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PERTTU LEPPÄNEN

Fire Safety of Metal Chimneys in Residential Homes in Finland

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ACADEMIC DISSERTATION
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of Tampere University,
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Responsible supervisor and Custos	Professor, D.Sc. Matti Pentti Tampere University Finland	
Supervisor	Professor, D.Sc. Mikko Malaska Tampere University Finland	
Pre-examiners	Professor, PhD Luke A. Bisby The University of Edinburgh Scotland	D.Sc Veli-Pekka Nurmi Safety Investigation Authority Finland
Opponent	Prof. emeritus, D.Sc Matti Kokkala VTT Technical Research Centre of Finland Ltd (Retirement 2017) Finland	

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PREFACE

This thesis is based on research carried out between 2010 and 2016 at Tampere University of Technology. Three studies investigated the fire safety of the chimneys and the flue gas temperatures of the fireplaces in the laboratory and in the field. The research projects were carried out under the leadership of Timo Inha. Lic.Sc. (Tech.).

I wish to thank my supervisors Professor Matti Pentti and Professor Mikko Malaska. The reviewers of thesis, Professor Luke A. Bisby from the University of Edinburgh and Veli-Pekka Nurmi, D.Sc (Tech), from the Safety Investigation Authority are kindly acknowledged for their comments and valuable suggestions to improve the thesis.

Thank you very much to my colleagues Martti Peltomäki, Mika Alanen, Annu Ruusala and Anssi Hentinen who helped me with the tests. Thanks to Professor Jari Mäkinen and Manuela Neri Ph.D. for co-authorship of my articles. I would also like to thank Manuela Neri for her good cooperation and stay at the Tampere University of Technology.

There were three research projects, which were funded by several organisations. The main sponsor of the all three was the Fire Protection Fund of Finland. Other funders were the Ministry of the Environment, the Ministry of the Interior, the Finnish Safety and Chemical Agency, the Federation of Finnish Financial Services, Schiedel Oy, Härmä Air Oy, the Juhani Lehikoinen Foundation, Linnatuli Oy, Hormex Oy, Ekovilla Oy, Paroc Oy Ab, Finnfoam Oy and Saint-Gobain Rakennustuotteet Oy. I would like to thank those in the steering groups for the research projects. Special thanks to Seppo Pekurinen and Matti J. Virtanen. Personal grants for writing this thesis were awarded by Pelastusalan tutkijakoulun apuraha väitöskirjaa varten and the postgraduate fund of the Confederation of Finnish Construction Industries RT. Thank you for your support.

My gratitude also goes to my parents and siblings. Finally, I would like to thank my dear wife Mari and children Venla, Alisa, Iisa, Viola, Eemi and Nooa.

Jyväskylä 29.8.2019
Perttu Leppänen

ABSTRACT

In recent years, numerous building fires have occurred in Finland where the fire started due to the ignition of flammable materials in the vicinity of metal chimney penetrations through floors, roofs and walls. In 2012, metal chimneys caused over 70% of all chimney-induced fires in residential buildings in Finland. The safety issue with metal chimneys is important, as they represent only 10% of all chimneys in Finland. To improve the fire safety of metal chimneys, an extensive research programme was conducted at the TUT Fire Laboratory of Tampere University of Technology (currently known as Tampere University) between 2010 and 2016. The study was mainly experimental. A series of laboratory and field tests were performed in order to determine the flue gas temperatures of fireplaces to be used in designing chimneys. The effect of the installation of metal chimneys and the effect of the smouldering combustion of the organic content of mineral wool on fire safety were studied using laboratory tests.

Several reasons for chimney penetration-induced fires have been identified: higher actual flue gas temperatures onsite than those assumed in chimney design, incomplete or insufficient chimney installations and the smouldering combustion of mineral wool insulation. Fireplaces and chimneys are tested in accordance with EN standards. The standard tests are conducted in predefined laboratory conditions. The actual conditions onsite may be very different from these laboratory conditions. Site conditions vary, for example due to fuel type and chimney-draught conditions, which depend on site conditions, time, draught controls and the chimney length and installation. Regardless of this variation in conditions, chimney design based on EN standard tests should lead to a fire-safe solution.

The flue gas temperature given on the CE marking of a fireplace may not always lead to a safe solution and should therefore not be used in designing a chimney. In the laboratory tests, the highest flue gas temperatures of the tested fireplaces measured in the temperature safety test were 124°C to 381°C higher than those given on the CE marking. In some field tests, the flue gas temperatures and chimney draught levels exceeded significantly those of the standard laboratory tests. The mean flue gas temperatures measured during the room heater and sauna stove tests were approximately 100°C higher than the flue gas temperatures given by the manufacturers in the CE marking of the fireplaces.

The study highlighted the differences between the conditions in real installations and those in the thermal performance tests prescribed by the standard for the certification of chimneys. It showed that the temperatures measured in the tests performed according to the standard can be lower than the temperatures that may occur in real installations. The standard's weaknesses concern the position of the chimney in the test structure and the hot gas measurement point in the tests. For chimney testing, hot gas can drop by over 150°C in temperature between the standard measurement point and the chimney penetration, so the chimney may be tested at too low a flue gas temperature. The highest risk is in the chimney thermal shock test as, in a soot fire, burning can occur just at the chimney penetration. The test results show that the flue gas temperature at the roof penetration may be 350°C lower than the test temperature. The position of the chimney in the test structure, in a corner of the roof and near two walls does not represent the worst condition in which a chimney may operate. In real installations, chimneys are usually completely surrounded by a roof that offers lower thermal conductivity than the walls of the test structure. In the test, the temperatures measured at the roof insulation were about 60°C higher than those measured on the walls.

The temperature in the chimney's roof penetration is affected by the smouldering combustion of mineral wool binder. Smouldering combustion generates additional heat in the penetration structure, which in turn increases the temperature of both the penetration insulation and the surrounding floor and roof structures. Experiments on mineral wool specimens show that smouldering combustion can increase the insulation temperature by hundreds of degrees, which in turn can increase the temperatures of the combustible roof construction materials located adjacent to the chimney penetration by over 100°C for a limited period of time.

Several factors that can increase the temperatures in the chimney penetration were identified in this research. It has also been shown that the simultaneous action of several factors is also possible, which can increase the penetration temperatures to the level of the ignition temperature. The study presents a number of methods for increasing the reliability of current EN standard tests and thereby improving the fire safety of metal chimneys.

TIIVISTELMÄ

Viime vuosina Suomessa on tapahtunut lukuisia rakennuspaloja, jotka ovat saaneet alkunsa metallisavupiippujen läpivienneistä välipohjien, kattojen ja seinien läpi. Vuonna 2012 metallisavupiiput aiheuttivat yli 70% kaikista savupiippujen aiheuttamista tulipaloista asuinrakennuksissa Suomessa. Metallisavupiippujen aiheuttamat tulipalot ovat merkittävä ongelma, koska metallisavupiippujen osuus kaikista savupiippuista Suomessa on vain 10%. Metallisavupiippujen paloturvallisuuden parantamiseksi tehtiin laaja tutkimusohjelma vuosina 2010-2016 Tampereen teknillisen yliopiston palolaboratoriossa (nykyään Tampereen yliopisto). Tutkimukset olivat pääasiassa kokeellisia. Laboratorio- ja kenttäkokeita suoritettiin savupiippujen suunnittelua varten käytettävän tulisijojen savukaasulämpötilan määrittämiseksi. Lisäksi laboratoriokokeilla tutkittiin metallisavupiipun asennustavan ja mineraalivillan sisältämän orgaanisen aineen palamisen vaikutusta metallisavupiipun paloturvallisuuteen.

Savupiipun läpiviennistä aiheutuneisiin paloihin tunnistettiin useita syitä: todelliset savukaasujen lämpötilat ovat korkeammat kuin savupiippujen suunnittelussa oletetaan, savupiipun virheellinen tai riittämätön asennustapa ja mineraalivillaeristeessä tapahtuva kytöpalo. Tulisijat ja savupiiput testataan EN-standardien mukaisesti. Standardikokeet suoritetaan ennalta määritellyissä laboratorio-olosuhteissa. Todelliset olosuhteet paikan päällä voivat olla hyvin erilaisia kuin nämä laboratorio-olosuhteet. Käyttöolosuhteet vaihtelevat, esimerkiksi polttoainetyypin ja savupiipun veto-olosuhteiden vuoksi, joka puolestaan riippuu rakennuksen sijainnista, tulisijan käyttöajasta, tulisijan säädöistä sekä savupiipun pituudesta ja savupiipun asennustavasta. Näistä olosuhteiden vaihtelusta huolimatta, EN-standardikokeisiin perustuvan savupiipun suunnittelun tulisi johtaa paloturvallisiin ratkaisuihin.

Tulisijan CE-merkinnässä ilmoitettu savukaasujen lämpötila ei välttämättä aina johda turvalliseen ratkaisuun, joten sitä ei pidä käyttää savupiipun suunnitteluun. Laboratoriokokeissa olleiden tulisijojen korkeimmat savukaasujen lämpötilat lämpötilaturvallisuuskokeessa olivat 124°C - 381°C korkeammat kuin CE-merkinnässä ilmoitetut savukaasujen lämpötilat. Joissakin kenttätesteissä savukaasujen lämpötilat ja savupiipun veto ylittivät huomattavasti standardikokeiden

arvot. Kenttäkokeissa kamiinojen ja kiukaan savukaasujen keskimääräiset lämpötilat olivat noin 100°C korkeammat kuin savukaasujen lämpötilat, jotka valmistajat olivat ilmoittaneet tulisijan CE-merkinnässä.

Tutkimuksessa havaittiin eroja metallisavupiippujen todellisten asennustapojen ja standardin mukaisten kokeiden olosuhteissa. Standardikokeissa mitatut lämpötilat voivat olla matalampia kuin lämpötilat todellisissa asennuksissa. Standardissa on puutteita koskien savupiipun asemaa testirakenteessa ja kuuman kaasun mittauspisteen sijaintia testissä. Savupiipun testauksessa kuuman kaasun lämpötila voi jäähtyä yli 150°C standardin mukaisen mittauspisteen ja savupiipun läpiviennin välillä, joten savupiippu voidaan testata liian matalalla savukaasulämpötilalla. Suurimman riskin aiheuttaa savupiipun nokipalo, koska nokipalossa palaminen voi tapahtua savupiipun läpiviennin kohdalla. Koetulokset osoittavat, että nokipalokokeessa kuuman kaasun lämpötila savupiipun läpiviennissä voi olla 350°C matalampi kuin testilämpötila. Savupiipun standardin mukainen testaustapa nurkassa lähellä kahta seinää ei edusta pahinta mahdollista savupiipun asennustapaa. Todellisissa asennuksissa savupiiput ovat yleensä täysin yläpohjaeristeen ympäröimiä. Yläpohjaeristeen lämmönjohtavuus on alhaisempi kuin testirakenteen seinien. Kokeissa yläpohjaeristeen kohdalta mitatut lämpötilat olivat noin 60°C korkeampia kuin standardin mukaisista kohdista seinistä mitatut lämpötilat.

Mineraalivillan orgaanisen aineen kytevä palaminen vaikuttaa savupiipun läpiviennin lämpötilaan. Kytevä palaminen tuottaa lisälämpöä läpivientirakenteeseen, mikä puolestaan nostaa sekä läpivientieristeen että ympäröivien välipohja- ja kattorakenteiden lämpötiloja. Mineraalivillaeristeille tehdyt kokeet osoittivat, että kytevä palaminen voi nostaa läpivientieristeen lämpötilaa sadoilla asteilla, mikä puolestaan voi nostaa rakennusmateriaalien lämpötiloja savupiipun läpiviennissä hetkellisesti yli 100°C.

Tässä tutkimuksessa tunnistettiin monia tekijöitä, jotka voivat nostaa lämpötiloja savupiipun läpiviennissä. Myös monien tekijöiden vaikuttaminen samanaikaisesti on mahdollista, mikä voi nostaa lämpötilat savupiipun läpiviennissä syttymislämpötilan tasolle. Tutkimuksessa esitetään monia tapoja nykyisten EN-standarditestien turvallisuustason lisäämiseksi ja siten metallisavupiippujen paloturvallisuuden parantamiseksi.

CONTENTS

TERMINOLOGY

Block chimney	A chimney that has been made from concrete flue blocks, for example. The flue blocks may be of single- or multi-wall construction.
Burning rate performance test	A test of slow heat release appliance corresponding to the nominal heat output test of other fireplace types
CE marking	The manufacturer's declaration that the product meets the requirements of the applicable EC directives
Chimney	Structure consisting of a wall or walls enclosing a flue or flues.
Chimney draught	The pressure difference between the chimney and the outside air that causes the flue gases to move in the chimney.
Euro-class A1	The highest class (non-combustible) of fire safety in construction products, determined in accordance with harmonised testing methods.
Firebox	The part of the appliance in which the fuel is burned
Flue	Passage for conveying the products of combustion to the outside atmosphere
Flue draught	See: Chimney draught.
Flue gas	Combustion gases and smoke from combustion which exit via a flue. It consists of nitrogen, carbon

	dioxide, water vapour, oxygen, particulate matter (like soot), carbon monoxide, nitrogen oxides, sulphur oxides, and so on.
Flue gas connector	Duct through which flue gases are conveyed from the appliance into the chimney flue
Heat stress test	Test from the thermal resistance of a chimney
Hot gas (chimney testing)	The gas used for testing the chimneys and produced by the hot gas generator
Inset appliance	Appliance with or without doors designed to be installed in a fireplace recess or an enclosure, or into the firebox of an open fire.
Masonry chimney	Chimney built of brick or stone
Mean flue gas temperature	Average temperature of the flue gas at a specified point in the measurement section
Metal chimney	Chimney with its flue liner made of metal, which may have additional surrounding structural elements and accessories, as well as insulation
Negative pressure chimney	Chimney designed to operate with the pressure inside the flue less than the pressure outside it
Nominal heat output test	Test of total heat output of the fireplace quoted by the manufacturer and achieved under defined test conditions when burning the specified test fuel
Nominal working temperature	Average flue gas temperature obtained during the nominal output test for the maximum temperature level
Positive pressure chimney	Chimney designed to operate with the pressure inside the flue greater than the pressure outside it

Room heater	Appliance with a fully enclosed firebox with a firedoor/doors that are normally closed, which distributes heat by radiation and/or convection and also provides hot water when fitted with a boiler.
Safety distance	The distance of the outer surface of the chimney/fireplace to combustible material
Sauna stove	A stove that has a fully enclosed firebox with a firedoor that is normally closed, which distributes heat by radiation and/or convection and is also fitted with stones or other heat retaining material onto which water is poured to produce hot steam/vapour that rises from the hot sauna stones.
Slow heat release appliance	Intermittent burning appliance with thermal storage capacity to accumulate heat into its mass such that it provides heat for a period of hours, specified by the manufacturer, after the fire has gone out
Smouldering combustion	Self-sustained combustion in porous materials without a flame.
Soot fire	Combustion of the flammable residue deposited on the flue liner
Temperature class	Gives the nominal working temperature of a chimney
Temperature safety test	A test whereby a safety distance is measured between the fireplace and the combustible material
Thermal shock test	A test of the resistance of the soot fire of the chimney
Trihedron	A test corner used for testing room heaters and slow heat release appliances

ABBREVIATIONS

CE	Certification mark that indicates conformity standards for products sold within the European market
EN	European Standard
EPS	Expanded polystyrene
FprEN	Final draft of the EN standard
PIR	Polyisocyanurate
prEN	Draft of the EN standard
PUR	Polyurethane
SFS	Finnish Standards Association
XPS	Extruded polystyrene
T600	Temperature class of chimney where the number is the working temperature

ORIGINAL PUBLICATIONS

Publication I	Leppänen P., Inha T. & Pentti M. An experimental study on the effect of design flue gas temperature on the fire safety of chimneys, Fire Technology, Vol. 51, Issue 4, 20 June 2014, pp. 847-866
Publication II	Leppänen P., Malaska M., Inha T. & Pentti M. Experimental study on fire safety of chimneys in real use and actual site conditions. Journal of Building Engineering, Vol. 14, November 2017, pp. 41-54
Publication III	Leppänen P., Neri M., Luscietti D., Bani S., Pentti M., Pilotelli M., Comparison between European chimney test results and actual installations. Journal of Fire Sciences, Vol. 35, Issue 1, January 2017, pp. 62-79
Publication IV	Leppänen P., Neri M., Mäkinen J. Heat release caused by the smouldering combustion of the binder of rockwool. Journal of structural mechanics. Vol. 48, No 1, 2015, pp. 68-82

AUTHOR'S CONTRIBUTION

Publication I	The author planned the research work together with T. Inha. The author carried out the experimental tests, performed data analysis and wrote the paper. The co-authors commented on the manuscript.
Publication II	The author planned the research work together with T. Inha. The author carried out the experimental tests, performed data analysis and wrote the paper. The co-authors commented on the manuscript.
Publication III	The author planned and carried out the experiments (HS0, HS1, SF1 and SF2) presented in this thesis. The author also performed data analysis and was responsible for reporting and writing these results in the article. Italian tests (SF3 and HSF3) and the numerical simulations were performed by M. Neri. The author worked as the corresponding author for this paper. The co-authors commented on the manuscript.
Publication IV	The experimental research was planned and carried out by the author. The literature review was prepared and written by M. Neri together with the author. The author also performed a data analysis and wrote the manuscript as the corresponding author. The Computational Modelling was carried out by J. Mäkinen.

1 INTRODUCTION

The principal aims of fire precautions are to safeguard life and property. These aims can be influenced in three ways: 1. Reducing fire incidence, 2. Controlling fire propagation and spread, 3. Providing adequate means of escape for occupants of buildings [Shields et al. 1987]. A fire that never happens causes no loss. Fire precautions can be divided into fire prevention and fire protection. Fire prevention is to prevent the outbreak of a fire and/or to limits its effects. Fire protection is to reduce danger to people and property by detecting, extinguishing or containing fires. Fire protection can be divided into passive and active fire protection. Passive fire protection attempts to contain fires or slow the spread, such as by fire-resistant walls, floors and doors. Active fire protection is the fire detection devices and fire extinguishing devices [Read et al. 1993].

