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, that can be made of flammable materials such as wood, wood fiber, cellulose, etc. This represents a dangerous condition that could 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 also certified chimneys were involved. The aim of the certification procedure is the determination of the distance between chimney and flammable structures to avoid fires. This paper describes the investigation performed to understand the causes of the high number of fires and to propose solutions to the roof fires problem. The study has been performed numerically and experimentally, and it has consisted of three steps. Firstly, the chimney certification procedure has been 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 have been identified. Finally, solutions and prescriptions to prevent roof fires have been proposed. These latter are a set of tables for checking chimney installations, and a universal device to be installed between chimney and roof to prevent the overheating of this 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 also certified chimneys were involved [Buffo et al., 2007, Dadone, 2009, Ministry of the Environment of Finland, 2011, International Partnership for the Investigation of Fires Explosion, 2015]. Chimney certification is regulated by the EN 1859 standard [EN1859:2009] that prescribes two tests to determine the safety distance between chimney and flammable structures: the Heat Stress Test (HST) reproduces chimneys normal use condition, 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 right angle and 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 m²K/W for the upper roof, and 232 mm and 5.90 m²K/W for the lower roof. The tests consist in feeding the chimney with gas at a predetermined temperature (T_{ch}) and in 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 reported on it. An example of 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 that is the class temperature of the chimney (the maximum temperature of the exhaust gas), and G20 that represents the minimum distance (in millimetres) between chimney and flammable materials. Even if in real installations, the clearance between chimney and roof must be sealed to avoid the entering of atmospheric agents, no information is reported in the label about how to seal it. This paper describes all the steps that have led to the understanding of the heat transfer at chimney roof penetration and to solutions for preventing roof fires. Data here reported were presented in several papers [Neri et al., 2015, Neri et al. ,2018, Neri et al., 2016, Neri et al., 2019, Leppanen et al., 2015, Leppanen et al., 2017], and the aim of this article is to describe the entire research. Besides this research, a study was performed to test a new developed composite material for chimney [Kererekes, 2018]. Leppänen [Leppanen et al., 2019] have investigated the smouldering combustion of mineral wool. The effect of the design flue gas temperature was performed [Leppanen et al., 2015, Leppanen et al., 2017]. The thermal performance of an innovative three-layers chimney was investigated in [Drozdzol, 2020]. Studies in the literature have investigated also aspects related to heat generators and emissions. For example, Polonini et al. [Polonini et al., 2018, Polonini et al., 2019] have shown that the exhaust gas temperature for a pellet stove between 7kW and 11kW is normally around 190°C and 230°C. In non-optimal burning condition the formation of soot can be up to 5 times more than in optimal burning conditions [Polonini et al., 2019]

2. Method and results

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

2.1 Analysis of the EN 1859 standard

Firstly, the chimneys certification procedure described in the EN 1859 [EN1859:2009] standard has been analysed to understand whether it represent the most critical chimney operating conditions. The main aspects analysed are 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 tests conditions. Even if 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 right angle and two roofs positioned at different eights. Since the limited horizontal thickness of the walls represents a thermal bridge, the roof temperature measured in the certification procedure may be lower than those 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 in two different points, that is, 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

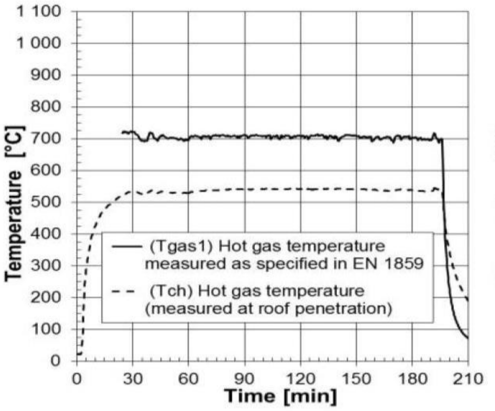

Fig. 1. Comparison between exhaust gas temperature measured in the vicinity of the heat generator, and that measured in the vicinity of the chimney roof penetration in the HST.

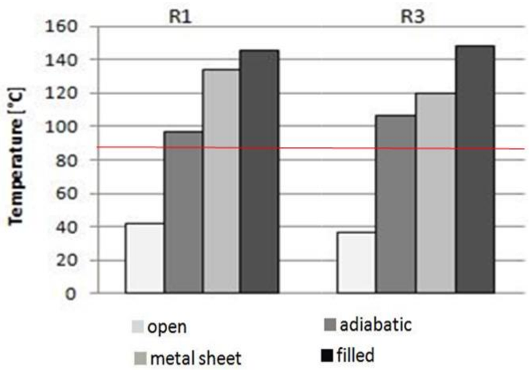

Fig. 2. Roof maximum temperature obtained on varying the clearance sealing mode. The red line represents the limit temperature prescribed by the EN 1859 [EN1859:2009] standard for the HST. Results have been obtained experimentally.

