Safety at Chimney-Roof Penetration: A Numerical Investigation

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Abstract

Chimneys convey exhaust gas produced in heat generators to the external ambient. To do this, they cross building elements such as floors and roofs, which can be made of flammable materials such as wood, wood fiber, cellulose, etc. This represents a dangerous condition that can lead to the overheating of the structure and, consequently, to possible fires. In recent years, numerous roof fires have occurred in Europe due to the presence of a chimney, and some of these have also involved certified chimneys. The aim of the certification procedure is the determination of the distance between chimney and flammable structures to avoid fires. This paper describes an investigation performed to understand the causes of the high number of fires and to propose solutions to the roof fires problem. The study was carried out numerically and experimentally, and consisted of three steps. Firstly, the chimney certification procedure was investigated to highlight possible weaknesses. Then, by means of a 2D and a 3D numerical models, the variables affecting heat transfer at chimney–roof penetration were identified. Finally, solutions and prescriptions to prevent roof fires are proposed. The solutions consist of a set of tables for checking chimney installations, and a universal device to be installed between chimney and roof to prevent the overheating of the latter, also in very critical conditions represented by soot fires, and installations in very thick and insulating roofs.

1. Introduction

In recent years, numerous roof fires have occurred in Europe due to the presence of a chimney, and some of these have also involved certified chimneys (Buffo and Dadone, 2007; Dadone, 2009; International Partnership for the Investigation of Fires Explosion, 2015; Ministry of the Environment of Finland, 2011). Chimney certification is regulated by the EN 1859 standard (CEN, 2009), which prescribes two tests to determine the safety distance between chimney and flammable structures: the Heat Stress Test (HST) reproduces the normal use condition of chimneys, while the Thermal Shock Test (TST) reproduces the soot fire condition. In both tests, the chimney must be installed in a test structure made of two walls at a right angle, with two roofs positioned at different heights. The roofs are made of an insulating layer between two wooden layers. The thickness (S) and the thermal resistance (R) are 132 mm and 3.04 m^{2}K/W for the upper roof, and 232 mm and 5.90 m^{2}K/W for the lower roof. Despite the tests are aimed to test the worst conditions, the increasing attention to energy efficiency requires thicker and more insulating roofs (Manfren et al., 2019). The tests consist of feeding the chimney with gas at a predetermined temperature (T_{ch}) and then measuring the temperature at chimney-roof penetration. The maximum temperatures (T_{max}) measured on the test structure must be compared with two limit temperatures (85 °C for HST, and 100 °C for TST). If the limit temperatures are not exceeded, the chimney is certified and a label is applied to it. An example of such a label is EN1856-1-T600-N1-D-V2-L50050-G20. From the thermal point of view, the main information reported in the label is T600, which is the class temperature of the chimney (the maximum temperature of the exhaust gas), and G20, which represents the minimum distance (in millimetres) allowable between the chimney and flammable materials. Even though in real installations the clearance between chimney and roof must be sealed to avoid the entering of atmospheric agents, no information is report-

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ed on the label on how the chimney should be sealed. This paper describes the steps that have led to an understanding of the heat transfer at chimney–roof penetration and to solutions for preventing roof fires. The data reported here were presented in several papers (Leppänen et al., 2015; Leppänen et al., 2017a; Neri et al., 2015a and 2015b; Neri et al., 2016; Neri and Pilotelli, 2018 and 2019), and the aim of this article is to describe the entire research body.

In addition to the above-mentioned research, a number of additional studies have been carried out. Kererekes (2018) outlined a test of a newly developed composite material for chimneys, while Leppänen and Malaska (2019) investigated the smouldering combustion of mineral wool. The effect of the design flue gas temperature has been investigated (Leppänen et al., 2015; Leppänen et al., 2017b), and the thermal performance of an innovative three-layer chimney was investigated by Drozdzol (2020).

Studies in the literature have also investigated aspects related to heat generators and emissions. For example, Polonini et al. (2018, 2019a, 2019b and 2019c) showed that the exhaust gas temperature for a pellet stove between 7 kW and 11 kW is normally around 190 °C and 230 °C. In non-optimal burning conditions, the formation of soot can be up to 5 times more than in optimal burning conditions.