Heating appliances are among the most prevalent causes of fire because they operate at temperatures above the ignition temperature of many common materials. In addition, combustion-type appliances may involve the hazards of an accumulated combustible mixture, the discharge of unburned fuel and exposure of fuel to ignition sources [Fire Protection Handbook]. In the Middle Ages, fireplaces did not have chimneys, so smoke and hot gases were extracted through walls and straw was used as the floor covering. In this environment, the fire risk was obvious, so all fires were required to be extinguished at night in 1189 in London. In the 14th century, fireplaces were equipped with chimneys made of hollowed out logs, which made the situation even worse, so log chimneys were forbidden in the 15th century [Read et al. 1993]. The first requirements for chimneys in Great Britain were introduced in the 1774 fire regulations [Shields et al. 1987]. These regulations specified the minimum thicknesses for chimney walls.

A heating system consists of a fireplace and a chimney. A typical fireplace is shown in Figure 1.1 a). In a fireplace, wood or other fuel burns and produces flue gas. Flue gases move out through chimney. Chimney types can be masonry, block or metal. A metal chimney is composed of a metallic inner tube, an insulating layer and a metallic outer tube. A cross-section of a metal chimney is shown in Figure 1.1 b). Metal chimneys are usually built from the chimney modules and collar plate joint modules. A chimney module is shown in Figure 1.1 c). There is usually penetration insulation around the chimney in the roof penetration. An example of penetration insulation is shown in Figure 1.1 d). A cross-section of a metal chimney penetration is shown in Figure 1.1 e).

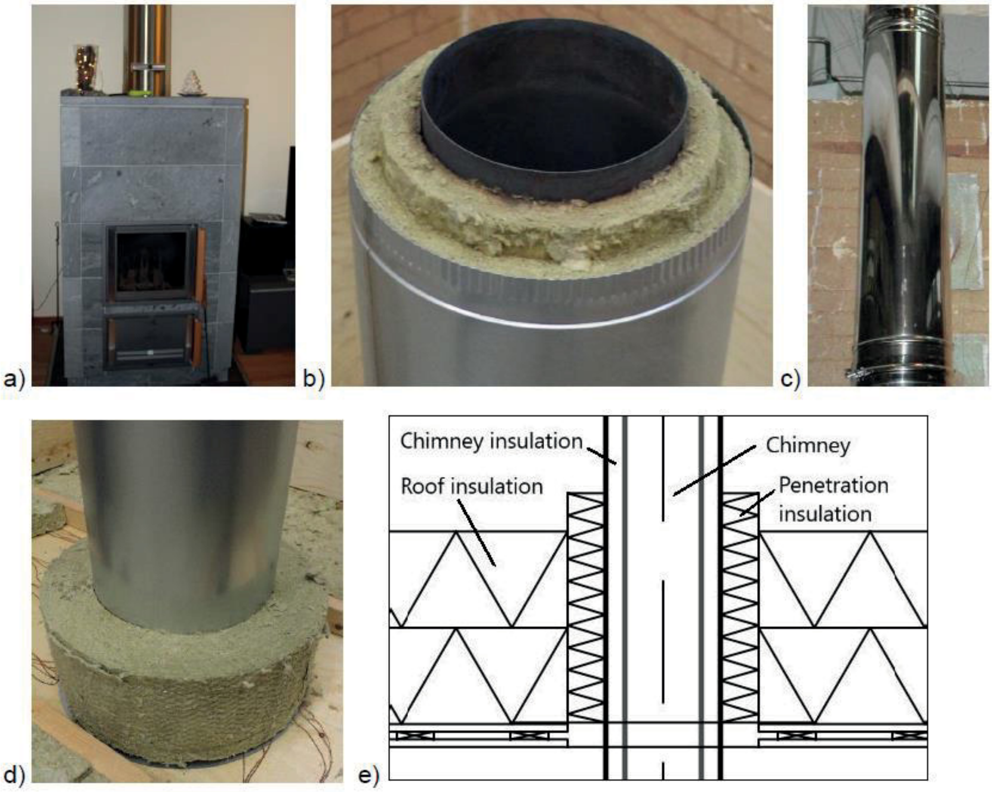


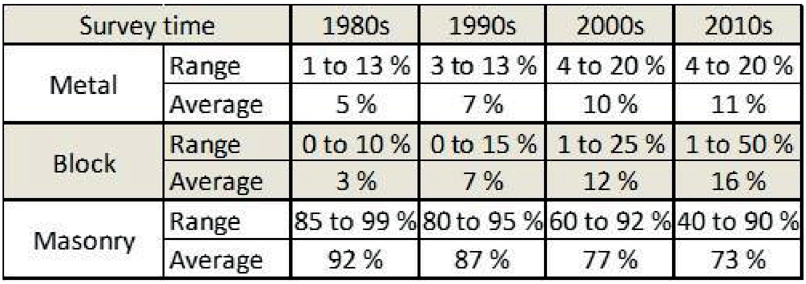
Figure 1.1 a) Fireplace b) Cross-section of a metal chimney c) Chimney module d) Penetration insulation e) Cross-section of penetration of metal chimney.

According to reports [Törmänen 2005, Saarnivuo 2005] for 2002–2004, about 500 fires break out in fireplaces and chimneys in Finland every year. This is 14-15% of all building fires in Finland. The number of the fires has increased so that, in every year between 2008 and 2014, 700–900 fires involved fireplaces and chimneys [Kokki et al. 2013, Ketola et al. 2014 and 2015]. In addition, 300-400 soot fires were ignited every year. Soot fire is a situation where the flammable residue deposited on the chimney flue liner burns rising the exhaust gas temperature.

A roof safety survey by chimney sweeps in 2011 revealed that metal chimneys accounted for about 6% of the all chimneys [Murtokare 2012]. The survey covered

1,047 buildings in different parts of Finland. A survey was also carried out in which 25 chimney sweeps from different parts of Finland were asked about the prevalence in metal chimneys [Article I]. Due to the small sample, the results were only indicative. The results of the survey are shown in Table 1.1. The high variation in the 2000s and 2010s may be because, in some of the areas, most of the buildings are new constructions and, in other areas, very few new buildings have been built. In new buildings, metal and block chimneys are more frequent. Typical chimney types in Finland are shown in Figure 1.2.

Table 1.1 Percentages of different chimney types of all the chimneys in the residential buildings of the entire building stock in Finland at different times [Article I].



Survey time		1980s	1990s	2000s	2010s
Metal	Range	1 to 13 %	3 to 13 %	4 to 20 %	4 to 20 %
	Average	5 %	7 %	10 %	11 %
Block	Range	0 to 10 %	0 to 15 %	1 to 25 %	1 to 50 %
	Average	3 %	7 %	12 %	16 %
Masonry	Range	85 to 99 %	80 to 95 %	60 to 92 %	40 to 90 %
	Average	92 %	87 %	77 %	73 %

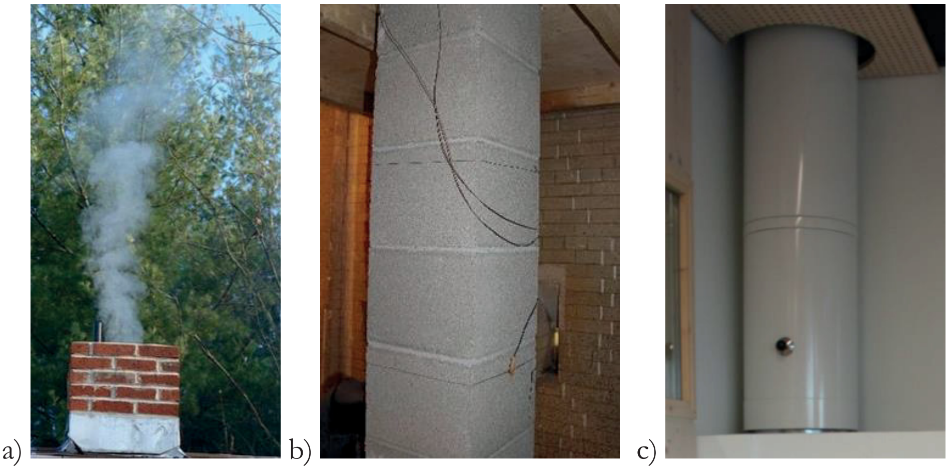


Figure 1.2 Different chimney types in Finland: a) Masonry chimney b) Block chimney c) Metal chimney.

Hakala et al [2014] investigated the database of the Finnish rescue services about fires caused by fireplaces and chimneys in 2012. The results showed that 36% of the fires were started in fireplaces and 64% in chimneys. Of the fires started in chimneys, 73% involved metal chimneys. The number of fires started in metal chimneys can be considered significant and alarming, as approximately 10% of chimneys caused over 70% of all chimney-induced fires. The indication is clear even if the samples of the survey are small and can be biased. The problem is made even more significant by the fact that all metal chimneys in Finland are relatively new. Fire safety problems with brick masonry chimneys are mainly due to degradation with age. Similar fire safety problems have also been reported in other European countries. In the Italian province of Brescia, about 300 fireplace- and chimney-induced fires occurred in 2007 [Buffo et al.]. Many of these fires in Finland and Italy started from the chimney-roof penetrations of metal chimneys. According to Leppänen [2010], metal chimneys caused about 500 building fires in Finland between 2004 and 2009.

In the chimney flue there is a high temperature, which may come from the fireplace or soot fire. The heat in the chimney is transferred through the chimney structure to the materials and structures surrounding the chimney penetration. The temperature rise in the surrounding structure depends on the temperature of the flue gas and the duration of the exposure. There is often combustible material around the chimney penetration. The building materials used in ceilings and roofs consist typically of wool insulation, plastic insulation, wood, wood-based materials and different roofing materials. Hot flue gases expose the chimney construction to heat, which increases the temperature of the chimney and the structures adjacent to it. An example of the temperatures at the penetration of the chimney is shown in Figure 1.3 a). Ignition from the penetration of a metal chimney is shown in Figure 1.3 b). A chimney roof penetration after fire is shown in Figure 1.3 c).

Figure 1.3 a) An example of the temperatures at the penetration of the chimney. The chimney locates in the middle of the figure. On the left side of the chimney is an insulation layer 200 mm thick and on the right side the insulation thickness is 600 mm. The temperatures are based on experimental measurement results.
b) Ignition from the penetration of the metal chimney. c) Chimney roof penetration after fire.

1.1 Fireplaces

Wood-burning fireplaces' flue gas temperature varies by hundreds of degrees during heating. The temperature of flue gases depends on many factors such as the fireplace, chimney, firewood, chimney draught and how the fireplace is used. The duration of heat mainly depends on the user. In soot fire, a deposit of soot on the chimney's inner surface ignites. In soot fire, gas temperatures are usual higher than the flue gas temperatures of fireplaces. In that case, the chimney will experience high temperatures.

1.1.1 Combustion and flue gas temperatures

The combustion of wood can be divided into three phases: (1) evaporation of moisture, (2) disintegration of the fuel due to temperature, i.e. pyrolysis, and (3) burning of the residual coke. The evaporation of moisture and pyrolysis are heat-consuming phases. The combustion of pyrolytic gases and residual coke are heat-generating phases. If the particle size of fuel is large, the phases occur simultaneously. The pyrolysis of wood takes place between 200°C and 500°C [Koistinen et al. 1986]. The share of volatile substances in air-dry wood is about 85%, so wood burns with a long flame. During combustion, the temperature of the flame is affected by such factors as the moisture in the wood and the amount of excess air. Wood flames emit relatively strong radiation as their water vapour and CO2 contents are high and they contain glowing carbon particles [Vuorelainen 1958].

The flue gas temperatures of fireplaces were measured in a laboratory study by Peacock [1987;1]. The study included 18 typical commercial fireplaces in the USA. The flue gas temperatures of the tested fireplaces are presented in Table 1.2. In Peacock's laboratory tests [1987;2], the highest flue gas temperatures in normal heating with wood as fuel varied between 426°C and 519°C, in overheating between 574°C and 855°C, and with coal as fuel between 327°C and 625°C. Hansen et al. [1997] studied damage to block chimneys. Their tests simulated possible intense heating. In intense heating, the highest flue gas temperature at the flue-gas connector exceeded 900°C. In Inha's experiments for sauna stoves, similar flue gas temperatures were also measured [Inha et al. 2011]. These studies did not precisely specify the methods for testing the fireplaces.

Table 1.2 Flue gas temperatures of fireplaces in Peacock's tests [1987;1].

Flue gas temperature	300–400°C	400–500°C	500–600°C	600–700°C	700–800°C
Number of fireplaces	1	3	0	9	5

As the above results show, the possibility of flue gas temperatures exceeding 600°C cannot be excluded, especially under continuous intense heating. However, the highest temperature class of chimneys is T600, which is designed for a maximum flue gas temperature of 600°C [EN 1443:2003]. Flue gas temperatures higher than those measured in tests are particularly problematic in metal chimneys because of their lightness. The exterior temperatures of masonry and block chimneys rise slowly because they retain more heat. The density of brick is ten times greater than the insulation used in metal chimneys. Because of this, fire risk can already arise over a shorter heating period.

1.1.2 The effect of actual site conditions and user performance

The actual site conditions and the way of using the fireplace can have an effect on the fires caused by metal chimneys. The ways of using room heaters have been studied in Norway [Hansen et al. 1998]. It was found that occupants refuel fireplaces at longer intervals and in larger batches than in standard testing. The study also revealed that heating periods are longer than in tests. According to the study, fireplaces were used for up to 18 hours per day. According to the measurements, chimney draughts are lower in actual use than in tests. The study highlighted a contradiction between the testing of fireplaces and their actual use in Norway. The difference was not considered significant enough to require changes in the test method for room heaters.

Finland has not studied how the actual use of fireplaces affects the temperature of flue gases. The use of fireplaces in Finland differs somewhat from what is customary in Norway. The biggest difference lies in the type of fireplaces used. The most common types in Finland are slow heat release appliances and wood-burning sauna stoves. Slow heat release appliances are not usually heated for as long as room heaters.

1.1.3 Soot fires

The critical condition of a soot fire, in which a deposit of soot on the chimney's inner surface ignites, was studied by Peacock [1986] by means of 12 tests. In the study, soot was built up in flue by burning green wood. After build-up, the soot was ignited and temperatures were measured in the chimney. The measured maximum temperatures during the tests were 908-1,370°C. Some of the results of these tests are shown in Table 1.3. The accumulation of soot was highest when 2,733 kg of wood was burned for 1,752 hours at an average ambient temperature of −6°C. Durations of soot fires in tests by Peacock are shown in Table 1.4.

Table 1.3 Minimum, average and maximum values of Peacock's soot fire tests [1986].

	Total wood burned [kg]	Duration of build-up [hr]	Thickness of deposit [mm]	Peak gas temperature in chimney and chimney connector [°C]	Peak gas temperature in chimney [°C]
Minimum	115	76	3–13	908	754
Average	940	605	9–21	1,042	952
Maximum	2733	1752	13–64	1,370	1,370

Table 1.4 Duration (minutes) of soot fires in tests by Peacock [1986]. The times given are how long the given temperature was exceeded.

Temperature in chimney	Minimum	Maximum	Average
$\geq$ 200°C	11	90	36
$\geq$ 400°C	8	82	28
$\geq$ 600°C	5	44	19
$\geq$ 800°C	2	18	10
$\geq$ 1000°C	0	8	2
$\geq$ 1200°C	0	3	0

As can be seen in Table 1.4, the soot fires had relatively short durations. The entire exposure time over which the temperature was more than 600°C lasted from 5 min to 44 min, the average being 19 min. The duration of the thermal shock test according to standard EN 1859 was 30 min and the test temperature was 1,000°C.

1.1.4 Chimney draught

The theoretical draught of the chimney (P_H) is calculated with the Eq. 1.1 [EN 13384-1], where H [m] is the height of chimney, g [m/s^2] is the gravitational constant, ϱ_L [kg/m^3] is the density of outdoor air and ϱ_m [kg/m^3] is the mean density of flue gases.

$$P_H = H \cdot g \cdot (\varrho_L - \varrho_m) \qquad (1.1)$$

The height of the chimney has an effect on the chimney draught. The second influential factor is the temperature of the outdoor air, which has an effect on the density of the air. The draught increases when outdoor air is cooling. The third influential factor is the temperature and composition of flue gases. Achenbach et al [1948] studied the performance of masonry chimneys under steady state conditions. The results demonstrated that higher inlet gas temperatures increased flue draught. The type of masonry material and liner, and the treatment of air space affected the flue draught very little. The study did not examine whether a higher draught raises the temperature of flue gases. In the testing of fireplaces, the typical draught is 12 Pa [e.g. EN 13240], but the draught can be considerably higher in reality. During intense heating, draught levels as high as 45 Pa has been measured [Hansen et al. 1997].

1.2 Chimneys and chimney-roof penetrations

Achenbach et al [1948] and Mitchell [1949] studied the fire safety of masonry chimneys. They tested 35 masonry chimneys of various types of construction. In the tests by Achenbach et al [1948], they used three different gas temperatures and three different gas flow rates. Mitchell [1949] also performed shock tests of half-hour duration at flue gas temperatures from 1,000°C. The tests of the EN standards of chimneys are very similar to those performed by Achenbach et al. and Mitchell. It can be assumed that these studies formed the starting points of the EN standard tests.

1.2.1 Metal chimneys

In the 2010s, the fire safety of metal chimneys has been studied in Finland and Italy. In the studies [Inha et al. 2011, Neri et al. 2015:2], it was demonstrated that the thickness of the thermal insulating layer of the roof had an effect on the temperatures of combustible materials located near the chimney penetration area. In the performed tests [Inha et al. 2011], the rise in temperature at a distance of 100 mm from the chimney's outer surface was about 150°C when the thickness of the roof insulation was increased from 200 mm to 600 mm. The tests were performed with an axisymmetric test structure and the flue gas temperature at the height of the penetration was maintained at a constant level of 700°C. The test structure is shown in Figure 1.4 a). The effect of the thickness of roof insulation on the temperatures of penetrations is shown in Figure 1.4 b).