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.

In the TST and the HST, depending on the chimney producer prescriptions, 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 cooling the roof; otherwise, the cooling process is limited. Despite these two possible conditions, in the chimney label no information is specified about the clearance sealing mode in the certification tests. To investigate the importance of this information, in an experimental campaign the clearance has been sealed in different ways in order to reproduce

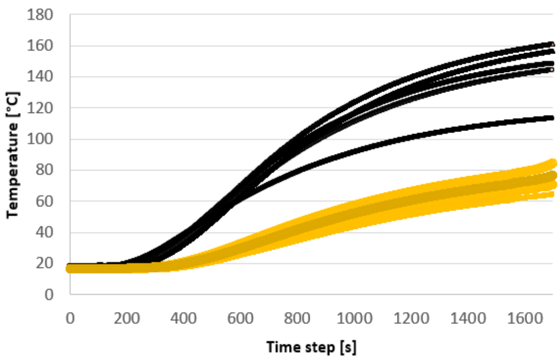

Fig. 3. Roof temperature measured in the corner test structure prescribed by the standard [EN 1859:2009] and in the axial-symmetric test structure where the chimney is completely surrounded by a roof.

possible real conditions. More precisely, the clearance has been left open, sealed with metal sheets, sealed with insulating panels, and 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 have been performed for two roofs called 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 m^2K/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.

By considering the roof thickness (S) and thermal resistance (R), it emerges that for real roofs 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 analysed also the influence of the position of the chimney in the roof. Fig. 3 compares the temperature measured when the chimney was installed at the center 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

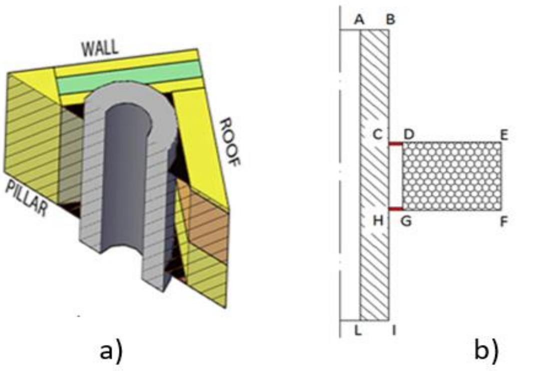

Fig. 4. The 3D numerical model a) and the 2D numerical model b) used to investigate the influence of the variables.

the roof is completely surrounded by the roof, the temperature is greater because the great horizontal thickness of the roof reduces the heat transfer towards the ambient.

Another aspect regards the TST initial condition. In the certification procedure, the TST is performed from ambient temperature, but real soot fires may occur immediately after the heat generator power on, or after a certain period of functioning. In this latter case, the roof temperature (Tmax) may be much higher than the ambient temperature. Then, the TST test condition is less severe.

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 would had not been possible because the tests prescribed by the standard [EN 1859:2009] are expensive and time consuming. For this, to investigate the heat transfer at chimney-roof penetration, the 3D and the 2D numerical models in Fig. 4 have been defined [Neri et al., 2015]. The 3D numerical model represents the certification procedure condition where the chimney is installed near two walls at 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 favour of safety

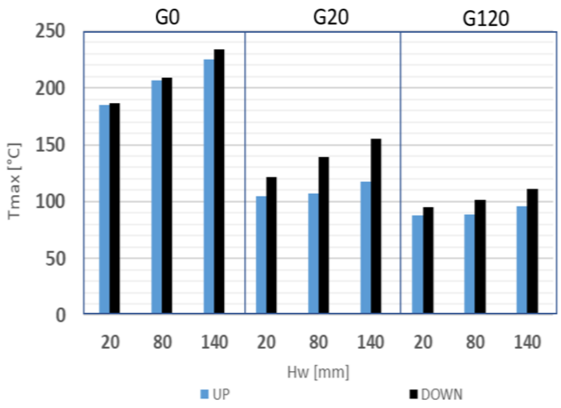

Fig. 5 Roof maximum temperature for a roofs made of a wooden layer and an insulating layer for different clearance width (G) and different thickness (Hw) and position of the wooden layer.