2. Method and Results

The investigation that led to the comprehension of heat transfer at chimney roof–penetration consisted of several steps. Firstly, the chimney certification procedure was analysed to highlight possible weaknesses. Since heat transfer at chimney–roof penetration depends on many variables, a numerical approach was necessary. For this, 2D and 3D numerical models were defined to estimate the steady temperature of a roof near a chimney. The numerical approach made it possible to analyse a wider range of configurations. Subsequently, the numerical results were analysed statistically to assess the influence of each variable on the maximum roof temperature. Regression models to estimate the maximum roof temperature were identified by means of the DoE (Design of the Experiments) technique. Since the regression models use several coefficients and variables, they were translated into tables, with which it is possible to check whether an installation is safe. Finally, a device for reducing the temperature at the chimney-roof penetration was defined.

2.1 Analysis of the EN 1859 Standard

Firstly, the chimneys certification procedure described in the EN 1859 (CEN, 2009) standard was analysed to understand whether it represents the most critical chimney operating conditions. The main aspects analysed were the position of the chimney in the roof, the exhaust gas temperature measurement point, the clearance sealing mode, the characteristics of the roof, and the initial test conditions. Even though in real installations chimneys are installed completely surrounded by a roof, in the TST and the HST tests, the chimney to be certified is installed in a test structure made of two walls at a right angle, with two roofs positioned at different heights. Since the limited horizontal thickness of the walls represents a thermal bridge, the roof temperature measured in the certification procedure may be lower than that measured in real installations. According to the standard (EN1859:2009), the exhaust gas temperature (Tch) must be measured in the vicinity of the heat generator. Fig. 1 shows the exhaust gas temperature measured near the exhaust gas generator as prescribed by the standard (EN1859:2009), and at the chimney–roof penetration. It can be seen that in the vicinity of the chimney–roof penetration, the exhaust gas temperature (Tch) can be much lower because of heat loses along the chimney flue. The difference in temperature can be up to 150 °C.

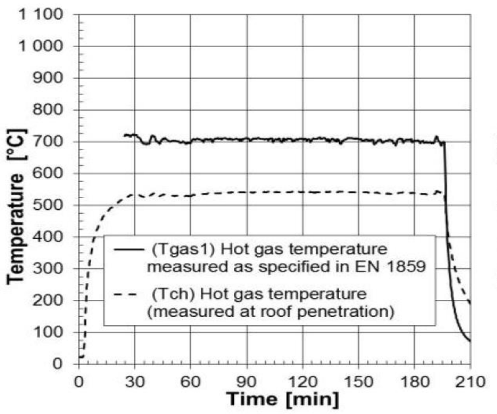

Fig. 1 – Comparison between exhaust gas temperature measured in the vicinity of the heat generator, and that measured in the vicinity of the chimney–roof penetration in the HST

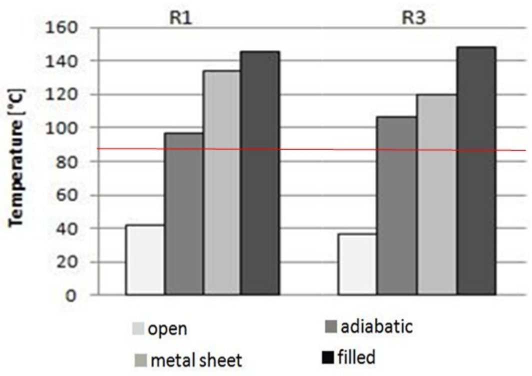

Fig. 2 – Maximum roof temperature obtained by varying the clearance sealing mode. The red line represents the limit temperature prescribed by the EN 1859 (EN1859:2009) standard for the HST. Results were obtained experimentally