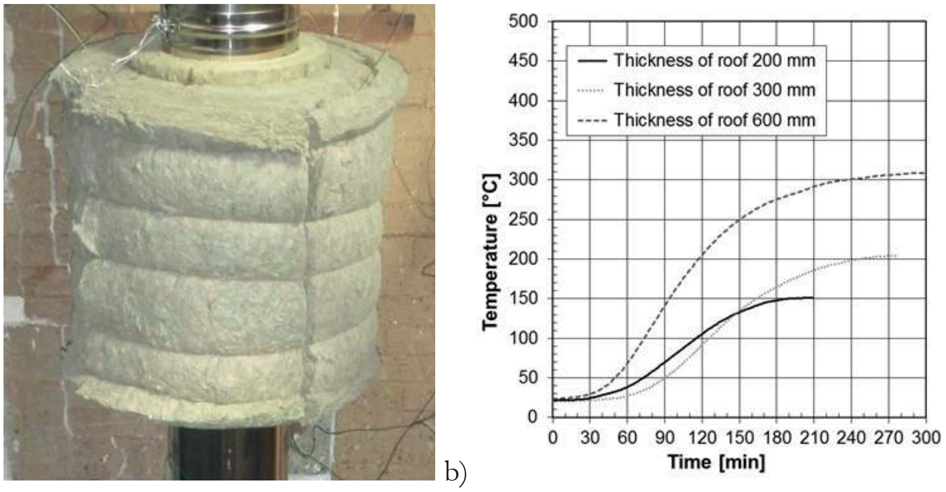

a) b)

Figure 1.4 a) Test structure, b) Effect of thickness of roof insulation on the temperatures of penetrations [Inha et al. 2011]. Temperatures are measured at a distance of 100 mm from the chimney's outer surface.

Higher insulation around the chimney prevents heat from escaping through the chimney penetration. Under short-term exposure, the ignition temperature of wood is about 250°C [Babrauskas et al. 2007]. In the case of tests, the ignition temperature is exceeded by a 600 mm roof thickness, but not by 200-300 mm. Figure 1.4 b) also shows the effect of exposure duration. If the critical temperature is 200°C, it will take 2 hours to reach the temperature with a roof thickness of 600 mm. To achieve the same temperature takes 4 hours when the roof thickness is 300 mm. The thickness of the roof in the EN standard test is 200 mm [EN 1859].

Neri studied how the chimney clearance sealing mode influences temperatures in chimney penetrations [Neri et al. 2015:1]. She tested four different sealing modes: 1. open, 2. sealed with metal sheets, 3. sealed adiabatically and 4. filled with insulating material. The chimney sealing mode filled with insulation material resulted in the highest temperatures in roof penetrations. This is the most-used chimney sealing mode in Finland. Also, roof layer arrangements have an influence on the maximum temperature position. In Italy, they also use thick horizontal wood layers, which affect the position of the highest temperature. In Finland, the building style is different and there are no wooden layers. In chimney tests according to standard [EN 1859], there is a wooden structure between the chimney and roof. Such wood structure is not actually used near chimneys in either Italy or Finland. Neri et al.

[2015:1] showed that this kind wooden structure can cause lower temperatures in the penetration.

In her doctoral thesis, Neri [2016] concentrated on an analysis and modelling of the temperatures at the penetrations of chimneys. Neri proposes changes to the test standard of metal chimneys [EN 1859] based on the method of installation in Italy. The development proposals are based on Article III and on her studies [Neri et al. 2015:1, 2015:2, 2015:3 and 2016]. According to Neri [2016], standard EN 1859 should be modified as follows:

- A clearance sealing mode and roof layer positions have an influence on the maximum temperature position, so thermocouples on the test structure should be positioned vertically, not horizontally [Neri et al. 2015:1]
- The hot gas temperature should be measured as close as possible to the chimney penetration [Article III]
- The final test condition does not always allow a steady-state temperature. The steady-state temperature on the test structure could be estimated with the heating curve model developed by Neri et al. [2016].
- The method of selecting the installation mode should be explained in the chimney installation manuals so that installation engineers can make choice.
- Tests are not suitable for chimneys that will be installed in very thick and highly insulating wooden roofs [Neri et al. 2015:1]
- Chimneys should be installed at the centre of a roof and not near the walls. This is because the thermal conductivity of the walls is higher than that of the roof so heat dissipation occurs [Article III]
- In the test structure, between the chimney and roof no wooden lath should be installed because it acts as a thermal bridge [Neri et al. 2015:1]

As a result of the fires caused by the chimneys, the investigation of the subject was started in Finland and Italy. In Finland, the research was started in 2010. In 2015, research co-operation was initiated for chimney testing, and Manuela Neri arrived at the Tampere University of Technology. Her goal was to develop a fire-safe chimney penetration detail. Her work was mainly done computationally. The experiments performed in this thesis were also used in her numerical simulations and calculations. Neri participated in writing Article III and Article IV. Correspondingly, the author assisted Neri in writing an article [2016]. In this thesis, the aim was to improve the fire safety of metal chimneys in Finland. The scope of the work was to develop background material for the development of standards of fireplaces and chimneys. The study was carried out using laboratory and field tests. The study focused not only on the chimney penetration, but also on the flue gas temperatures of the fireplace.

1.2.2 Smouldering combustion of the organic content of mineral wool

The constant smouldering burning spreads the combustion without a flame. Once started, the smouldering process is characterised by the three zones represented in Figure 1.5. Zone 1 near to the heat source has already undergone the smouldering process and char has been formed. In zone 2 the process is being developed, and in zone 3 far from the heat source the process has not yet occurred. Only in porous burning materials can constant smouldering burning take place. The maximum temperature in the reaction area in most organic materials is 400-750°C in standing air and pyrolysis begins at 250-300°C [Drysdale 1998].

Mineral wool products are often used as penetration insulation materials in chimney penetrations. According to standard EN 13501-1, they are classified as non-combustible. Despite the classification as class A (non-combustible) material, mineral wool always contains a small amount of organic material, which creates favourable conditions for smouldering combustion. Heat release caused by smouldering combustion was clearly recognised when two chimney-tests were carried out on the same structure [Inha et al. 2011]. In the test, a metal chimney was connected to a sauna stove and installed through a 200 mm-thick mineral wool roof insulation layer. Temperatures were measured from a thermocouple located in the middle of the thermal insulation layer and 100 mm from the face of the chimney flue. The test structure is shown in Figure 1.6 a). The temperatures during tests 1 and 2 are shown in Figure 1.6 b). The solid curve for Test 1 includes the additional heat release generated by the burning of the organic material. The chimney test was then repeated using the same structure, the result of which is the temperature development depicted by the dashed curve for Test 2. The organic material burned in Test 1, while the additional heat generation was no longer detected in the second test. The difference between the two curves can be interpreted as the additional heat generated by the burning of organic material. The maximum difference in temperature was measured at 140 minutes and was 230°C. After reaching its maximum value, the temperature of Test 1 starts to decrease, which means that the organic content has burnt off. The temperatures in both tests are then approaching a similar temperature level. The estimated duration of the temperature peak in this test was approximately 150 minutes. Based on the experiments [Inha et al. 2011], heat release occurred especially in high roof insulation thicknesses.

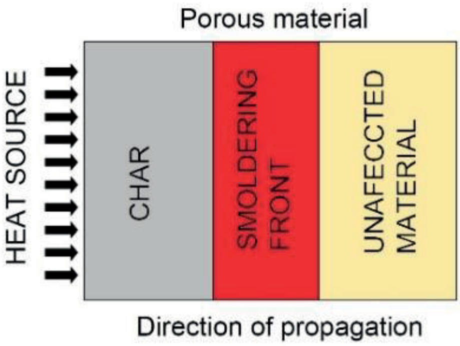
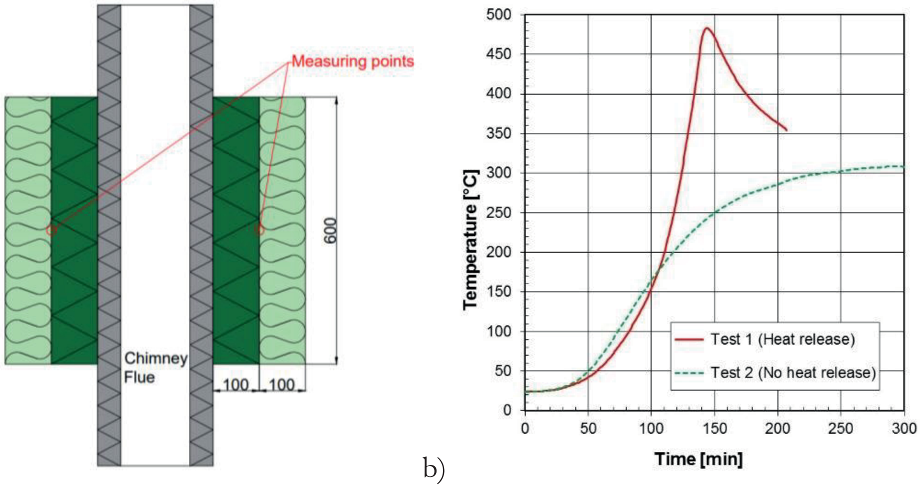


Figure 1.5 Representation of smouldering process.



a) b)

Figure 1.6 a) Test structure, b) Temperatures at penetration at a distance of 100 mm from the surface of the chimney in tests 1 and 2.

1.3 Relevance of the research

In Finland, many fires caused by metal chimneys have occurred in spite of the CE markings of the fireplaces and chimneys. Previous studies have shown that the flue gas temperatures of fireplaces in actual installations and conditions can be very high and higher than in the test conditions specified in the EN standards. The high flue gas temperature increases the temperatures of structures and materials located near the chimney penetration, which increases the risk of fire. Figure 1.7 shows an idealised vertical section where a chimney penetrates a roof construction. In this idealised example, a 100-mm-thick penetration insulation is used around the chimney flue and the outer face of the penetration insulation defines the safe distance from the chimney flue. In actual chimney installations, the insulation thickness and safety distance required are normally designed on a case-by-case bases and depend on chimney and penetration construction as well as on the properties of penetration insulation products. Roof constructions, including thermal insulation and timber roof structures, are installed in contact with the penetration insulation. In the figure, the temperature distributions for three different continuous working flue gas temperatures are presented. The penetration detail is considered fire-safe if the temperatures do not exceed 85°C outside the safe distance of 100 mm. The 500°C temperature corresponds to temperature class T400 of EN 1856-1. In this idealised detail, the temperatures of this 500°C -curve do not exceed the 85°C limit and the detail meets the standard requirements. If the actual flue gas temperatures are higher, 600°C and 700°C, the limit value will be exceeded, and the hatch marks indicate the area where temperatures may exceed the ignition temperatures of building materials and the fire hazard is apparent. Actual flue gas temperature levels higher than assumed in the chimney penetration design may create a potential fire risk. However, there has been little or no research on the actual flue gas temperatures of fireplaces in real use and under actual site conditions in buildings. There is no sufficient information available to identify the difference between the actual site conditions and the EN standard test conditions, and to assess whether the differences affect the fire safety of chimney penetrations. In order to ensure a fire-safe chimney design, the flue gas temperatures given in the CE markings of fireplaces should cover all possible operating conditions including use contrary to operating instructions. In this research, the conditions typical in Finland are of particular concern.

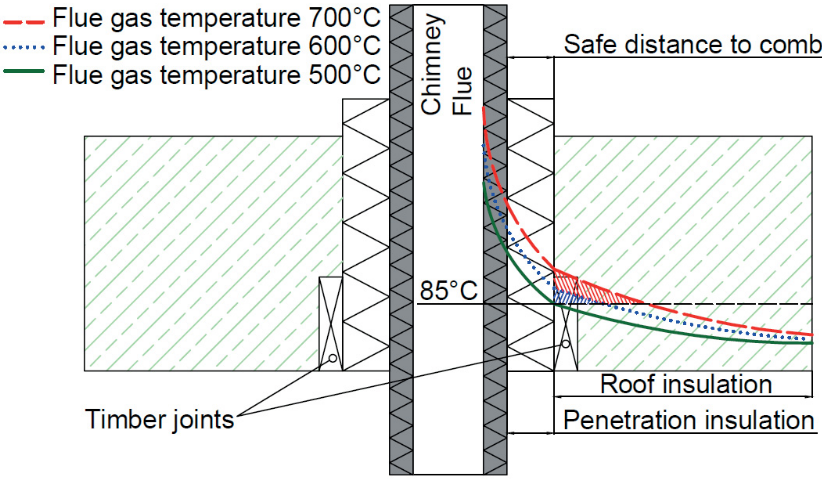


Figure 1.7 Idealised figure of a vertical section of a roof and the temperature distributions across the chimney penetration structures. The three temperature curves represent three different flue gas temperatures - 500°C, 600°C and 700°C. In this idealised figure, the lowest 500°C temperature represents an acceptable performance as the temperatures do not exceed 85°C outside the safe distance of 100 mm. When the flue gas temperatures are higher, 600°C and 700°C, the 85°C limit will be exceeded, and the hatch marks indicate the area where temperatures may exceed the ignition temperatures of building materials.

Roof and floor construction and the requirements for thermal insulation solutions vary between countries and depend on climate conditions, legislation and traditions. The test and product standards of chimneys, however, do not consider the variations in penetration construction and site conditions. Neri [2016] listed the weaknesses of standard EN 1859 based on the Italian installation methods and details. As the site conditions in Finland and Italy differ significantly, especially in weather conditions, thermal insulation requirements and typical construction details, it is unclear if all the findings of Neri are applicable in Finland and if the findings cover all possible conditions in Finland. More research is required to demonstrate how well the EN standard test conditions and construction of chimneys correspond to the site conditions, building construction and structural details in Finland.

One potential reason identified for chimney-penetration-induced fires is the smouldering combustion of mineral wool insulation, penetration insulation, installed around the chimney flue. Mineral wool contains binder and other organic materials and the smouldering combustion of this organic material can generate additional heat that, in turn, increases the temperature of both the penetration insulation and the surrounding floor and roof structures. Research by Inha et al. [2011] showed that the smouldering combustion of mineral wool insulation can raise the temperature of chimney penetrations and create a potential fire hazard in the surrounding structures. Further information was required considering the level of temperature rise, the effects of insulation thickness on the temperature rise and the distribution of temperature rise over the cross-section of penetration insulation.

2 OBJECTIVES

The research aimed to establish whether the measurement methods used in fireplace and chimney tests according to EN standards cause a fire safety risk to chimneys and the whether the testing of fireplaces and chimneys corresponds well enough to their actual use in Finland. One objective of the study was to try to influence the development of European's standards, the national regulations of Finland and the manufacturers' instructions.

The scope of this study is the fire safety of metal chimneys in Finnish households. The structure and installation of the chimney are essentially connected with the fire safety of the chimney, but the fireplace and its use also have an influence. In addition, the smouldering combustion of the organic content of mineral wool can have an effect on the fire safety of chimneys. The compatibility of fireplaces and chimneys tested according to EN standards and the fire safety of the penetrations of metal chimneys are also studied. In addition, the effect of the conditions and use of fireplaces on the temperature of the flue gases is estimated. The effect of the smouldering combustion of mineral wool on the temperatures of the penetration of the chimney is studied.

The study was partly done in collaboration with Manuela Neri from the University of Brescia, Italy. The collaboration concerned testing set-up and method. The goal of Neri's study was to develop a fire-safe chimney penetration detail. Her work was mainly done computationally. The experiments performed in this study were also used in the calculations and numerical simulations. In this study, the aim was to improve the fire safety of metal chimneys in Finland. The aim of the study was to influence the standards of fireplaces and chimneys. The study was carried out using laboratory and field tests. The study focused not only on the chimney penetration, but also on the flue gas temperatures of the fireplace.

In this thesis study, the actual flue gas temperatures of fireplaces in real use and under actual site conditions were investigated using field tests. However, it was impossible to include the full range of actual conditions and operating environments. The experiments chosen have been considered to represent the most typical cases and factors. The ignition properties of different materials have not been studied in detail, but fire risk caused by generally used materials at the penetrations of metal chimneys is discussed. The wall penetrations of metal chimneys have not been studied because they do not fall into the test standard for chimneys. The metal chimneys connected to boilers have been omitted from the study. The fires caused by leaks of flue gases have not been studied because they seem not to be a problem for metal chimneys in Finland.

2.1 Research questions

The main research questions can be formulated as follows:

1. Flue gas temperatures
    1.1. Does the fireplace standard test method give a fire-safe temperature class to a chimney?
    1.2. How could the fire-safe temperature class of the chimney be determined?
2. Chimney and chimney penetration design
    2.1. Does the current standard test method of metal chimneys lead to a fire-safe penetration structure in Finnish conditions?
    2.2. How should the test method of metal chimneys be updated to Finnish conditions?
    2.3. How does the smouldering combustion of the penetration insulation affect the fire safety of the penetration structure?

2.2 Research methods

The study was performed mainly experimentally. A series of laboratory and field tests were performed in order to determine the flue gas temperatures of fireplaces to be used in designing chimneys. The effects of the metal chimney installations and the smouldering combustion of the organic content of mineral wool on fire safety were also studied in the laboratory tests. The scheme of the research approach is shown in Figure 2.1.

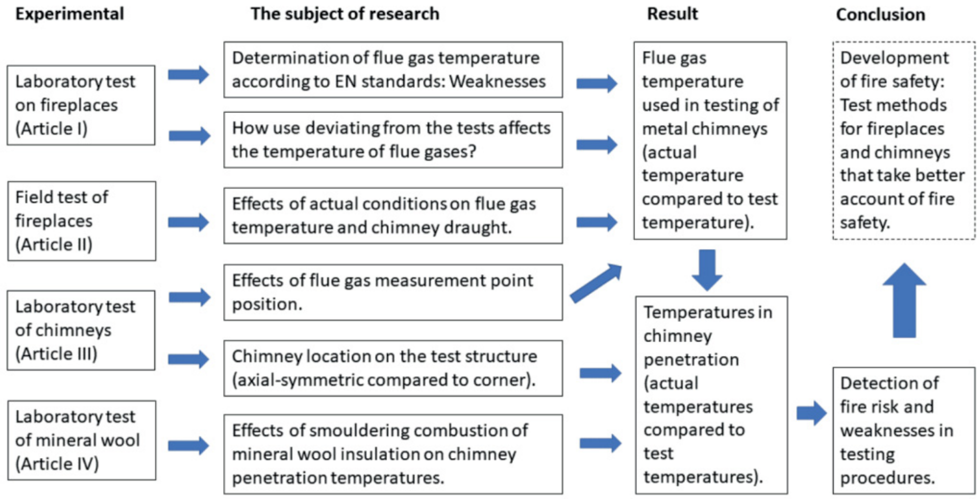


Figure 2.1 Scheme of the research approach.