because air infiltration through the material is excluded. By comparing numerical and experimental results, it has been shown that in the certification procedure the steady temperature is often not achieved because tests are stopped in advance (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., 2015]. The model allows to know the steady temperature by performing shorter experimental tests. By means of the 2D and the 3D numerical models, the variable affecting heat transfer at chimney-roof penetration and their influence have been investigated. The following variables have been considered: roof thickness (S), roof thermal resistance (R), clearance sealing mode, distance between chimney and roof (G), roof layers position (the influence of the wooden and the insulating layers position respectively), chimney thickness (Sch), chimney thermal resistance (Rch), chimney layers position, and exhaust gas temperature (Tch). The range of each variable has been identified and numerical simulations have been performed to assess the roof temperature variation. For example, to investigate the influence of the roof layers position, numerical simulations have been performed by considering two roofs of the same thickness (S) and thermal resistance (R) made of an insulating and a wooden layer and the layers position has been changed. Fig. 5 shows the roof maximum temperature

T400			Sc	50			70						
G	Hw	Hi	λc / λi	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 installtions. 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.

depending on the wooden layer position and for several clearance widths (G).

3.1. Tables for checking chimney installations

The roof maximum temperatures (Tmax) obtained numerically have been 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, it has been used 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 has been necessary to analyse different types of roofs separately and, consequently, many regression models have been found. Three chimney-roof configurations have been considered that are, 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 has been considered. Since the regression models can be source of errors, they have been presented in the form of a table as shown in Fig. 6: the characteristics of the roof are reported on the left side hand, and the characteristics of the chimney are reported at the top. By joining the characteristics of the roof and of the chimney

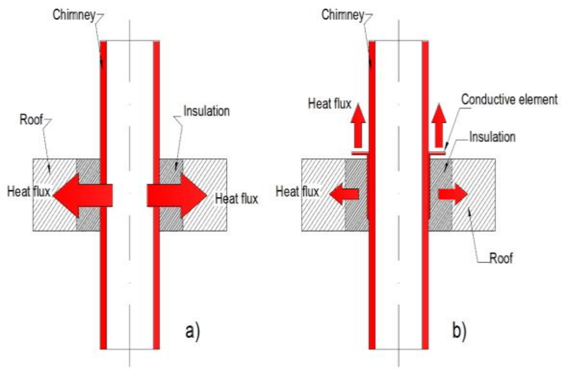

Fig. 7. Representation of the heat flux with only insulation in the clearance a), and with the device in the clearance b).

respectively, a box is identified: a green box represents a safe installation, 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 they must be installed at 20 mm from flammable materials (G). From Fig. 6, it can be seen that the chimney installers can not choose a chimney 50 mm thick (Sc) because the related box is white. At the contrary, a chimney 70 mm thick can be installed safely because the related box is green.

2.2 Device for limiting the temperature at the chimney-roof penetration (CEIL device)

To limit the roof temperature also in very critical operating conditions, a device to be installed between chimney and roof has been designed [Neri et al., 2019, Neri et al., 2020]. The device must be installed as shown in Fig. 7 b). The device 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 a 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 that guarantees a lower roof temperature has been investigated numerically as shown in Fig. 8. In the numerical simulations the horizontal thickness of the device has been set equal to 100 mm. The thermal conductivity of the insulating layer has been set equal to 0.04 W/mK and the thermal conductivity of the conductive 15 W/mK that is a value representative of steel. Firstly, the influence of a conductive element in the insulating layer between chimney and roof has been assessed (configurations B1, B2, B3 and B4). A way to reduce thermal bridges between the indoor and the external ambient has been investigated by considering configurations (C1, C2 and C3). Then, it has been investigated how to further reduce the roof temperature by adding more insulating elements (D1, D2 and D3). The roof temperature obtained numerically for the different configurations of the device are shown in Fig. 9. Results were verified experimentally [Neri et. al, 2020].

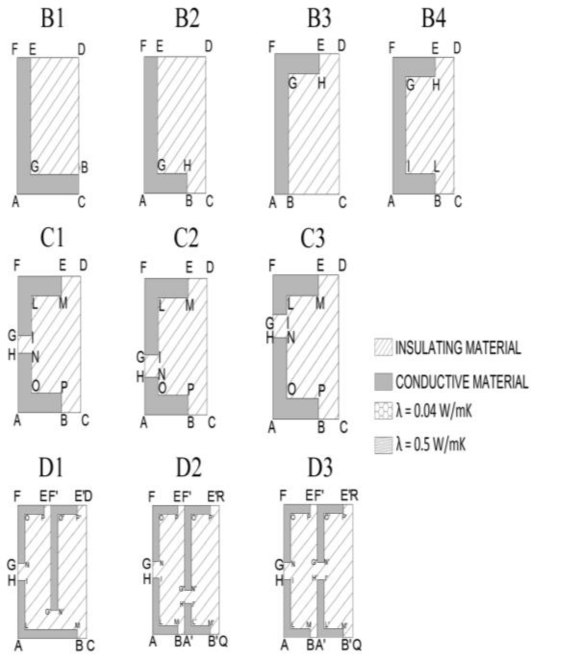

Fig. 8. Configurations considered in the numerical analysis to design the device to limit theroof temperature.