In the TST and the HST, depending on the prescriptions provided by the chimney producer, the chimney can be installed in contact with or spaced from flammable materials. Consequently, the clearance between chimney and roof can be sealed or left open. If the clearance is left open, air can circulate and cool the roof; otherwise, the cooling process is limited. Despite these two possible conditions, no information is specified on the chimney label about the clearance sealing mode in the certification tests. To investigate the importance of this information, in an experimental campaign the clearance was sealed in different ways in order to reproduce possible real conditions. More precisely, the clearance was either left open, sealed with metal sheets, sealed with insulating panels, or filled with insulating materials. Leaving the clearance open allows complete air circulation. Sealing the clearance blocks the air between chimney and roof, but metal sheets allow heat transfer between the air trapped in the clearance and ambient, while the insulating panels reduce it. The tests were performed for two roofs, labelled R1 and R3. Roof R1 is the thickest roof prescribed by the standard (EN1859:2009), and roof R3 is 450 mm thick and its thermal resistance is 8.34 m²K/W. Fig. 2 shows the roof temperature measured experimentally in the different conditions. It can be seen that if the clearance is left open, the roof temperature is much lower than 85 °C, but if the clearance is closed or filled the roof temperature can be 110 °C higher.

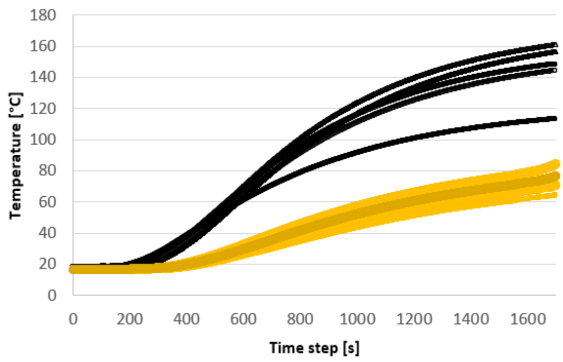

Fig. 3 – Roof temperature measured in the corner test structure prescribed by the standard (EN 1859:2009) and in the axial-symmetric test structure where the chimney is completely surrounded by a roof

By considering the roof thickness (S) and thermal resistance (R), it emerges that for real roofs they can be greater than those in the certification procedure, especially in energy-saving buildings. However, real roofs can be made of more layers and of different characteristics (EN 1859:2009). The investigation also analysed the influence of the position of the chimney in the roof. Fig. 3 compares the temperature measured when the chimney was installed at the centre of a roof (black lines), and in a corner test structure (yellow lines). It can be seen that the roof temperature strongly depends on the chimney position in the roof and the difference in temperature can be up to 80 °C: if the chimney is completely surrounded by the roof, the temperature is greater because the horizontal thickness of the roof reduces the heat transfer towards the ambient.

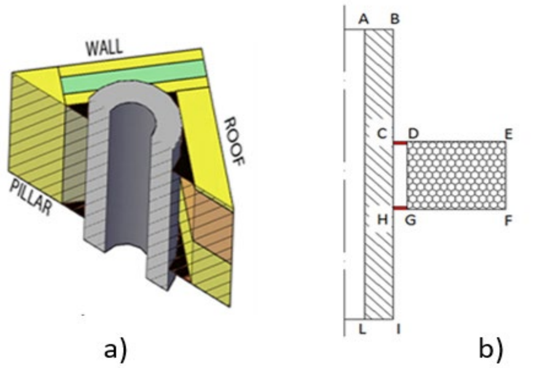

Fig. 4 – The 3D numerical model a) and the 2D numerical model b) used to investigate the influence of the variables

Another aspect relates to the initial TST condition. In the certification procedure, the TST is performed at ambient temperature, but real soot fires may occur immediately after the heat generator is activated, or after a certain period of operation. In the case of the latter situation, the roof temperature (Tmax) may be much higher than the ambient temperature. Consequently, the TST condition is insufficiently strict.