Article I: A series of laboratory tests to EN standards was performed in order to determine the flue gas temperatures of fireplaces to be used in designing chimneys. The differences between the flue gas temperatures of the nominal heat output test and the temperature safety test were determined. Another aim was to evaluate how the use of fireplaces deviating from the tests affects flue gas temperatures.

Article II: A series of field tests was performed in order to determine the actual flue gas temperatures of fireplaces and actual chimney draughts.

Article III: The effect of the installation solution of metal chimneys on fire safety was studied in laboratory tests. The tests simulated how the actual installation and actual conditions of the chimneys affect the temperature of nearby combustible materials. The effect of the flue gas temperature measuring sections of chimney's tests was also studied.

Article IV: The effect of the smouldering combustion of the organic content of mineral wool on fire safety was studied in the laboratory tests. The objective of the study was to determine the heat released from the charring of the organic content of mineral wool.

The testing arrangements, conditions and measurements are described in articles I - IV.

3 FLUE GAS TEMPERATURES

The flue gas temperature of the fireplace has an effect on the fire safety of the chimney. The objective of performed laboratory tests is to estimate whether the present temperature of flue gases has been given correctly or whether another way would be better. Furthermore, in the laboratory tests it was estimated how use deviating from the tests affects the temperature of flue gases.

Laboratory tests are always simplified and differ from actual field conditions. Conditions vary due to chimney draught conditions that depend on site and time, as well as the length and installation method of the chimney. In addition, the actual use of a fireplace differs from test use, at least in terms of wood batch sizes, firewood charging intervals, fuel used and draught control. EN standard tests should cover a credible worst-case scenario except for a deliberate misuse of the fireplace. A series of field tests was made to study flue gas temperatures and draught in fireplaces. Together with the field experiments, how well the EN standard tests simulate real conditions was also studied.

Section 3.1 presents EN standard test methods for fireplaces. Sections 3.2 and 3.3 present laboratory and field experiments to assess if the flue gas temperature of a fireplace can lead to a fire-safe chimney design. Section 3.4 presents conclusions of the tests.

3.1 EN standards test methods of fireplaces

Fireplaces are subjected to a nominal heat output test and a temperature safety test in accordance with EN standards [e.g. EN 13240]. The former describes the planned use of the fireplace while the latter is intended to ensure the fire safety of the area around the fireplace. In EN standard tests at nominal heat output, properties such as efficiency, heat output and emissions are determined for fireplaces. Safety distances of fireplaces are determined in a temperature safety test. The test arrangements of the most common fireplace types in Finland are shown in Figure 3.1. Testing of different fireplaces types is shown in Table 3.1.

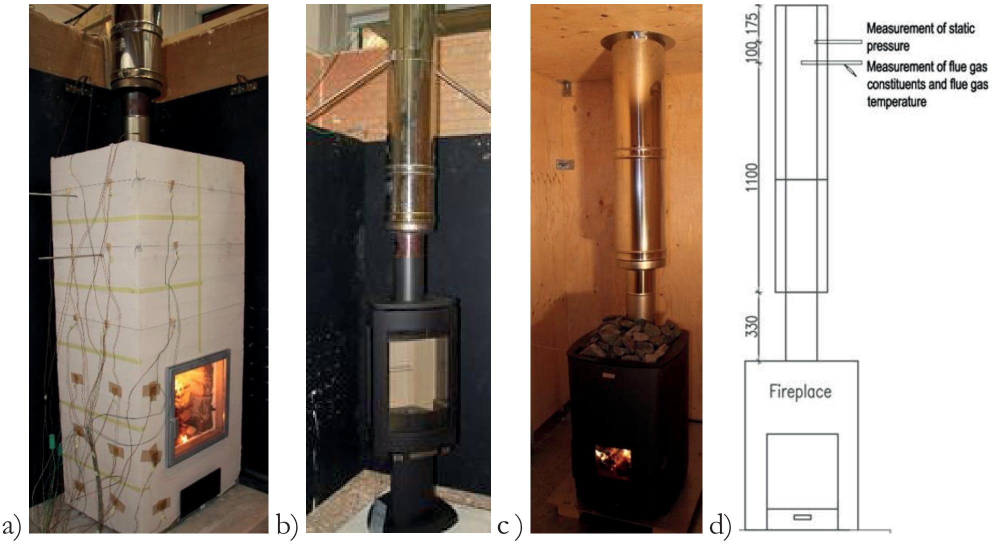


Figure 3.1 Test arrangement of fireplaces: a) Slow heat release appliance, b) Room heater, c) Sauna stove, d) measurements.

Table 3.1 Testing of different fireplace types according EN standards.

Fireplace	Test	Test structure	Wood batches	Draught
Room heater	Nominal heat output test Temperature safety test	Trihedron Trihedron	Standard[1] Standard[2]	12 Pa 15 Pa
Slow heat release appliance	Burning rate performance test[3] Temperature safety test	Trihedron Trihedron	Manufacturer Double batches[4]	12 Pa 15 Pa
Sauna stove	Nominal heat output test Temperature safety test	Sauna test room[5] Sauna test room[6]	Manufacture Maximum	12 Pa 15 Pa

[1] Calculated on the basis of the manufacturer's informed heat output of appliance

[2] Calculated on the basis of the area of the firebox bottom

[3] Corresponds to nominal heat output test

[4] Batches of the same sizes are burned after a burning rate performance test

[5] Maximum manufacturer's informed sauna volume

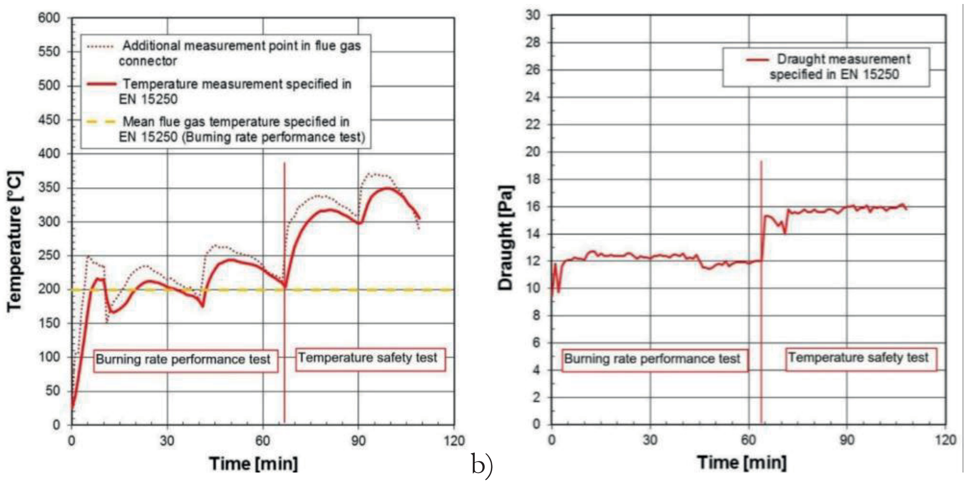
[6] Minimum manufacturer's informed sauna volume

Room heaters

When testing a room heater at nominal heat output, the fireplace is heated according to the instructions specified in the standard. In the temperature safety test of a room heater, wood batches are burned until the surface temperatures of the adjacent wall have stabilised [EN 13240].

Slow heat release appliance

The burning rate performance test of slow heat release appliances according to the EN standard takes place using wood batches specified by the manufacturer. The temperature safety test of a slow heat release appliance uses double batches: new batches of the same sizes are burned after a burning rate performance test [EN 15250] The burning rate performance test and temperature-safety test results of a slow heat release appliance are shown in Figure 3.2 a). Figure 3.2 b) shows the measured flue draught levels in the same tests.



a) b)

Figure 3.2 Typical a) temperature and b) draught measurements from a burning rate performance test and a temperature safety test of a slow heat release appliance. Horizontal dashed line represents the mean temperature recorded in the CE marking [Article I].

Sauna stove

The test of a sauna stove at nominal heat output according to the EN 15821 standard takes place in the sauna test room specified in the standard. The temperature of the sauna test room must reach 90°C using the batches specified by the manufacturer. In the temperature safety test, the temperature of the sauna test room is allowed to stabilise at 60°C, after which draught is increased to 15 Pa (-0 Pa / +2 Pa) and the firebox is filled to the upper edge of its opening. In the test, the temperature of the sauna test room must reach 110°C. If it is not reached, another batch is added.

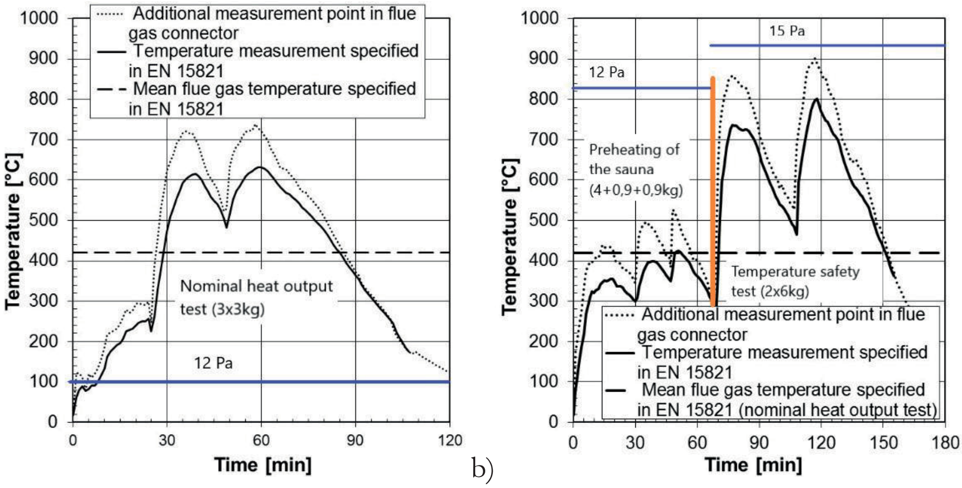
3.2 Laboratory tests on fireplaces

Nominal heat output tests and temperature safety tests described in standards [EN 13240, EN 15250, EN 15821] were performed on a room heater, a slow heat release appliance and a sauna stove [Article I]. In addition, some over loading tests were performed after standard tests on the room heater and the slow heat release appliance. The overloading tests used larger wood batches and higher chimney draught. A bathing test was performed on the sauna stove. In the bathing test, people took a bath in the test sauna during which water was thrown on the sauna stove to produce steam. The purpose of the tests was to evaluate how the way fireplaces are used affects the flue gas temperature.

The highest flue gas temperature in the nominal heat output test for the sauna stove was about 200 °C higher than the average flue gas temperature. This average flue gas temperature is indicated on the CE mark of the appliance. In the temperature safety test, the difference to the declared flue gas temperature was even higher. Flue gas temperature in the sauna stove test is shown in Figures 3.3 a) and 3.3 b). In the bathing test, flue gas temperatures were at the same level as in the temperature safety test. Flue gas temperature in the sauna stove bathing test is shown in Figure 3.4.

In the nominal heat output test on the room heater and the burning rate performance test on the slow heat release appliance, the difference between the average flue gas temperature and the highest flue gas temperature was less than 50°C. In the temperature safety test, the difference to the declared flue gas temperature was about 100°C. Flue gas temperature during the slow heat release appliance tests is shown in Figure 3.5. Flue gas temperature during the room heater tests are shown in Figures 3.6 a) and 3.6 b).

The effect of wood batches and the chimney draught on the temperature of flue gases were measured in a laboratory [Article I]. When wood batches were 1.3 kg larger (3.0kg) and the draught of the chimney was 12 Pa, the highest temperature of flue gases was about 90°C higher than when wood batches were normal (1.7 kg). When the heating was continued with the same size of wood batches (3 kg) and the draught of the chimneys was increased to the value 15 Pa, the highest temperature of flue gases rose and was 160°C higher than in normal use (Figure 3.6 a)).



a)

b)

Figure 3.3 Flue gas temperatures a) in the sauna stove nominal heat output test, b) in the sauna stove temperature safety test.

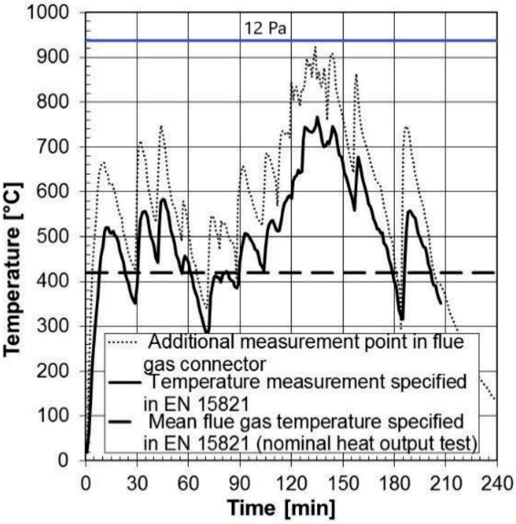


Figure 3.4 Flue gas temperatures in the sauna stove bathing test.

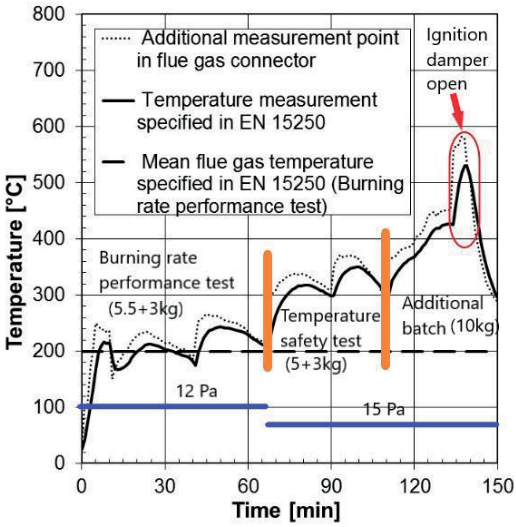
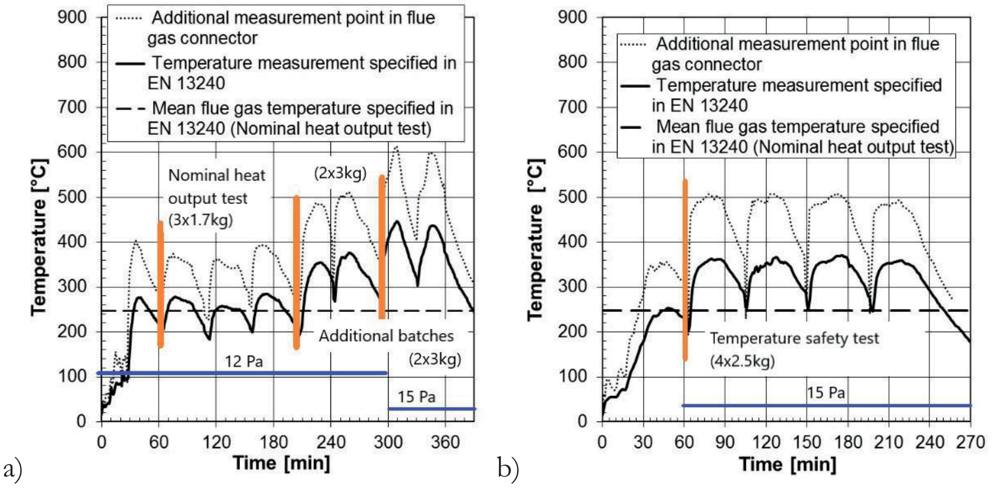


Figure 3.5 Flue gas temperatures in the temperature safety test of the slow heat release appliance and during the additional batch.



a)

b)

Figure 3.6 Flue gas temperatures a) in the room heater nominal heat output test and during the additional batch, b) in the room heater temperature safety test.

3.3 Field tests of fireplaces

The test subjects were room heaters, slow heat release appliances and sauna stoves. The tests aimed to use the fireplaces according to the operating instructions. The fireplaces tested in field experiments are shown in Figure 3.7.

Figure 3.7 The fireplaces tested in field experiments: a) Room heater and site measurement equipment, b) Slow heat release appliance, c) Exterior view of lakeside sauna and sauna stove.

Room heaters

The tests were performed on three similar room heaters [Article II]. The results of the tests were much the same. In the tests, the mean flue gas temperatures were approx. 100°C higher than those indicated in the CE marking. The chimney draught was also higher than in the EN standard tests. In field tests, the chimney draught was on average 30-35 Pa, while in the EN standard tests the chimney draught is 10-17 Pa. The test results for room heater 1 are presented in Figure 3.8. The first graph represents the flue gas temperature and the second is the draught. The solid red line is the data recorded during the test.

Slow heat release appliance

The test was performed on a slow heat release appliance [Article II]. The flue gas temperatures and flue draught of the slow heat release appliance tested are shown in

Figure 3.9. The average flue gas temperature was about 50°C higher than the temperature of the flue gases indicated on the CE marking. The chimney draught was up to 40 Pa when 11 Pa was used for the fireplace testing. The field-measured flue gas temperatures were higher than what had been reported in previous laboratory tests performed by Inha et al [2012] on the same type of appliance. In these tests, flue gas temperatures were measured from the point specified in standard EN 15250 as well as from the flue gas connector. The mean flue gas temperature was only 11°C higher in the connector than that measured from the point specified in standard EN 15250. In Inha's test, the mean temperature measured from the point specified in the standard was 250°C, more than 40°C higher than the flue gas temperature specified in the CE marking. In the field test, the mean flue gas temperature was about 20°C higher still.