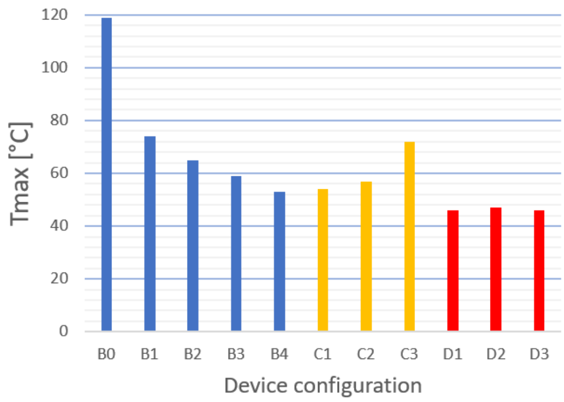

Fig. 9. Roof maximum temperature estimated for different device configurations. The device configurations are shown in Fig. 8. The configuration identified with B0 is made of insulating material only.

3. Discussion

From the consideration above reported, it emerges that the certification procedure does not reproduce the worst chimney operating conditions. This can be one of the causes of the high number of roof fires occurred in Europe. This discrepancy is due to several aspects such as the position of the chimney in the test structure, the clearance sealing mode, and the exhaust gas temperature measurement point. For this, modifications to the certification procedure have been proposed [Leppanen et al., 2017]. Since the exhaust gas temperature in correspondence of the chimney-roof penetration can be lower than the temperature measured in the vicinity of the heat generator (Fig. 1), the related thermocouples must be installed in the vicinity of the roof. In this way, it will be possible to regulate the exhaust gas temperature with more precision. This guarantees the prescribed exhaust gas temperature in correspondence of the chimney-roof penetration, where flammable material temperatures are measured. According to Fig. 2 the clearance sealing mode strongly affects the roof temperature, then the sealing type must be specified in the label reported on certified chimneys. In this way, chimney installers can install the chimney as done in the certification procedure. According to Fig. 3, the chimney must be installed completely surrounded by a roof in order to limit the dissipation of heat through the walls of the test structure. Since Fig. 5 shows that the roof maximum temperature depends on the roof characteristics, the roof of the test structure must be similar to that in which the chimney will be installed. For this, it is necessary to specify the characteristics of the roof in the label reported on certified chimneys. To reproduce the most critical chimney operating condition, 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 know the actual roof maximum 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 has been designed. The device is made of insulating and conductive elements. In Fig. 9, it can be seen that the presence of a conductive element determines a roof temperature lower than in the configuration made of 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 un upper and a lower parts spaced of some millimetres. However, the shape of the conductive elements affects the roof temperature: among configurations C1, C2 and C3, the lowest roof temperature has been obtained for configuration C2, characterized of 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 70°C lower despite 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 condition. 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 has been designed. This latter limits the roof temperature also in very critical chimney operating conditions, that is, also during soot fire events. By means of these results the risk of roof fires can be reduced significantly.

References

[1] Buffo, S., and P. N. Dadone. 2007. "Studio Statistico Vigili Del Fuoco di Brescia Sulle Cause dell'Incendio Tetto". (Brescia Italian: Vigili del Fuco di Brescia)

[2] Dadone, P. N. 2009. "Analisi 00. Casi Verificatisi sul Territorio della Provincia di Brescia e Statistica delle Cause Incendi Tetto e Canne Fumarie", *Incendi tetto e Canne Fumarie Proceeding Conference*, Brescia (in Italian)

[3] Drozdzol, K. 2020. "Experimental fire testing of an innovative three-layer chimney for residential buildings" *Journal of Building Engineering.* Doi: 10.1016/j.jobe.2019.101019

[4] EN 1859:2009+A1:2013 "Chimneys test methods" Brussels.