2.1.1 Numerical models to estimate the temperature at chimney–roof penetration

Since heat transfer at chimney–roof penetration depends on several variables, an extensive experimental campaign was not possible because the tests prescribed by the standard (EN 1859:2009) are expensive and time consuming. For this reason, the 3D and the 2D numerical models in Fig. 4 were defined to investigate heat transfer at chimney–roof penetration (Neri et al., 2015a). The 3D numerical model represents the certification procedure conditions where the chimney is installed near two walls at a right angle, while the 2D numerical model represents real installation conditions where the chimney is completely surrounded by a roof. The numerical models estimate the steady roof temperature correctly and in favor of safety. In the majority of cases, the calculated temperature is higher than the actual roof temperature because in the models air infiltration through the material is completely excluded. By comparing numerical and experimental results, it was shown that in the certification procedure the steady temperature is often not achieved because tests are stopped earlier (when the increase in the roof temperature is lower than 2°C/30 minutes). To estimate the steady temperature from the temperature-time curves obtained experimentally, the *Heating Curve Model* has been proposed (Neri et al., 2015a). This model makes it possible to calculate the steady temperature by performing shorter experimental tests. By means of the 2D and the 3D numerical models, the variables affecting heat transfer at chimney–roof penetration and their influence were investigated. The following variables were considered: roof thickness (S), roof thermal resistance (R), clearance sealing mode, distance between chimney and roof (G), position of roof layers (the influence of the position of the wooden and insulating layers), chimney thickness (Sch), chimney thermal resistance (Rch), position of chimney layers, and exhaust gas temperature (Tch). The range of each variable was identified and numerical simulations performed to assess the roof temperature variation. For example, to investigate the influence of the position of roof layers, numerical simulations were performed by considering two roofs of the same thickness (S) and thermal resistance (R) made of an insulating and a wooden layer and the position of the layers was changed. Fig. 5 shows the maximum roof temperature depending on the position of the wooden layer and for several clearance widths (G).

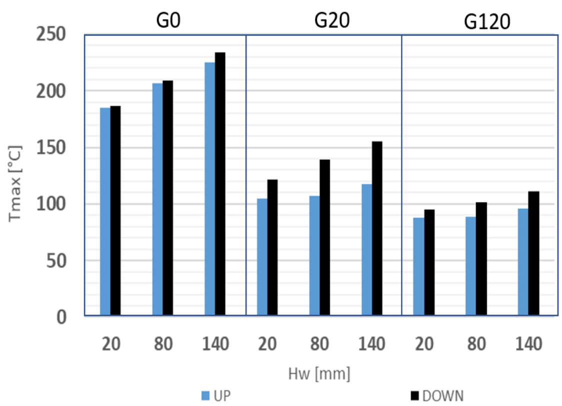

Fig. 5 – Maximum roof temperature for a roof made of a wooden layer and an insulating layer for different clearance widths (G) and different thicknesses (Hw) and positions of the wooden layer

2.2 Tables for Checking Chimney Installations

The maximum roof temperatures (Tmax) obtained numerically were analysed statistically in Neri et al. (2017) by means of the DoE technique (Montgomery, 2002; Montgomery et al., 2003). The DoE is usually used to design experimental campaigns but, in this case, was used it to determine the weight of each variable. The result of the statistical analysis is a set of regression models for calculating the roof maximum temperature (Tmax). To obtain accurate regression models, it was necessary to analyse different types of roofs separately and, consequently, many regression models were found. Three chimney-roof configurations were considered, specifically: roofs made of a wooden layer above an insulating layer, roofs made of an insulating layer above a wooden layer, and roofs with a wooden layer between two insulating layers. Only the case with clearance sealed adiabatically was considered. Since the regression models can be a source of errors, they are presented in the form of a table in Fiure 6: the characteristics of the roof are reported on the left side hand, and the characteristics of the chimney are reported at the top. Consulting the table by selecting the characteristics of the roof and of the chimney identifies a box: a green box represents a safe installation, while a white box represents an unsafe installation. For a given chimney-roof configuration, if a white box is identified, a more insulated chimney can be chosen or the distance between chimney and roof (G) can be increased. For example, let us consider exhaust gas at 400°C, a roof made of a wooden layer and an insulating layer. The insulating layer is 60 mm thick (Hi) and the thermal conductivity is equal to 0.055 W/mK. The wooden layer is 20 mm thick (Hw). The chimney installer can choose among chimneys made of a material of thermal conductivity (λc) equal to 0.04 W/mK of different thickness, and these must be installed at 20 mm from flammable materials (G). From Fig. 6, it can be seen that the chimney installers cannot choose a chimney that is 50 mm thick (Sc) because the related box is white. By comparison, a chimney that is 70 mm thick can be installed safely because the related box is green.