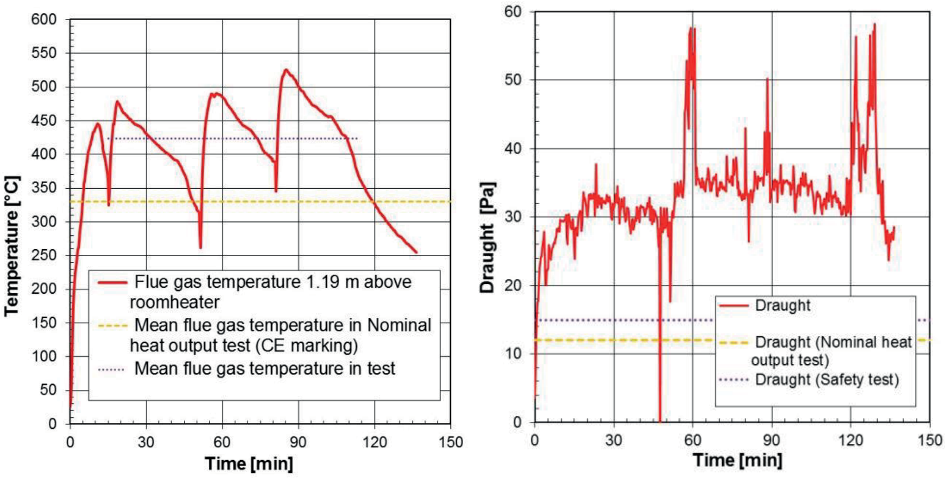


Figure 3.8 Flue gas temperatures and flue draught of test on Room heater 1.

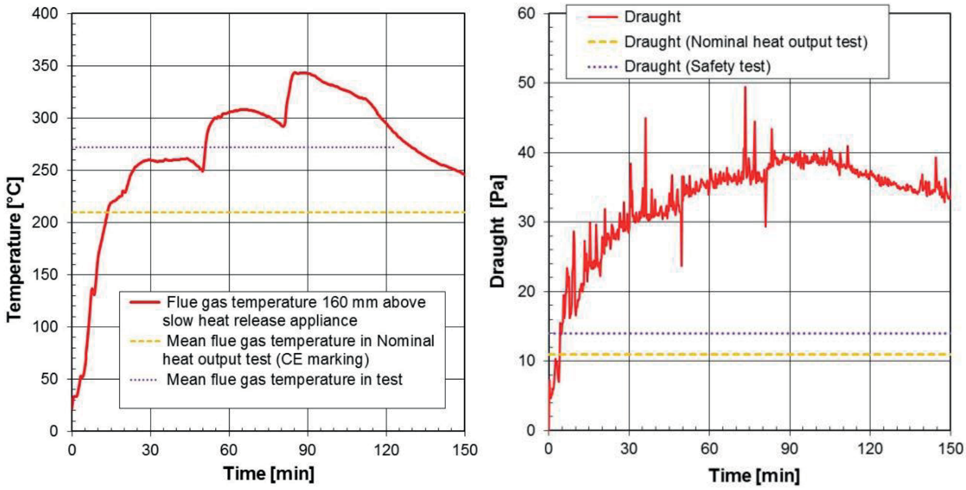


Figure 3.9 Flue gas temperatures and flue draught of test on the slow heat release appliance.

Sauna stove

The sauna stove was tested [Article II] for conditions corresponding to normal use in Finland as the site conditions were very different from those specified in the standard EN 15821. Outdoor air temperature during the test was 0°C, which was also the temperature of the lakeside sauna at the beginning of the test. The sauna stove was first heated so that the temperature of the air in the sauna was 100°C. After that, people bathed in the sauna. The wood batches were about the same size as the additional batch of the nominal heat output test. However, the heating of the sauna causes higher flue gas temperatures than maintaining the temperature. The manufacturer of the sauna stove also gave the highest flue gas temperature of the temperature safety test. The flue gas temperatures of the sauna stove were measured, and the sauna temperatures are presented in Figure 3.10 a), and flue draught in Figure 3.10 b). The mean flue gas temperature measured 1.5 m above the sauna stove was 355°C. The chimney draught was in the same range as the CE test of the fireplace.

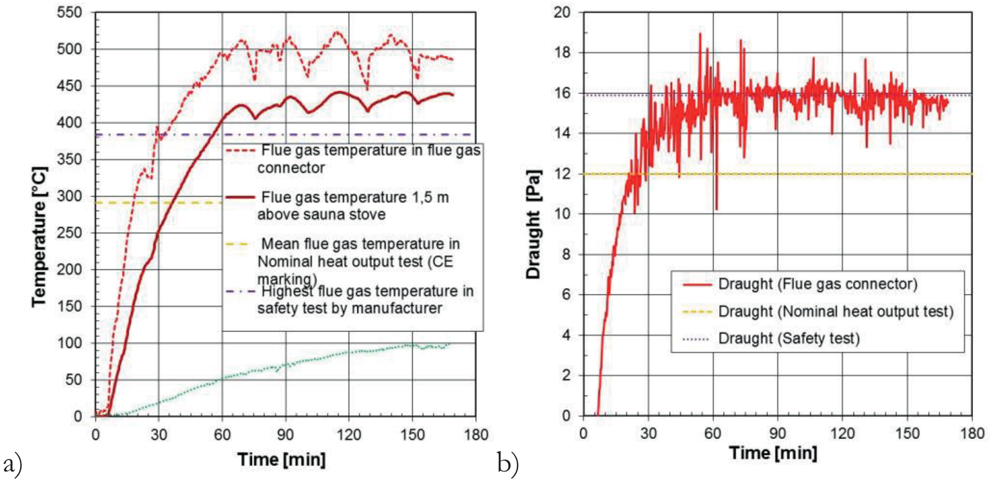


Figure 3.10 a) Flue gas and sauna temperatures b) Chimney draught of the sauna stove test.

3.4 Conclusions

The temperature specified in the CE marking of fireplaces is measured at nominal heat output when the tested fireplace is heated according to the manufacturer's instructions. According to the EN standards, fireplaces must also be subjected to a temperature safety test. The test is made to determine the safety distances of a fireplace, but the standard does not require measuring flue gas temperatures. In laboratory tests, the highest flue gas temperatures of the tested fireplaces measured in the temperature safety test were 124°C to 381°C higher than those given on the CE marking. Overloading raised the highest flue gas temperature by 199°C to 347°C above the flue gas temperature indicated on the CE marking.

In all field tests, flue gas temperatures higher than those specified in the manufacturer’s instructions were measured. The mean flue gas temperatures measured during the room heater and sauna stove tests were approximately 100°C higher than the flue gas temperatures given by the manufacturers in the CE marking of the fireplaces. The highest measured flue gas temperatures were 300°C above the temperatures given in the CE marking. For the slow heat release appliance, the temperature difference was lower. In field tests, the chimney draught was higher than in the CE test of fireplaces, except for the field test on the sauna stove.

4 FIRE SAFETY OF METAL CHIMNEYS AND CHIMNEY PENETRATIONS

The installation method of the chimney and the location of measurement points in the test have an effect on the measured temperatures of adjacent combustible material. The testing of the chimney differs in many ways from how installation is actually carried out in Finland.

Section 4.1 presents EN standard test methods for metal chimneys. Section 4.2 presents laboratory experiments to assess if the EN standard test methods of metal chimneys lead to a fire-safe chimney design. Section 4.3 presents the conclusions of the tests.

4.1 EN standard test methods of metal chimneys

EN standards present 11 temperature classes for chimneys: T80, T100, T120, T140, T160, T200, T250, T300, T400, T450 and T600 [EN 1443]. The number refers to the maximum nominal operating temperature (°C). In the highest temperature classes, T400, T450 and T600, the hot gas temperature used in testing the chimney is 100°C higher than the operating temperature indicated by the temperature class. When choosing a chimney, the temperature class based on chimney tests must be equal or higher than the mean flue gas temperature recorded in the CE marking of the fireplace connected to the chimney.

A metal chimney can be tested as free standing (Figure 4.1 a)) or installed in a corner enclosed (Figure 4.1 b)) or not enclosed (Figure 4.1 c)). In the tests, the chimney is installed upright and a horizontal pipe is connected to it for feeding hot gas. The temperature of the hot gas is measured from the horizontal pipe. The test corner has two floor structures, the first one 1,400 mm above the horizontal pipe. In chimney tests, the temperature of a wood surface is measured at the safety distance from the chimney surface at the floor structures and 300 mm below the upper one [EN 1859] A horizontal section of the test arrangement of chimneys is shown in Figure 4.1 d).

4.1.1 Heat stress test

The thermal resistance of a metal chimney is tested by feeding hot gas into it until equilibrium is reached. Equilibrium is considered to have been reached when the temperature of the test chimney or structure increases by no more than 2°C/30 min. The manufacturer declares that the minimum distance to combustible material and the performance must be demonstrated by tests. The surface temperature of any combustible material at the safety distance from the chimney must not exceed 85°C when the ambient temperature is 20°C. [EN 1856-1, EN 1859]

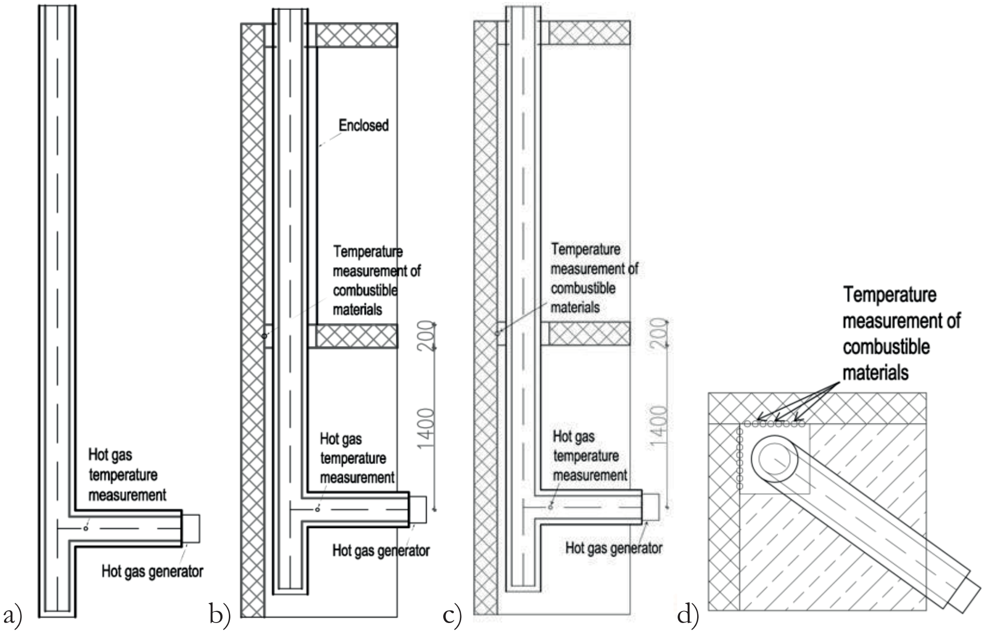


Figure 4.1 Test arrangements of metal chimney a) Free standing, b) Installed in a corner enclosed, c) Installed in a corner not enclosed and d) Chimneys horizontal section.

4.1.2 Thermal shock test

Chimneys designated as soot-fire resistant are also subjected to a thermal shock test. In the test, hot gas temperature must be 1,000°C (20°C/+50°C) for 30 minutes, after which the hot gas generator is turned off. The temperatures of the chimney and the surrounding area are monitored until they reach the maximum value and start to fall. The maximum surface temperature of combustible materials must not exceed 100°C when the ambient temperature is 20°C. If a metal chimney is designed to withstand a soot fire, its thermal resistance is checked by a Heat stress test before and after the thermal shock test [EN 1856-1, EN 1859].

4.2 Laboratory tests on metal chimneys

4.2.1 Hot gas temperatures in metal chimney tests

Tests were performed on two different chimneys [Article III]. The hot gas temperature was measured from the point described in the standard EN 1859 and at the penetration of the chimney. In Figure 4.2, which refers to the heat stress test T600 performed on a 25 mm-thick chimney, the hot gas temperature at the chimney roof penetration was about 150°C lower than that measured at the standard's point [EN 1859]. The effect is still higher in the thermal shock tests. In thermal shock tests, the maximum hot gas temperature at the chimney roof penetration was about 350°C lower than that measured at the standard's point on a 25-mm-thick chimney (Figure 4.3 a)). The difference is smaller by about 150°C when a 65-mm-thick chimney is used (Figure 4.3 b)).

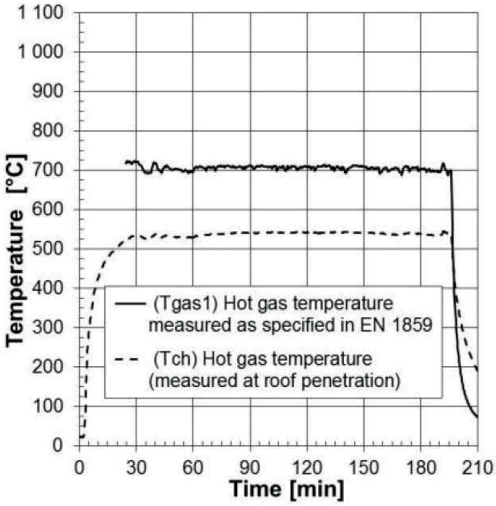
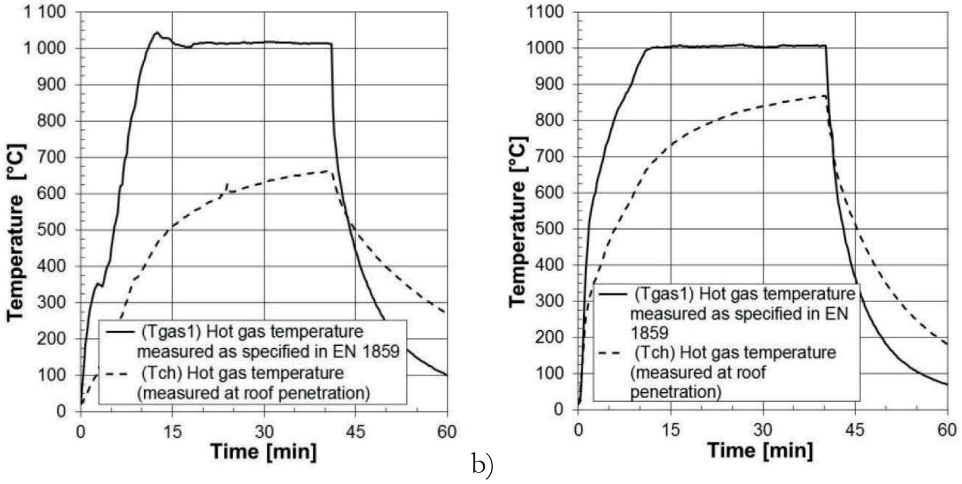


Figure 4.2 Comparison between hot gas temperatures measured according to EN 1859 and in the vicinity of the roof penetration: Heat stress test (T600) performed on a 25-mm-thick chimney.

4.2.2 Chimney test arrangement and temperature measurement point locations

Two heat stress tests were carried out to investigate the influence of the position of the chimney in the roof [Article III]. The first one was performed at the corner as described in EN 1859. The second was made with an axisymmetric test structure. In the first test, the combustible material temperatures were measured from a corner as the standard EN 1859 represents, and from the roof on the vertical surface of the insulation. In the second test, the temperatures were measured from the vertical surface of the insulation. The arrangements for these two tests on metal chimneys are shown in Figure 4.4.

Higher temperatures have been measured on the roof insulation where they can be on average 60°C higher than those measured on the walls (Figure 4.5 a)). The highest temperature was measured on the axisymmetric test structure (Figure 4.5 b)). The difference in temperature was due to the fact that the walls offered higher thermal conductivity than the roof. The thermal conductivity of the roof insulation used in the test was very low (plastic-based insulation material) which accentuated the effect.



a) b)

Figure 4.3 Comparison between hot gas temperatures measured according to EN 1859 and in the vicinity of the roof penetration: a) Thermal shock test performed on a 25-mm-thick chimney and. b) Thermal shock test performed on a 65-mm-thick chimney.

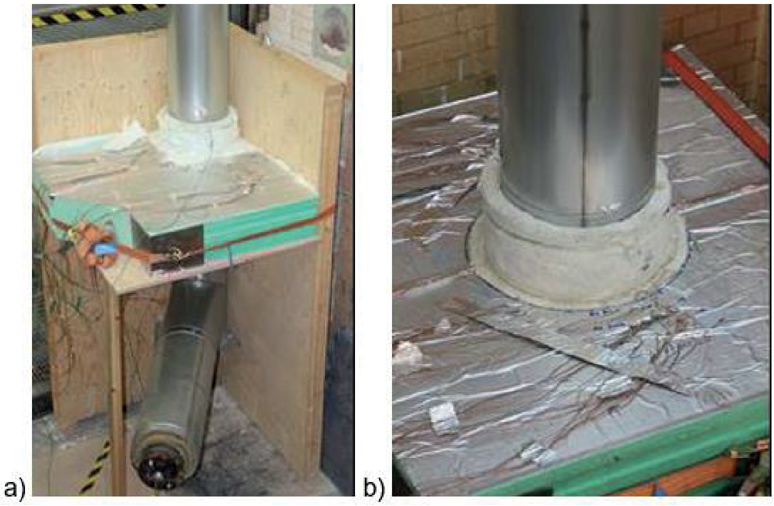


Figure 4.4 Test arrangement of metal chimneys: a) corner installation, b) axial-symmetric installation.

