent were designated in the Czech Republic. The ISO calculation was selected as the "representative" technique, primarily due to its long-term, extensive use.

All the presented techniques, i.e., ISO, NFPA, ASET, and CSN, were compared to each other for the four characteristic types of fire suitable for general comparisons. In some cases, the thermal output of the fire reaches values exceeding 100 MW (ultra-fast fire growth). This value is rather extreme in buildings. The comparison of the calculation techniques were intentionally performed so as not to limit the thermal output of the fire; thus, it was possible to verify their use in a wide range. In real situations, it would be necessary to assess the maximum value of the released heat flux that can be achieved. For comparison, the ratio of the smoke-free layer and clear height of space z/H were used, which makes it possible to display the results clearly. The results were applied to the conditions of the area and height of space expressed by the ratio A/H^2. The ratio of the area to the height of space in the given form is usual in the case of the application of one of the calculation techniques (such as the limits of the NFPA technique).

The newly derived CSN technique was presented using Equation (19), which is intended for non-production buildings. Equations (19) and (20) were derived using the same procedure, i.e., by substituting Equations (15) and (16) in Equation (7). The results obtained using Equation (19) for non-production buildings can also be considered relevant in relation to Equation (20) for production buildings. The results gained using the individual methods were compared to the percent bias (PBIAS) and root mean square error (RMSE) methods. These methods are appropriate when comparing a set of etalon values and evaluated values. The ISO equation was the etalon value.

The largest deviation determined by the PBIAS method was determined when comparing ASET-ISO techniques for ultra-fast fire growth, which amounted to 19.7%. The ASET calculation technique provides more negative results than the ISO calculation technique (the descent of the smoke layer in the area of space occurs faster). In all cases, the NFPA calculation technique provides more positive results than the ISO calculation technique (the descent of the smoke layer in the area of space occurs more slowly). The largest deviation between NFPA-ISO calculation techniques was 16%. The CSN-ISO calculation techniques achieve a very favourable agreement, with the largest deviation between CSN-ISO calculation techniques being 1.6%.

The largest deviations determined by the RMSE method were found in all cases when comparing NFPA-ISO calculation techniques. The largest deviation was achieved with a medium fire development of 0.160. The ASET-ISO calculation techniques achieved the largest deviation of 0.092 for medium fire growth and ultra-fast fire growth. The deviations between the CSN-ISO calculation techniques were lower by an order of magnitude and reached the largest deviation of 0.007. The RMSE method can be considered more relevant in terms of evaluating deviations in this case. This is due to the fact that, in some cases, especially when using the NFPA calculation technique, there are partly positive and partly negative deviations. When using the PBIAS method, there is a certain bias in the evaluation in these cases. On the contrary, the RMSE technique eliminates this shortcoming.

It can be assumed that the cause of the differences between the compared calculation techniques is the diversity of their authors, different forms of origin (experimentally or analytically) and, probably, not completely identical conditions of their origin. The more detailed evaluation of the causes of deviations is problematic due to the lack of published data.

In view of the very good agreement with the ISO equation, the CSN equation can be preliminarily recommended for use.

5. Conclusions

One of the important requirements for buildings in terms of the sustainability of the indoor environment is to ensure an acceptable quality of the environment in the event of emergencies, including fires. The accompanying phenomena of fires are of fundamental importance for the quality of the environment. It is mainly a matter of the area of space filling with smoke if it is not discharged into an external environment. Smoke has a significant effect on the safe evacuation of people. An evaluation of the evacuation of people is generally based on a comparison of the required safe escape, the RSET time, to the available safe escape, the ASET time. The smoke layer interface descent can also be evaluated using simplified calculations.

The aim of this study was to assess the usability of the newly derived CSN calculation technique for the assessment of the decrease in the level of smoke layer interface in the closed area of space without its release into an external environment, in connection to the standards for the assessment of the buildings in terms of fire safety in the Czech Republic. The current calculation technique used in the Czech Republic for the assessment of the decrease in the level of the smoke layer interface is unsatisfactory and, in many cases, can provide misleading results. The reason for this is the fact that it does not consider the area of space where the smoke layer interface decreases.

The newly derived CSN calculation technique was compared to other selected simple calculation techniques. The comparison was made for the so-called characteristic types of fire, which are slow, medium, fast, and ultra-fast fire growth as well as other selected conditions. The deviations obtained by the simple techniques and by the fire model have been evaluated by the PBIAS and RMSE methods, whereas the standard equation has been the ISO equation. The statistical comparisons show the largest deviations between the NFPA and the ISO computation and smaller differences between ASET and ISO computation. The deviations between the CSN and the ISO calculation techniques are negligible.

The CSN technique is a significant progress for the assessment of the safety of people during their evacuation in connection to the standards for the assessment of buildings in terms of fire safety in the Czech Republic. In the following period, the CSN calculation techniques will be verified using the fire models and then a real, large-scale experiment will be carried out. In the future, it is expected that the CSN technique will replace the current unsatisfactory technique in the design standards. According to the fact that the CSN technique has been derived from the ISO calculation technique, its verification can also contribute to the development of this internationally applied calculation technique. In the final consequence, the further verification of the newly created technique can also contribute to the global knowledge of the solution to this issue.

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Nomenclature

A	floor area of enclosure (m^2)
$ASET$	available Safe Egress Time (min)
E	etalon value (-)
$\overline{E}$	average of etalon values (-)
H	height of enclosure (m)
L_f	mean flame height (m)
MBE	mean bias error (-)
P	value of assessed model (-)
$PBIAS$	percent bias (%)
RHR_f	maximum heat release ($kW.m^{-2}$)
$RMSE$	root mean square error (-)
$RSET$	required Safe Egress Time (min)
Q	heat flux (kW)
a	coefficient expressing combustion rate from aspect of character of flammable materials (-)
k_v	air intake constant (0.064 $m^{4/3}.s^{-1}.kW^{-1/3}$)
m	number of samples (-)
n	n-th power (-), n = 2 for quadratic fire
p	fire loading ($kg.m^{-2}$)
$\overline{p}$	average fire loading ($kg.m^{-2}$)
p_1	probability of the occurrence and the spread of the fire (-)
t	fire growth time (s)
t_g	time needed to reach reference rate (the reference flow is understood to be the value of thermal 1055 kW) (s)
$t_{(z)}$	time until attainment of smoke layer 2.5 m above floor (s)
z	interface height above the base of fire source (m)
α	fire growth rate ($kW.s^{-2}$)
χ	fraction of heat released that is emitted as thermal radiation (-)
ρ_s	smoke density ($kg.m^{-3}$)

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