T400			Sc	50			70						
G	Hw	Hi	λi \ λc	0.03	0.04	0.06	0.03	0.04	0.05	0.06	0.07	0.08	0.11
20	20	60	0.03										
			0.055										
			0.08										
		140	0.03										
			0.055										
			0.08										
		220	0.08										
	80	60	0.03										
			0.055										
			0.08										
		140	0.03										
			0.055										
			0.08										
		220	0.08										

Fig. 6 – Table for checking chimney installations. T400 is the temperature class of the chimney, G is the distance between roof and chimney, Hw and Hi are the thickness of the wooden and the insulating layers respectively. λi and λc are the thermal conductivity of the insulating layer of the roof and of the chimney

2.3 Device For Limiting the Temperature at the Chimney–Roof Penetration (CEIL Device)

In order to limit the roof temperature even in very critical operating conditions, a device to be installed between the chimney and roof was designed (Neri and Pilotelli, 2019; Neri at al., 2020). The device must be installed as shown in Fig. 7b) and it is made of insulating and conductive elements: the insulating elements limit the heat flux towards the roof, whereas the conductive elements dissipate the heat in the surrounding. The difference between standard insulation and the effect of the device is shown in Fig. 7: the conductive elements act as cooling fins. The shape of the conductive elements, which guarantee a lower roof temperature, were investigated numerically as shown in Fig. 8.

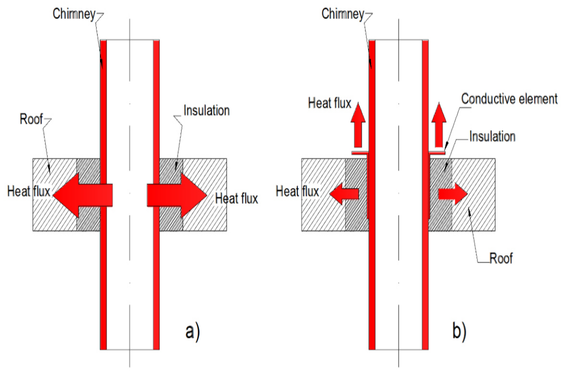

Fig. 7 – Representation of the heat flux with only insulation in the clearance a), and with the device in the clearance b)

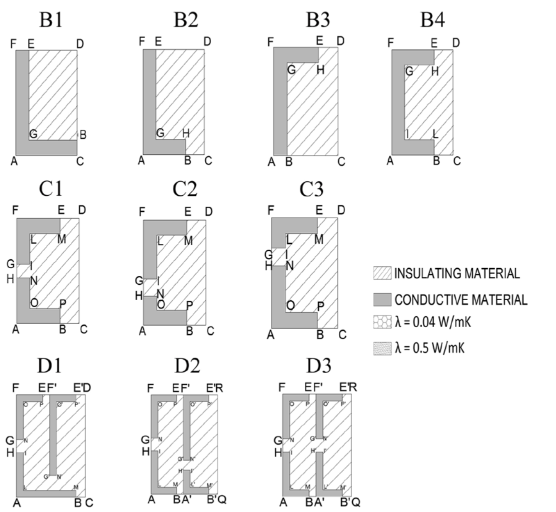

Fig. 8 – Configurations considered in the numerical analysis to design the device to limit the roof temperature

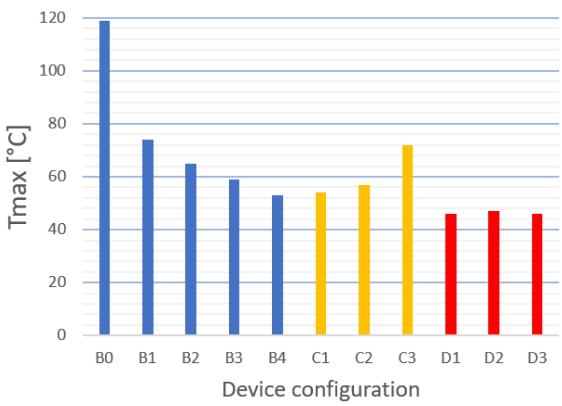

Fig. 9 – Maximum roof temperatures estimated for different device configurations. The device configurations are shown in Fig. 8. The configuration identified with B0 is made of insulating material only.