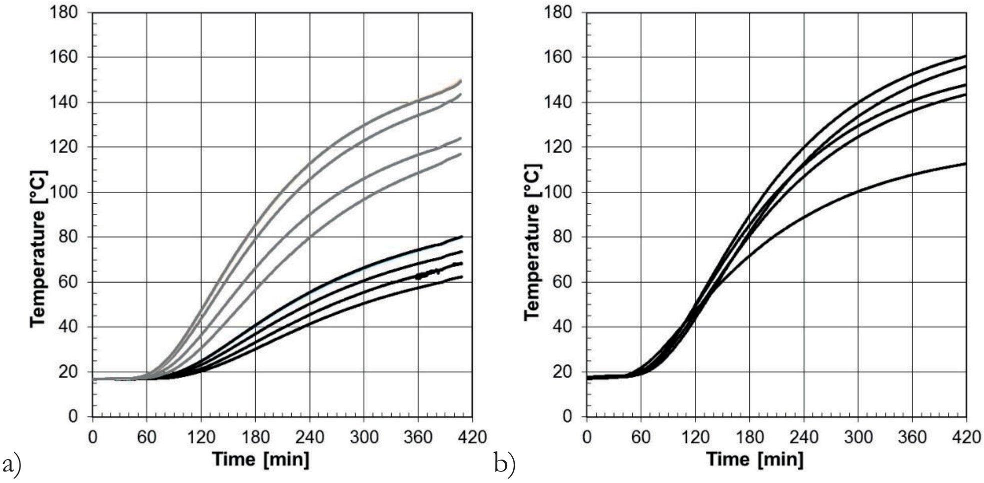


Figure 4.5 Temperatures measured at combustible materials: a) Corner test structure. On surface of wood (black) and on surface of insulation (grey), b) Axial-symmetric test structure.

4.3 Conclusions

In the EN standard tests of metal chimneys, the flue gas temperatures are measured from the horizontal flue pipe near the hot gas generator. This point is located far from the chimney-roof-penetration and the test results show that the flue gas temperature can drop significantly between the standard measurement point and the penetration. In the thermal shock test conducted in this study, the gas temperature in the chimney roof penetration can be about 350°C lower (Figure 4.3 a)) than that at the standard measurement point. In the heat stress test, the difference was found to be about 150°C (Figure 4.2).

The testing position of the chimney in a corner of the roof and near two walls does not represent the worst condition in which a chimney may operate. In real installations, chimneys are usually completely surrounded by a roof that offers lower thermal conductivity than the walls of the test structure. Based on the experiments, the temperature of the combustible material can be up to 80°C higher than at the standard measuring point. In the tests, the roof insulation was of the PIR type. PIR insulation has low thermal conductivity, which leads to a high difference in temperatures. PIR insulation products are used as thermal insulation for roofs in Finland, and the higher temperatures should be taken into account in chimney design.

5 COMBUSTION OF ORGANIC CONTENT OF MINERAL WOOL

Previous research has demonstrated that the smouldering combustion of mineral wool insulation products can increase the temperatures of chimney penetration construction during heater operation [Inha et al. 2011]. However, further information was required considering the level of temperature rise, the effects of insulation thickness on the temperature rise and the distribution of temperature rise over the cross-section of penetration insulation. An experimental study was carried out to answer these questions and to evaluate the effects of the burning of the organic material in mineral wool on the fire safety of a chimney penetration [Article IV].

5.1 Test set-up and programme

An experimental study was carried out to evaluate the effects of the burning of organic material in mineral wool on the fire safety of a chimney penetration [Article IV]. The test samples were 300 mm square and 100 mm thick. The test samples were made of two approximately 50-mm-thick mineral wool boards placed together back to back. The test samples were covered with aluminium foil, except for the side facing away from the furnace, to reduce the airflow inside of them. A foil-covered test sample is shown in Figure 5.1 a). One test series included two separate rounds of heating, the first and the second. During the first round, the organic material in the insulation burns causing additional heat. During the second round, the organic material has already burned and does not have an effect on the temperature variation in the insulation. The second round of heating is thus similar to a situation in which there is no organic material in the insulation. The temperature of the test samples was measured from the surface facing the furnace between the aluminium foil and the mineral wool, as well as from various points at 10 mm intervals through the cross-section all the way to the side facing away from the furnace. The test arrangement and measurement of temperature is shown in Figure 5.1 b). The test samples were installed into a 100-mm-thick support structure placed on the furnace's front opening. The support structure was made of two 50-mm-thick mineral wool boards tied together.

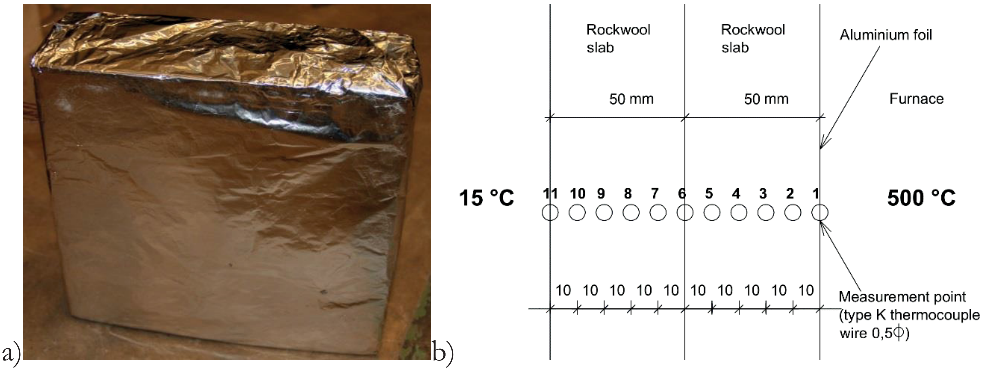
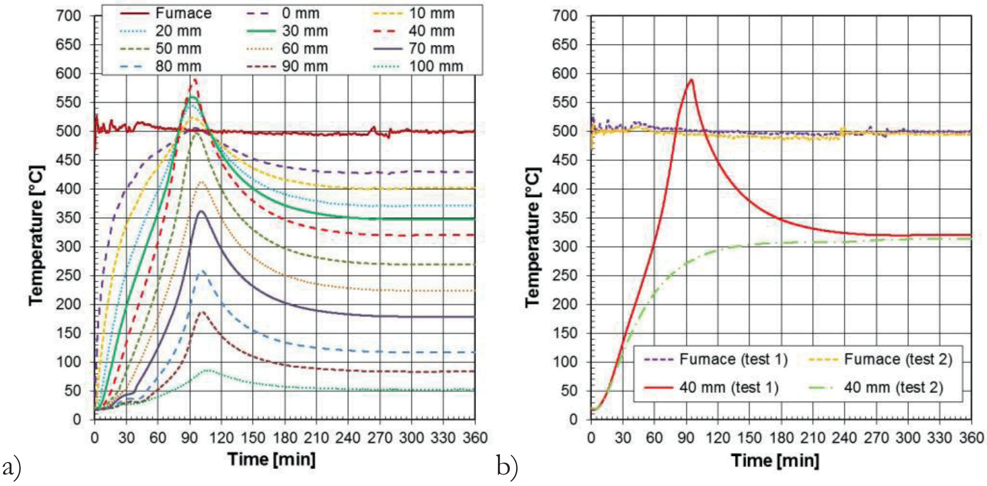


Figure 5.1 a) Test specimen before the tests. b) test arrangement and measurement of temperature. Dimensions in millimetres.

At the start of the first heating, the furnace temperature was raised from room temperature to a target temperature of 500°C. During the heating of the furnace, 50-mm-thick mineral wool slab was used to cover the hole reserved for the test sample. After the furnace temperature had plateaued at 500°C, the hole cover was removed and replaced with the test sample. The test was then continued at 500°C until the temperatures measured from the sample did not change anymore, after which point the furnace was turned off. During the second heating, the test samples from the first round of heating were tested again in a manner similar to the first round. The experiment simulates a situation where there is hot gas inside the chimney and a stone wool as an insulation in the chimney. In typical chimney penetrations, the thicknesses of chimney insulations and penetration insulations vary between vary from 20 mm to 100 mm and from 50 mm to 150 mm. The flue gas temperatures can vary from 200°C to 1,000°C. Based on tests by Inha et al. [2011], temperatures up to 500°C were measured inside the penetration insulation in this kind of penetration construction. This served as input for the test program reported in this thesis.

5.2 Temperature rise due to organic content burning

A temperature graph for the first heating is illustrated in Figure 5.2 a). The graph represents the temperatures on the test sample cross-section at 10 mm intervals, during the first round of heating and with the furnace temperature at 500°C. Additional heat release was clearly noticeable. The highest temperatures were reached for about 90 minutes. After this, they decreased. With this test arrangement, the largest temperature rise generated by the burning of organic material was measured at approximately the centre of the test sample. When moving towards the surface facing away from the furnace, the additional heat was significantly reduced, as there was less burning of the organic material and less heat release due to the lower temperature. No burning of organic material occurred near the outer surface of the test sample, and the additional heat could be transferred from the centre to the surrounding area through the surface. Also, convection affects the temperatures on the side facing away from the furnace. This outcome differs from a chimney penetration, as the penetration insulation faces the thermal insulation within the roof. This observation means that the additional heat is not able to cool down in the same way as during the furnace test. Figure 5.2 b) illustrates the temperature graph for the first and second rounds of heating measured at a distance of 40 mm from the surface facing the furnace. The heat release generated by the burning of organic material was evident during the first round, but the second heating of the same test sample did not create any heat release. When comparing the result from the first and second rounds of heating, the temperature rise generated by the burning of organic material is visible. The maximum difference in temperature was measured at 90 min and was over 270°C. [Article IV].



a)

b)

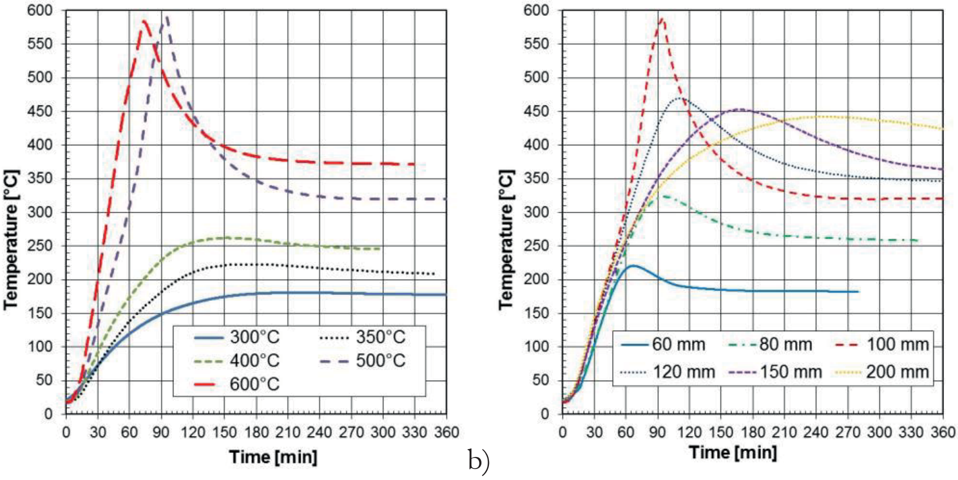
Figure 5.2 a) The charring of the binder of mineral wool causes a momentary temperature rise inside the mineral wool. b) Differences in the temperatures observed within the specimen 40 mm from the furnace between the first and second test when the temperature of the furnace was 500°C.

The test results show that the temperature rise generated by the burning of organic material may increase the temperatures of penetration structures up to the ignition threshold of these materials.

5.3 Effect of test temperature and test specimen thickness

Also, the test temperature and the thickness of the test specimen may influence the smouldering combustion of mineral wool insulation. This was studied in two test series [Article IV]. In the first test series, tests were performed on different furnace temperatures (300°C, 350°C, 400°C, 500°C and 600°C). Specimen thickness was 100 mm in the tests. In the second test series, the tests were performed on different thicknesses of mineral wool layers (60 mm, 80 mm, 100 mm, 120 mm, 150 mm and 200 mm). During the tests, the temperature of the furnace was 500°C.

The temperatures within the specimens 40 mm from the furnace during different tests are shown in Figure 5.3. It can be concluded that the heat release is not very high at furnace temperatures below 400°C. The organic material starts to evaporate when the temperature reaches 250°C. The test results of Figure 5.2a) show that the insulation temperatures reach 250°C at a distance of 80 mm from the furnace at a test temperature of 500°C. At test temperatures of 400°C and 350°C, a temperature of 250°C is achieved at distances of 40 mm and 20 mm, respectively. At a test temperature of 300°C, a temperature of 250°C is reached only at the measuring point on the furnace side.

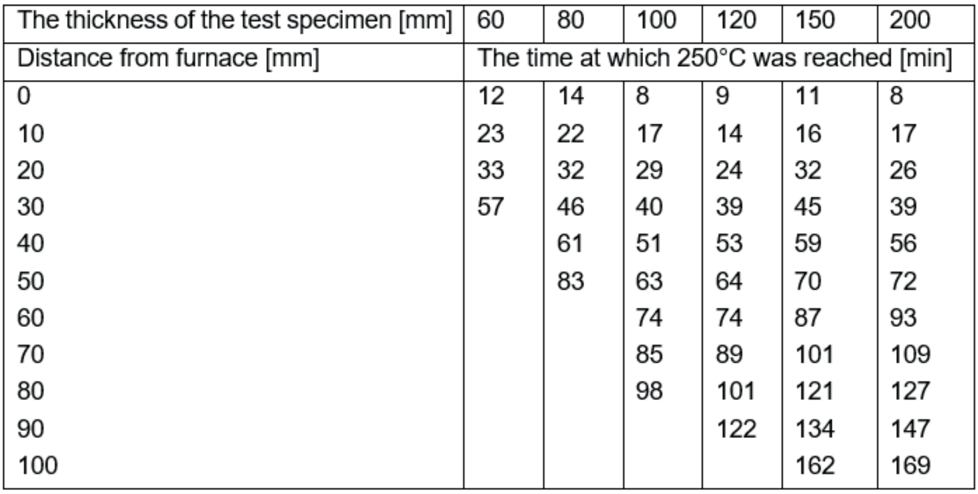


a) b)

Figure 5.3 Temperatures in mineral wool measured 40 mm from the furnace. a) Furnace temperature was 300°C to 600°C and specimen thickness was 100 mm, b) Specimen thickness was 60 mm to 200 mm and furnace temperature 500°C.

As shown in Figure 5.3b), the maximum temperature rise is achieved when the thickness of the mineral wool specimen is 100 mm. With a thickness less than 100mm, the amount of heat required for combustion does not accumulate in the mineral wool and a temperature of 250-300°C is not achieved in such a large part of the test specimen. The results also show that the temperature rise starts to decrease when the thickness of the specimen is increased from 100 mm and the temperature peak becomes gentler. Peak temperatures are also later achieved on thicker specimens. It looks as if the organic content burns more slowly in thicker mineral wool layers. One possible explanation is that the temperature required for combustion is reached more slowly on thicker specimens. The times at which 250°C was reached at different measuring points are shown in Table 5.1. The differences in the measuring points near the furnace are small, but at points farther from the furnace the temperature of 250°C is reached more slowly in the thicker test specimens. However, this does not explain the slower heat peak, but is rather a result of it. A second possible explanation for the phenomenon is the differences in the supply of oxygen for combustion. The fact that the amount of air required for combustion does not effectively penetrate the thicker insulator layer is probably an explanation here. In the test arrangement, the test specimens were covered with aluminium foil, except for the opposite surface of the furnace. In this case, the distance travelled by the combustion air through the test specimen increases as the thickness of the test specimen increases. Also, gases released from the combustion reaction may have an effect on the phenomenon and further research is needed on the subject.

Table 5.1 The time at which 250°C was reached at different measuring points.



The thickness of the test specimen [mm]	60	80	100	120	150	200
Distance from furnace [mm]	The time at which 250°C was reached [min]					
0	12	14	8	9	11	8
10	23	22	17	14	16	17
20	33	32	29	24	32	26
30	57	46	40	39	45	39
40		61	51	53	59	56
50		83	63	64	70	72
60			74	74	87	93
70			85	89	101	109
80			98	101	121	127
90				122	134	147
100					162	169

5.4 Conclusions

The temperature by the chimney roof penetration is affected by the possible smouldering combustion of the organic content of surrounding mineral wool. The test results show that the smouldering combustion of the organic content in typical chimney penetration insulation products generates heat, and can increase the temperature in chimney penetration materials by hundreds of degrees for a limited period of time. The highest temperature rise was achieved when the temperature of the furnace was 500°C and the thickness of the test structure was 100 mm. Such conditions are possible in the penetrations of metal chimneys, as the flue gas temperatures of the fireplaces vary between 200 and 1,000°C and the thicknesses of penetration insulations vary between 50 and 150 mm. This additional heat may briefly increase the temperature in the chimney penetration by over 200°C.

6 DISCUSSION: MAIN FACTORS AFFECTING THE FIRE SAFETY OF CHIMNEYS

There are many factors affecting the fire safety of metal chimneys: the actual use of fireplaces, actual conditions, and apparent flaws in fire safety standards concerning differences between the testing of the chimneys and the fireplaces, between the chimney testing and actual installations and the possible combustion of the organic content of the adjacent mineral wool insulation.

6.1 Flue gas temperatures

The determination of the design flue gas temperature of fireplaces is problematic with all fireplace types tested according to EN standards [e.g. EN 13240]. Higher temperatures were measured in the temperature safety tests than in the nominal heat output tests [Article I]. The flue gas temperature of the fireplace, based on the optimal use of the fireplace and on exact conditions, is used for the designing of the chimney. Whether the given flue gas temperature is safe to use for the designing of the chimney depends on the real temperatures of flue gases. In turn, the real temperatures of flue gases depend on real site conditions and on the actual use of the fireplace. For chimney design, the temperature of the flue gases in the fireplaces is given as the average temperature measured during the EN standard test. The highest temperatures have not been used because their variation is higher. In addition, the importance of peak temperatures is small because the chimney insulation acts as a buffer that "smooths out" the temperatures. It is therefore better to compare the average flue gas temperatures of the experiments. However, peak temperatures can have an impact on the durability of the chimney materials.

The temperatures and draught levels measured in the field tests were higher than those measured in the EN standard tests. The effect of the actual site conditions on the flue gas temperature of the fireplace was about 100°C. The main reason for the higher flue gas temperatures in field tests is assumed to be the flue draught, which was stronger than in the standard nominal heat output test. As a consequence of the stronger draught, wood batches had to be fed more often than in the standard nominal heat output test which in turn raised the flue gas temperature. In addition, the locations of the temperature measurement points of all the three field tests were closer to the fireplace than the measurement point specified in the standard. Closer to the fireplace, higher values are obtained for both flue gas temperature and chimney draught. The field test temperature and draught values were higher even though the difference between the measurement points was taken into account in the analysis of the results. The effect of the measurement point location is estimated in the Article II. All field tests were executed in normal summer conditions. It should be noted that, in more severe conditions such as winter, the chimney draught and the temperature of flue gases can be higher. In a test the flue gas temperature increased by approximately 50°C when the flue draught was 8 Pa higher than in the standard test [Article II]. Excessive draught can be restricted with a chimney-draught limiter. The problem is that the value of an excessive draught is not known.