[5] International Partnership for the Investigation of Fires Explosions and Other Major Incidents. Accessed 21 July 2015, www.burgoynes.com

[6] Kererekes, Z., E. Lublóy, B. Elek and A. Restás. 2018. "Standard fire testing of chimney linings

from composite materials." *Journal of Building Engineering* 19, pp. 530-538. doi: 10.1016/j.jobe.2018.05.030

[7] Leppänen, P., M. Neri, D. Luscietti, S. Bani, M. Pentti and M. Pilotelli. 2017. "Comparison between European chimney test results and actual installations." *Journal of Fire Sciences*, 35 (1), pp. 62-79. Doi:10.1177/0734904116680222.

[8] Leppänen, P., and M. Malaska. 2019. "Experimental Study on the Smouldering Combustion of Mineral Wool Insulation in Chimney Penetrations." *Fire Technology*. doi: 10.1007/s10694-019-00849-1

[9] Leppänen, P., T. Inha and M. Pentti. 2015. "An experimental study on the effect of design flue gas temperature on the fire safety of chimneys." *Fire Technol*ogy 51:847-86. doi: 10.1007/s10694-014-0415-4

[10] Leppänen, P., M. Malaska, T. Inha and M. Pentti. 2017. "Experimental study on fire safety of chimneys in real use and actual site conditions" *Journal of Building Engineering* 14: 41-54, doi:10.1016/j.jobe.2017.09.014.

[11] Ministry of the Environment of Finland. 2011. "Finnish Concern on Fire Safety Risk Due to CE Marking of Appliances Fired by Solid Fuel and Chimney Products".

[12] Montgomery, Douglas. 2002. *Design and Analysis of Experiments*. 5th Edition. John Wiley and Sons

[13] Montgomery, Douglas, and George Runger. 2003. *Applied Statistical and Probability for Engineers*. 3th Edition. John Wiley and Sons.

[14] Neri, M., P. Leppänen, S. Bani, M. Pentti and M. Pilotelli. 2015. "Experimental and Computational Study of the Temperatures Field Around a Chimney Roof Penetration." *Fire Technology*, doi:10.1007/s10694-015-0540-8.

[15] Neri, M., D. Luscietti, S. Bani, A. Fiorentino and M. Pilotelli. 2015. "Analysis of the temperatures measured in very thick and insulating roofs in the vicinity of a chimney." Journal of Physics: Conference Series, Volume 655, conference 1. Doi: 10.1088/1742-6596/655/1/012019

[16] Neri, M., D. Luscietti, A. Fiorentino, and M. Pilotelli. 2016. "Experimental Analysis of Chimneys in Wooden Roofs." *Fire Technology*. doi: 10.1007/s10694-015-0525-7

[17] Neri, M., D. Luscietti, A. Fiorentino, and M. Pilotelli. 2017. "Statistical Approach to Estimate the Temperature in Chimney Roof Penetration" *Fire Technology*, 54 (2), pp. 395-417. DOI: 10.1007/s10694-017-0689-4

[18] Neri, M., and M. Pilotelli. 2018. "Data on temperature-time curves measured at chimney-roof penetration." *Data in Brief* 20: 306-315, doi:10.1016/j.dib.2018.08.017.

[19] Neri, M., and M. Pilotelli. 2019. "Device for Limiting the Temperature at Chimney-Roof Penetration in Very Critical Chimney Operating Conditions." *Fire Technology*. Doi: 10.1007/s10694-019-00837-5

[20] Neri, M., P. Leppänen, M. Alanen, D. Luscietti, S. Bani, and M. Pilotelli. 2020. "Effects of the coupling of insulating and conductive materials to limit the temperature at chimney-roof penetration." *Fire Technology*. Doi: 10.1007/s10694-020-00947-5

[21] Polonini, L. F., D. Petrocelli, S. P. Parmigiani and A. M. Lezzi. 2019. "Pm – O2 correlation in combustion processes in pellet stoves and boilers" European Biomass Conference and Exhibition Proceedings, pp. 497-503.

[22] Polonini, L. F., D. Petrocelli, S. P. Parmigiani and A. M. Lezzi. 2019. "Experimental study of PM emissions from wood pellet stoves with an innovative burning pot" *Journal of Physics: Conference Series*. Doi: 10.1088/1742-6596/1224/1/012018

[23] Polonini, L. F., D. Petrocelli, S. Parmigiani, and A. M. Lezzi. 2019. "Influence on CO and PM emissions of an innovative burner pot for pellet stoves: an experimental study" *Energies.* doi: 10.3390/en12040590

[24] Polonini, L. F., D. Petrocelli, S. P. Parmigiani and A. M. Lezzi. 2018. "Experimental study of PM emissions from wood pellet stoves with innovative burning pots", *EUBCE 2018,* Copenhagen