In the numerical simulations the horizontal thickness of the device was set at 100 mm. The thermal conductivity of the insulating layer was set equal at 0.04 W/mK and the thermal conductivity of the conductive at 15 W/mK, which is a value representative of steel. Firstly, the influence of a conductive element in the insulating layer between chimney and roof was assessed (configurations B1, B2, B3 and B4). A way to reduce thermal bridges between the indoor and the external ambient was investigated by considering configurations (C1, C2 and C3). Next, it was investigated how to further reduce the roof temperature by adding more insulating elements (D1, D2 and D3). The roof temperatures obtained numerically for the different configurations of the device are shown in Fig. 9. Results were verified experimentally (Neri et. al, 2020).

3. Discussion

From the results and discussions in the previous sections, it emerges that the certification procedure does not reproduce the worst chimney operating conditions. This may be one of the causes of the high number of roof fires to have occurred in Europe. This discrepancy is due to several factors, such as the position of the chimney in the test structure, the clearance sealing mode, and the exhaust gas temperature measurement point. Because of this, modifications to the certification procedure have been proposed (Leppänen et al., 2017a and 2017b). Since the exhaust gas temperature at chimney–roof penetration can be lower than the temperature measured in the vicinity of the heat generator (Fig. 1), the related thermocouples should be installed in the vicinity of the roof. In this way, it is be possible to regulate the exhaust gas temperature with more precision. This guarantees the prescribed exhaust gas temperature at chimney–roof penetration, where flammable material temperatures are measured. As can be seen in Fig. 2, the clearance sealing mode strongly affects the roof temperature, and as a consequence the sealing type should be specified in the label applied to certified chimneys. In this way, chimney installers can install the chimney as it was installed in the certification procedure. As shown in Fig. 3, the chimney should be installed so that it is completely surrounded by a roof in order to limit the dissipation of heat through the walls of the test structure. Fig. 5 shows that the maximum roof temperature depends on the characteristics of the roof, and this means that the roof of the test structure should be similar to that in which the chimney will be installed. For this reason, it is necessary to specify the characteristics of the roof in the label applied to certified chimneys. To reproduce the most critical chimney operating conditions, the TST must be performed immediately after the HST. If in the HST and in the TST it is not possible to achieve the steady condition, the final temperature should be estimated by means of the *Heating Curve Model*. In this way, it is possible to calculate the actual maximum roof temperature.

To check chimney installations, a set of tables have been proposed. They can be used in the design phase but also for checking existing chimney installations any time there are doubts about their safety. So far, only the configuration with clearance sealed adiabatically has been considered, but further studies could extend the analysis to other clearance sealing modes and also to the configurations with chimneys in contact with flammable materials.

Finally, a device to be installed between chimney and roof was proposed. The device is made of insulating and conductive elements. In Fig. 9, it can be seen that the presence of a conductive element leads to a lower roof temperature compared to that of a configuration with only insulating material

(B0). The shape and the number of the conductive elements affect the roof temperature: the higher the number of conductive elements, the lower the roof temperature. The higher the number of wings of the conductive element, the lower the roof temperature (B4). To limit thermal bridges through the device, the conductive element can be made of an upper and a lower parts spaced by several millimetres. However, the shape of the conductive elements affects the roof temperature: among configurations C1, C2 and C3, the lowest roof temperature was obtained for configuration C2, characterized by parts of the same size. By comparing the roof temperature obtained with only insulating material (B0) and with the final version of the device (D3), it can be seen that the final version of the device determines a temperature that is 70°C lower, despite the fact that the distance between chimney and roof is unchanged.

4. Conclusions

This paper has shown the main steps of a numerical and experimental study that has led to the understanding of heat transfer at chimney–roof penetration. First of all, it has been shown that the certification procedure does not reproduce the worst chimney operating conditions. Since information from the certification procedure does not guarantee safe installations, tools for checking chimney installations have been proposed to help chimney installers. A set of tables to check whether a chimney can be installed in a given roof safely has been proposed. For very critical operating conditions, such as soot fires and very thick roofs, a device for limiting the roof temperature was designed. The latter limits the roof temperature even in very critical chimney operating conditions, that is, even during soot fire events. By following the proposed recommendation the risk of roof fires can be reduced significantly.

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