6.1.1 Actual use of fireplaces

The way fireplaces are used has a considerable impact on their flue gas temperatures. As fireplaces are often considered simple and easy-to-operate appliances, users often do not read the manufacturer’s instructions or follow them accurately. It is difficult to notice excessively high flue gas temperatures to prevent the user from overheating the fireplace. With more intense heating, the highest temperatures can be hundreds of degrees above the flue gas temperature indicated on the CE marking of the fireplace [Article I]. It is very hard to estimate the size of wood batch without weighing, but in the study a double wood batch was used to demonstrate the effects of overloading on temperatures. The larger batch raised the highest temperature of flue gases by more than 100°C [Article II]. A normal wood batch and one twice the size are shown in Figure 6.1. The double batch considerably increased the flue gas temperature, causing a potential fire risk if the chimney attached to this fireplace is not designed for the higher temperature level.

One solution to avoid overloading is to design the firebox such that there is no room for an oversized batch. In this case, the fireplace would not be overloaded even if the firebox was completely filled and the solution provides sufficient space above the firewood for an effective burning process. However, many sauna stoves on the market have a firebox twice as big as the maximum wood batch given in the manufacturer’s instructions, so a potential risk exists of flue gas temperatures exceeding the temperatures used in the chimney design.

Figure 6.1 a) Normal wood batch (1.4 kg). b) A wood batch twice as large (2.8 kg).

Ignition dampers are used in slow heat release appliances where the flue gas channels inside the appliance are long and it is difficult to provide sufficient flue draught for ignition. A shorter access is therefore provided for the flue gases from the firebox into the chimney through a damper temporarily open during the ignition. Inha et al [2011] performed two tests using a slow heat release appliance with an ignition damper. The measured flue gas temperatures were 120°C higher when the ignition damper was left open. In normal use, the damper is open during the ignition and closed when the fire has well ignited.

6.1.2 Flue gas temperature for the designing of a chimney

The tests for fireplaces conducted in this research show that the flue gas temperature can be hundreds of degrees higher than temperature given in the CE marking of fireplaces. Therefore, the mean flue gas temperature of the nominal heat output test can be too low for the design of chimneys. Site conditions and the way fireplaces are operated also have an impact on flue gas temperatures. In addition, the draught of the chimney can be much higher than in the tests of fireplaces. A higher draught raises the temperature of flue gases.

In this study, a very limited number of fireplaces were tested, so it was not possible to design a completely new test. It would also have been difficult and time-consuming to get new testing methods into the standards. The temperature safety test for fireplaces is designed to emulate the continuous intense heating of a fireplace, so it would be natural also to use the same conditions and results for chimney design. In Article I, it was proposed that the highest temperature of the temperature safety test be used. The justification for the maximum temperature is that, even if more conservative than the mean temperature, the solution provides some level of safety margin. Also, the tests carried out in real use and actual site conditions (see Article II) demonstrate that the conditions can vary a lot and a safety margin is needed. The current method of determining flue gas temperature is shown in Figure 6.2 a) and the proposed new method of determining flue gas temperature is shown in Figure 6.2 b). In this example, the proposed new method would raise the design temperature by approximately 125°C. This in turn would lead to chimney class T400 instead of T300.

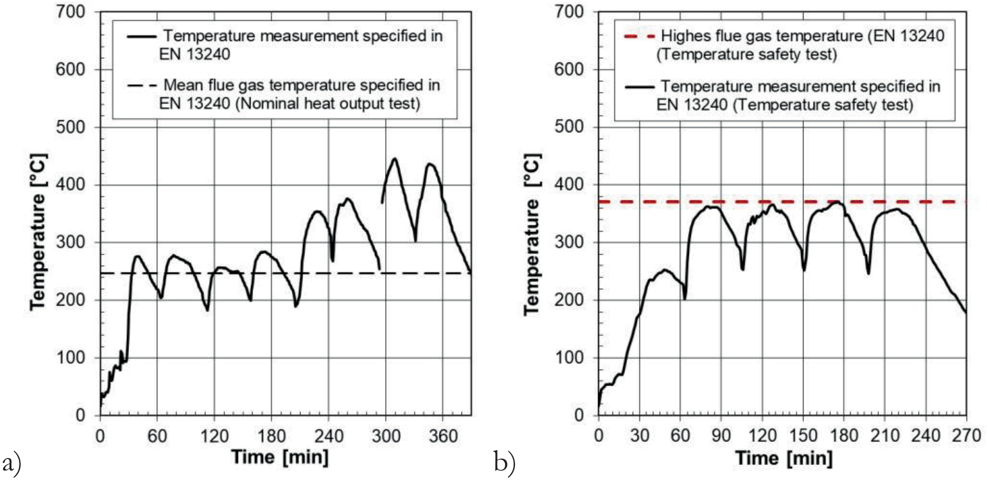


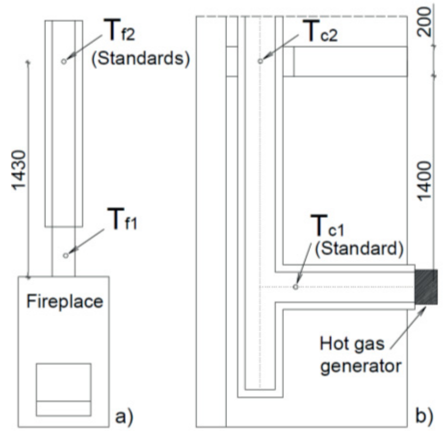
Figure 6.2 a) Flue gas temperatures in the nominal heat output test of the room heater and during the additional batch. Horizontal dashed line represents the mean temperature recorded in the CE marking. b) Flue gas temperatures in the temperature safety test of the room heater. Horizontal dashed line represents the proposed flue gas temperature to chimney design.

6.2 Chimney penetration

The analysis focuses on the influence of the position of the chimney in the roof and on the effect of the hot gas measurement point on the basis of data obtained by the experimental tests.

6.2.1 Hot gas temperature measurement point

EN standard tests for fireplaces and chimneys measure flue gas temperature at different locations. The flue gas temperature of the fireplaces is determined according to the standards at 1.43 m from the top of the fireplace (see T_{f2} in Figure 6.3a). The flue gas temperature cools down in the chimney, so closer to the fireplace the flue gas temperature is higher than the flue gas temperature measured at the standard point. The chimney penetration through the roof can be closer to the fireplace than the standard measuring point. For chimney testing, the gas measuring point is located in the horizontal flue pipe 1.4 m below the chimney penetration, refer to T_{c1} in Figure 6.3b). Also, in the chimney testing the hot gas cools down. The flue gas temperature T_{c1} used in chimney testing is 100°C higher than the required chimney temperature class based on temperature measurements T_{f2}. This 100°C difference does not necessarily cover the cooling of the flue gas between measuring points at T_{c1} and T_{c2} in Figure 6.3b). It would not be necessary to consider the cooling of the gas temperature if the measuring points were the same in both tests.



Fireplace/ Chimney	Test	T_{f1}/T_{c1} [C°]	T_{f2}/T_{c2} [°C]
Room heater	Nominal heat output test	333	247
	Temperature safety test	449	330
Sauna stove	Nominal heat output test	479	420
	Temperature safety test	694	616
Slow heat release appliance	Burning rate performance test	219	199
	Temperature safety test	334	311
Metal chimney 1 (25mm-thick)	Heat stress test (T600)	705	538
	Thermal shock test	1016	591
Metal chimney 2 (65mm-thick)	Thermal shock test	1005	800

Figure 6.3 Gas temperature measurement points used in the experiments on a) fireplaces and b) chimneys and a table showing the average temperatures determined in different experiments. T_{f2} and T_{c1} refer to the flue gas temperatures monitored in the EN standard tests for fireplaces and chimneys, respectively.

Gas temperature measurement points used in the experiments on fireplaces and chimneys and average temperatures determined in the different experiments of this study are shown in Figure 6.3. Although the chimney is tested at a temperature of 700°C (T_{c1}), the actual gas temperature in the penetration can be significantly lower 538°C (T_{c2}) as can be seen in Figure 6.3. This means that the chimney and chimney penetration are tested at a lower gas temperature than the fireplace produces. The situation is even worse in a soot fire situation. According to Peacock tests [1986], the peak temperature of a soot fire can be over 1,200°C, but the typical peak temperature range is 800°C to 1,000°C. The burning can occur at the chimney penetration, but in the chimney testing the gas temperature at the penetration is not known. Although the chimney is tested at a temperature of 1,000°C, the actual gas temperature in the penetration can be only 591°C as shown in Figure 6.3. The difference in temperature measured according to the standard EN 1859 and that measured in the vicinity of the chimney roof penetration depends on the chimney characteristics. Based on the above analysis, the hot gas temperatures in the EN 1859 test should be measured as near as possible to the chimney roof penetration to correctly determine the temperature of the soot fires.

6.2.2 Test set-up

The position of the chimney in the EN standard test structure does not represent the worst condition in which a chimney may operate. In real installations, chimneys are usually completely surrounded by a roof that offers lower thermal diffusivity than the walls of the test structure. By comparing the temperatures estimated for the corner test structure and those for the axisymmetric test structure, the highest temperature has been obtained for the latter scenario. This is due to the fact that a chimney completely surrounded by an insulating layer is in a more critical condition than that in the test structure where heat can find an easier way out through the timber wall construction. The highest temperatures measured in a chimney test in the middle of the chimney penetration are shown in Figure 6.4. As measured from standard points, the temperature is below 85°C and the test is approved. However, when measured from the floor insulation side, the temperature is almost 70°C higher. The highest temperature measured from an axisymmetric test structure and installation was 160°C [Article III]. Based on these results, the chimney should be installed at the centre of the test roof, and test temperature measurement should be placed in the insulation material, not in the timber wall structure.

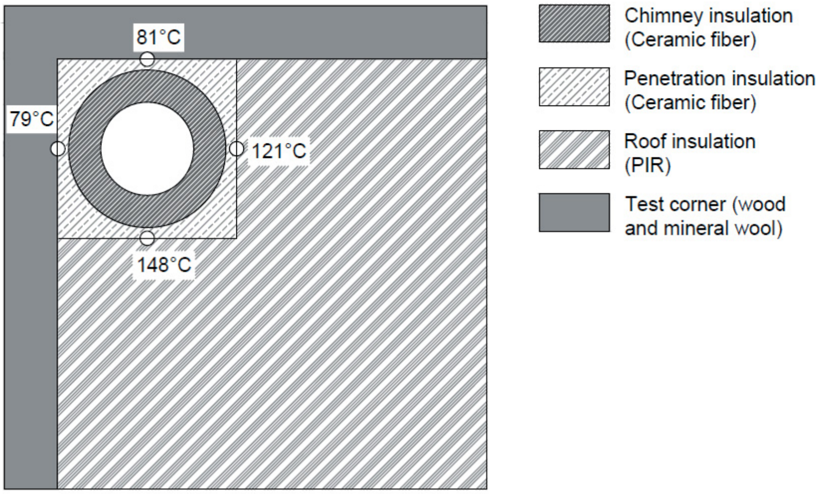


Figure 6.4 Highest temperatures measured in the chimney test in the middle of the chimney penetration.

6.2.3 Effects of different factors on the temperature in the penetration

There are several factors that can increase the temperatures in the chimney penetration. The effects of various factors are studied and analysed in Article III, Article IV and Inha et al. [2011]. The main results are summarised in Table 6.1 [Leppänen et al. 2017]. It can be seen from the results that increasing the penetration temperatures to the level of the ignition temperature typically requires the simultaneous action of several factors. The exception is the thickening of the roof insulation layer. In addition, moderately long use of fireplaces or the burning of soot fires is typically needed. However, light metal chimneys are more sensitive to temperatures higher than the tested ones because they have less heat-retaining mass than masonry chimneys.

Table 6.1 Effect of various factors on the temperature in a chimney penetration.

Changes in temperature and structure	Increase in temperature of penetration structure
The actual flue gas temperature is 150°C higher [Article III]	50-70°C
Thickness of roof insulation increased from 200 mm to 600 mm [Inha 2011]	150°C
Corner installation changed to axisymmetric [Article III]	up to 80°C
Smouldering combustion of organic content of mineral wool [Inha 2011, Article IV]	up to 100°C

The effects of higher flue gas temperatures on the combustible materials of the penetration construction are analysed in detail in Article III in two different chimneys. The effects are highly dependent on the chimney construction and on the penetration insulation. The effect of the insulation thickness on the temperatures of combustible materials is based on tests performed by Inha et al. [2011]. In these tests, the flue gas temperature used was higher than in the standard EN 1859 testing. The higher gas temperature increases the difference in temperatures. The effect of the smouldering combustion is estimated at up to 100°C. However, the effect can be higher based on the tests of Article IV and chimney tests by Inha et al. [2011] where the temperature difference between two consecutive tests was as high as 276°C and 170°C, respectively.

6.2.4 Temperature limits defined by adjacent structures and materials

The standard chimney test method of EN 1859 limits the maximum temperatures of structures adjacent to the chimney to 85°C. Exposure to high temperatures at the chimney penetrations is usually short-term (some minutes to a few hours). Under short-term exposure, the 85°C temperature limit would seem to apply to wood and wood-based materials. Matson et al [1959] made a comprehensive study of wood ignition temperatures including tests on different wood species. They presented a compilation of experimental tests where ignition temperatures were around 200°C or higher, but under long-term exposure the ignition temperatures were lower. After 20 hours of exposure, lower ignition temperatures can be as low as 120°C [Kordina et al. 1983.] In some instances, the exposure times to chimneys and chimney penetration structures may be quite long, especially when the chimney passes through efficient thermal insulation.

According to the specifications of different plastic insulation materials, the flash ignition temperatures of these materials are 300°C to 500°C [McGee 2006]. The main problem with plastic-based insulation materials is their softening and dimensional instability at relatively low temperatures. EPS and XPS insulations, in particular, may have defective deformations already before the 85°C temperature limit specified in standard EN 1856 1 for normal operating conditions is achieved [Malaska et al. 2017]. In addition, the thermal diffusivity of PUR and PIR insulation materials are lower than the thermal diffusivity of the mineral wool used in chimney tests. This further raises temperatures near the penetration.

6.3 How to improve the chimney EN test method to suit Finnish conditions

6.3.1 Installation of chimneys in Finland

A Finnish house, for instance, normally has an insulated ceiling below a ridge roof. The second possibility is for the insulation layer to follow the shape of the roof. In chimney test standard [EN 1859], the insulation thickness of the floors is 200 mm. The insulation thicknesses in real structures vary considerably in Europe. In Finland, it is nowadays typical to use insulating layers over 400 mm and even 600 mm thick. The test arrangements for metal chimneys and the most typical actual installation examples of metal chimneys in Finland are shown in Figure 6.5. According to the standard [EN 1859], the clearance can be made without insulation material. In Finland, there is always insulation material in the clearance for thermal insulation reasons.

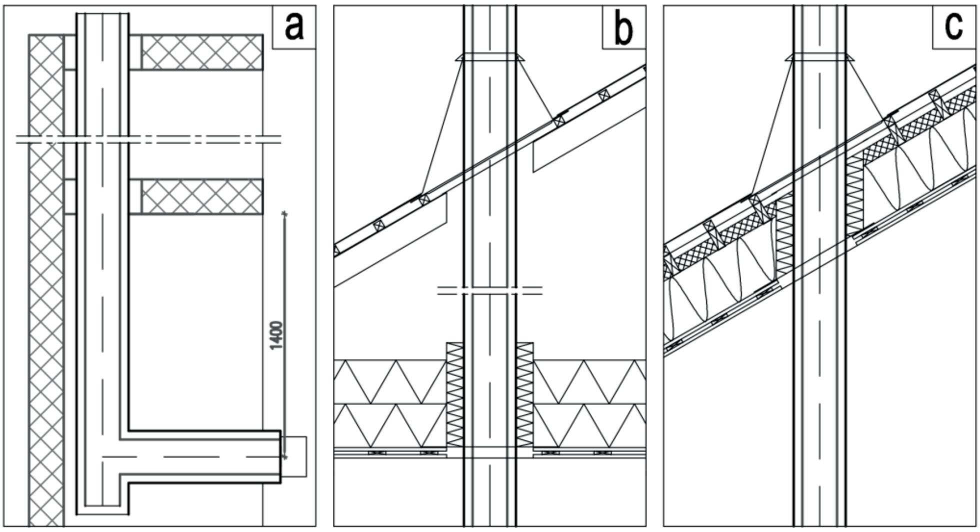


Figure 6.5 a) Test arrangement of metal chimneys. b) Installation example: Thermally-insulated ceiling and uninsulated roof. c) Installation example: Thermally-insulated roof.

6.3.2 New test arrangement

Metal chimneys are tested according to standard EN 1859. Based on this study, a few improvements to the test arrangement of chimneys can be proposed. The proposed test arrangement is more in line with the actual conditions in Finland. Hot gas temperature should be measured in the penetration. Thicker roof insulations are taken into consideration (this is being added to the test standard of chimneys [prEN 13216-1:2016]). The chimney should be installed at the centre of the roof in the test structure and no open clearance should be used between the chimney and insulation. The temperature of combustible material by the penetration should be measured in the insulation material and not at the corner on the surface of the timber wall structure. The current test arrangement and new proposed test arrangement are shown in Figure 6.6. The proposed changes concern the test structure and the location of the measurement points. The results of this study did not indicate needs for changes in details of the standard test method such as gas temperatures, tests durations or temperature limits.

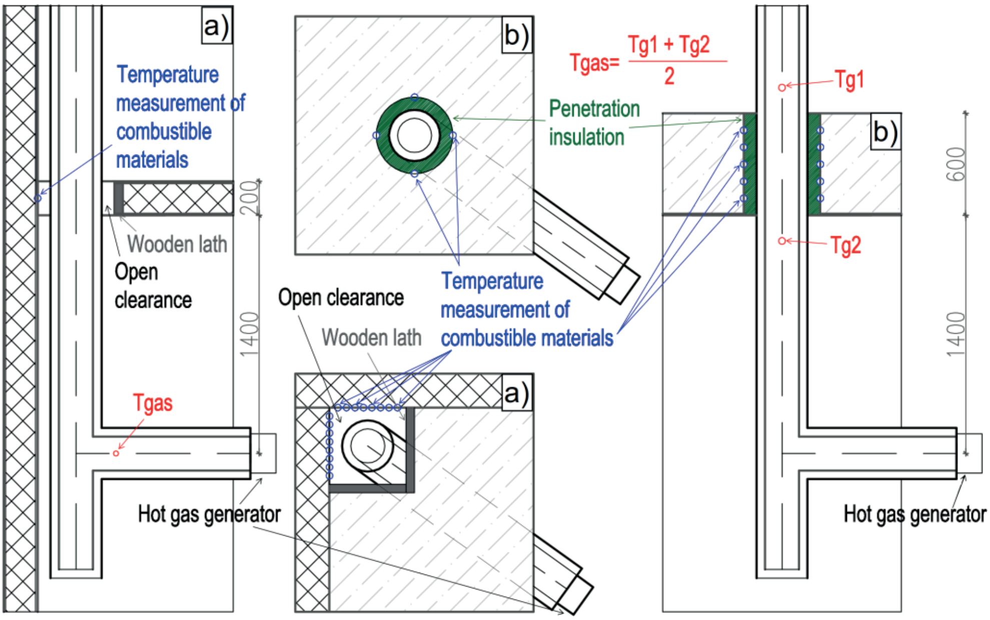


Figure 6.6 a) Current standard test arrangement of metal chimneys (EN 1859) and b) New proposed test arrangement.

6.4 Requirements for penetration insulation

Temperatures in a chimney penetration can be affected by the smouldering combustion of mineral wool's organic content. There have been recent fires where the chimney penetration has caught fire during the first heating of a new chimney. Many factors affect the fire, and smouldering combustion is not the only one. It is, however, a highly potential fire risk. Once the mineral wool binder has burnt, it will no longer produce heat. The problem cannot be avoided by heating the fireplace less during the first few times. At lower temperatures, organic matter combustion may not occur, but when the fireplace is then heated more intensively at a later stage, the organic content burns and releases the additional heat. At the roof penetration, even a small rise in temperature can cause ignition if the temperature is already near the ignition temperature due to, for example, the other potential reasons listed in Table 6.1, so the burning of the binder should be limited at the chimney penetration.

In EN standard tests on chimneys [EN 1859], the temperature is not measured in the penetration insulation. In the tests, only the temperature of gas and combustible material is measured, so the temperature in the mineral wool is not known. It is therefore not known how close the ignition temperature is to the chimney test situation, but the best way to prevent the problem is to restrict the insulation materials to be used in the chimneys and near the penetrations of chimneys. A small amount of organic matter may be acceptable, but more research is needed to define a safe limit value. Additional heat should be determined at different amount of organic content. Based on this, a safe limit amount of organic content could be defined.

7 CONCLUSIONS

Laboratory tests and field experiments have been carried out on fireplaces. The tests show that the use of current EN standards for fireplaces does not always lead to fire-safe chimney design. The mean flue gas temperature of the nominal heat output test is too low to present the actual flue gas temperatures in residential homes in Finland.

In this thesis, the influence of several factors on the fire safety of metal chimneys has been investigated experimentally. The study highlighted the differences between the conditions in real installations and those in the thermal performance test prescribed by standard EN 1859. Research showed that the temperatures measured in the tests performed according to the standard EN 1859 can be lower than the maximum temperature that may occur in real installations.

Laboratory tests have also been carried out on penetration insulation products made of mineral wool to investigate their performance when exposed to high temperature levels. The test results showed that the temperatures in the chimney penetration area can be significantly affected by the possible smouldering combustion of the organic material in mineral wool. Due to the additional heat release from smouldering, the ignition temperatures of combustible roof construction materials located adjacent to chimney penetration may be exceeded during normal fireplace operation. The temperatures can increase by over 100°C for a limited period of time.

7.1 Flue gas temperatures

Based on the results of this study, it can be concluded that the EN standard test conditions for fireplaces do not represent the actual site conditions and the real fireplace operation adequately. In some field tests, the flue gas temperatures and chimney draught levels significantly exceeded those of the standard laboratory tests. The mean flue gas temperatures measured during the room heater and sauna stove tests were approximately 100°C higher than the flue gas temperatures given by the manufacturers in the CE marking of the fireplaces.

Chimney design is currently based on the mean flue gas temperature of the nominal heat output test given in the CE marking of a fireplace. The temperature safety test is designed to emulate the continuous intense heating of a fireplace and the results of this study show that it reflects better the actual conditions and temperatures. However, the current test standard does not require the flue gas temperatures to be monitored during the temperature safety test. In the laboratory tests, the highest flue gas temperatures of the tested fireplaces measured in the temperature safety test were 124°C to 381°C higher than those given on the CE marking. In order to provide adequate fire safety margin, it is proposed that flue gas temperatures also be monitored in temperature safety tests and that the chimney design temperature be selected based on this data.

In the nominal heat output test of fireplaces, the flue draught is set to 12 Pa. In the temperature safety test, the draught of the chimney is increased to 15-17 Pa. In the field tests, draught levels as high as 30-40 Pa were measured in normal operation, which significantly exceed the level used in standard tests. The higher draught of the chimney raises the temperature of flue gases.

The exact recommended wood batch sizes are not normally used when heating a fireplace nor is draught control necessarily done properly. Both these faulty operations can increase the flue gas temperature by more than 100°C. If the possibility of misuse is ignored in the chimney and chimney penetration design, the design may lead to a lower temperature class than a fire-safe construction would require. This creates a potential fire risk.

In this study, it was not possible to design a completely new test method, but the temperature safety test for fireplaces is designed to simulate continuous intense heating of a fireplace, so it would be natural also to use the same condition and results in chimney design. Currently chimney design is, however, based on the results of the nominal heat output test, which is assumed to simulate the normal operation of a fireplace where flue gas temperatures appear to be lower than in the temperature safety test. Based on laboratory and field experiments [Articles I and II], the flue gas temperature may be higher in actual use than flue gas temperatures in the temperature safety test, so the average temperature of the flue gases in the temperature safety test is not sufficient for chimney design. Instead, the highest temperature of the temperature safety test, for example, must be used to achieve an adequate level of safety.

7.2 Chimney penetration

7.2.1 Hot gas temperature measurement point

The flue gas temperature of the fireplace is measured at the height of the possible chimney penetration, but in chimney testing, the hot gas temperature is measured 1.4 m below the chimney penetration. For chimney testing, hot gas can drop over 150°C between the standard measurement point and the chimney penetration, so the chimney may be tested at too low a flue gas temperature. The highest risk is in the chimney thermal shock test as, in a soot fire, burning can occur just at the chimney penetration. The test results show that the flue gas temperature at the roof penetration may be 350°C lower than the test temperature, so the hot gas temperature measurement point should be situated in the roof penetration.

7.2.2 Test set-up of chimneys

The study highlighted the differences between the conditions in real installations and those in the thermal performance test prescribed by the standard EN 1859 for the certification of metal chimneys. The experimental results show that the surface temperatures to EN 1859 in the test structure do not represent the maximum temperatures that may occur in real chimney installations.

The position of the chimney in the test structure, in a corner of the roof and near two walls, does not represent the worst condition in which a chimney may operate. In real installations, chimneys are usually completely surrounded by a roof that offers lower thermal conductivity than the walls of the test structure. In the study [Article III], a corner test was conducted as described in the standard EN 1859. The combustible material temperatures were measured from the wooden corner wall construction as described in EN 1859 and from the roof insulation. The temperatures measured from the roof insulation were about 60°C higher than those measured on the walls. Another test was conducted with an axisymmetric test structure where temperatures were measured from the surface of the roof insulation. The temperature results were even higher than those of the corner test. It is therefore proposed that the chimney be installed at the centre of the test floor and that temperatures be measured on the insulation material, not on the wood construction. The chimney test arrangement should be changed as shown in Section 6.3.2.

7.2.3 Smouldering of the organic content of mineral wool

The results of this study showed that conditions in chimney penetrations are favourable for the smouldering combustion of the organic material in mineral wool insulation products used in the chimney penetrations. Experiments on mineral wool specimens show that smouldering combustion can increase the insulation temperature by hundreds of degrees, which in turn can increase the temperatures of combustible roof construction materials located adjacent to chimney penetration by over 100°C for a limited period of time. The effects of this phenomenon on the temperatures were greatest when the insulation material is exposed to 500°C – 600°C temperatures and the thickness of the test specimen was 100 mm. Many factors increase the temperatures in the chimney penetration, and several factors can affect the temperature simultaneously. If the temperature is already near the ignition level temperature, even a small rise can cause ignition. The smouldering combustion can be a potential fire hazard if the heat release is not limited to fire-safe levels.

This risk can be prevented by restricting the amount of organic material in insulation materials. Insulation materials containing organic material can be used in chimneys and chimney penetrations. However, the amount of organic matter must be limited. The test results of this study were not yet comprehensive enough to define a safe limit value and further research is required. Additional temperature rise due to smouldering combustion of the organic material should be determined for different amount of organic content. Based on this, a safe limit amount of organic content could be defined.

7.3 Suggestion for further research

People's way of using and operating fireplaces

This thesis has focused on the standard testing of fireplaces. In addition, this study has used the fireplaces according to the operating instructions in the field tests. In the study, it was not possible to study people's actual way of using fireplaces. The way fireplaces are used has a considerable impact on their flue gas temperatures.

Actual conditions and their effect on the draught of chimneys and flue gas temperatures of fireplaces

In the study, it was not possible to study the variations of typical conditions on the draught of the chimney and on the temperature of the flue gases of the fireplace. In long-term constant measuring in actual locations, it is possible to estimate the effect of both the conditions and the use.

Wall penetrations of metal chimneys

An analysis of the wall penetrations of metal chimneys test should be performed. A testing method would have to be developed for the wall penetrations of metal chimneys.

The effect of the amount of organic content of mineral wool on heat release

Only one product has been used in the tests presented in Article IV. Using different products, it is possible to see how the amount of organic content influences heat release.

General model of the heat release of the burning of the organic content of mineral wool

A numerical study of the heat equation reveals the location and moment in time where heat release has an effect on the temperature field. The result of numerical modelling provides the heat release function of time and position, but a more complex smouldering combustion model needs to be studied in order to predict temperature peak in mineral wool generally.

Developing a non-combustible test method

A new non-combustible test method should be developed, which would take the burning of the organic content of insulation material into consideration. The smouldering combustion of the organic content of the insulation material would have to be distinctly evident in the method, and the criteria would have to be tight enough to prevent heat release on the penetration of the chimney.

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Publication I	Leppänen P., Inha T. & Pentti M. An experimental study on the effect of design flue gas temperature on the fire safety of chimneys, Fire Technology, Vol. 51, Issue 4, 20 June 2014, pp. 847-866
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Publication III	Leppänen P., Neri M., Luscietti D., Bani S., Pentti M., Pilotelli M., Comparison between European chimney test results and actual installations. Journal of Fire Sciences, Vol. 35, Issue 1, January 2017, pp. 62-79
Publication IV	Leppänen P., Neri M., Mäkinen J. Heat release caused by the smouldering combustion of the binder of rockwool. Journal of structural mechanics. Vol. 48, No 1, 2015, pp. 68-82

PUBLICATION
I

An experimental study on the effect of design flue gas temperature on the fire safety of chimneys

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Perttu Leppänen*, Timo Inha and Matti Pentti,
Department of Civil Engineering, Tampere University of Technology, P.O. Box 600, 33720
Tampere, Finland
* Corresponding author: perttu.leppanen@tut.fi

Abstract

Recently, numerous fires have started in Finland around roof penetrations of metal chimneys. One reason for the fires is the high flue gas temperatures of fireplaces. EN standards do not determine the flue gas temperatures of fireplaces meant for the specification of temperature classes of chimneys. At present, the design of chimneys is based on the temperature indicated in the CE marking of fireplaces. The temperature indicated in the CE marking is the mean temperature of the nominal test. Tests on different fireplaces were conducted. Flue gas temperatures of the fireplaces were measured during a nominal test, a safety test and extra heating. Even in the nominal test, the highest flue gas temperature was 37 to 212°C higher than the mean temperature. The highest flue gas temperature in the safety tests was about 120 to 380°C higher than the mean temperature indicated in the CE marking. During the extra heating test, the highest flue gas temperature was 160 to 350°C higher than that indicated in the CE marking. Due to the present method of determining flue gas temperatures, chimneys may be tested at a too low temperature.

Keywords flue gas, temperature, fireplace, chimney, fire safety, test

1. Introduction

There are about 1.1 million detached houses [1] and about 0.5 million vacation homes in Finland [2]. Almost all detached houses in the country have a fireplace – many have several. Practically all vacation homes are assumed to have a fireplace. In Finland firewood provided about 40% of the heating energy consumed by detached houses in 2007/2008. A survey indicated that the use of firewood in heating detached houses had increased 20% in 15 years [3]. Wood is often used as an additional heat source. People want to increase the use of firewood because it is a renewable fuel.

In recent years, many fires in Finland have started around metal chimney roof penetrations. According to Leppänen's study [4], metal chimneys caused an average of 87 fires in Finland in 2004–2009. A thematic investigation of fires started from fireplaces and chimneys was conducted at Finnish fire and rescue stations in 2012 [5]. The review covered 12 stations. A total of 126 fires related to the theme were recorded. Of the fires, 36% had started from fireplaces and 64% from chimneys. A spark from the fireplace started 47% of the fires originating from fireplaces. Of the fires started from chimneys 73% involved metal chimneys. In 47% of the cases involving chimneys, the fire had started from a roof penetration and in 22% from a wall penetration of a metal chimney.

The number of fires started by metal chimneys in Finland is really significant, as metal chimneys have become common here only recently. A roof safety survey by chimney sweeps in 2011 revealed that metal chimneys accounted for about 6% of the total [6]. The survey covered 1047 buildings in different parts of Finland. In addition, an inquiry targeting chimney sweeps in connection with this study, to which 25 chimney sweeps from different parts of Finland responded, asked about the prevalence and fire hazards related to metal chimneys. Due to the small sample, the results were only indicative but clear enough. The results of the inquiry are shown in Table 1.

***Table 1** Shares of different chimney types of all the chimneys of the residential buildings of the whole building stock in Finland at different periods.*

		1980's	1990's	2000's	2010's
Metal chimney	**Range**	1 to 13 %	3 to 13 %	4 to 20 %	4 to 20 %
	Average	5 %	7 %	10 %	11 %
Block chimney	**Range**	0 to 10 %	0 to 15 %	1 to 25 %	1 to 50 %
	Average	3 %	7 %	12 %	16 %
Masonry chimney	**Range**	85 to 99 %	80 to 95 %	60 to 92 %	40 to 90 %
	Average	92 %	87 %	77 %	73 %

According to inquiry share of the metal chimneys is about 10 % of all the chimneys of the residential buildings at today. It is alarming that in 2012 approximately 10% of chimneys caused over 70% of all chimney-induced fires in Finland. Moreover, wall penetrations of metal chimneys that accounted for about 8% of all metal chimney penetrations, were responsible for a third of all fires induced by metal chimneys. The results are so clear that there is no doubt about the significance of the problem even though the samples are small and can be biased. The problem is made even more significant by the fact that all metal chimneys in Finland are relatively new. Fire safety problems with brick masonry chimneys are mainly due to degradation with age. In a study by Inha et. al. [7] on the fire safety of light-weight metal chimneys, high flue gas temperatures of sauna stoves were found to be one cause of fires.

The objective of this research was to determine the difference between the flue gas temperatures of the nominal heat output test and the temperature safety test. Another aim was to evaluate how use of fireplaces deviating from the tests affects flue gas temperatures. The research aimed to establish whether the measurement method used in fireplace tests according to EN standards poses a fire safety risk in the case of chimneys. This article is related to a larger research entity on the fire safety of fireplaces and chimneys. Its purpose is to determine whether the testing of fireplaces corresponds to their actual use in Finland. The compatibility of fireplaces and chimneys tested according to EN standards and the fire safety of the penetrations of metal chimneys are also studied.

2. Flue gas temperatures of fireplaces

The combustion of wood can be divided into three phases: 1. Evaporation of moisture, 2. Disintegration of the fuel due to temperature, i.e. pyrolysis, and 3. Burning of the residual coke. Evaporation of moisture and pyrolysis are heat consuming phases. The combustion of pyrolytic gases and residual coke are heat generating phases. If the particle size of fuel is large, the phases occur simultaneously. Pyrolysis of wood takes place at about 200 to 500°C. [8] The share of volatile substances in air-dry wood is about 85%. Thus, wood burns with a long flame. During combustion the temperature of the flame is affected by things such as the moisture in the wood and the amount of excess air. Wood flames emit relatively strong radiation as their water vapour and CO_2 contents are high and they contain glowing carbon particles. [9] The burning of wood is intended to produce energy through combustion. Thus, the heat of flue gases escaping into the chimney is wasted heat.

The fire safety of the fireplaces and chimneys has not been studied in recent years. Flue gas temperatures of fireplaces were measured in a study by Peacock in the 1980's [10]. The study included 18 typical commercial fireplaces in the USA. Flue gas temperatures of the tested fireplaces are presented in Table 2. The study revealed that the typical fireplaces for sale in the 1980's produced higher flue gas temperatures than the ones studied 40 years earlier. In Peacock's tests [11] the highest flue gas temperatures in normal heating with wood as fuel were 426 to 519°C, in overheating 574 to 855°C, and with coal as fuel 327 to 625°C.

Table 2 *Flue gas temperatures of fireplaces in Peacock's tests [10].*

Flue gas temperature	300-400 °C	400-500 °C	500-600 °C	600-700 °C	700-800 °C
Number of Fireplaces	1	3	0	9	5

Hansen et al. [12] performed laboratory tests from cracking of chimneys. The chimneys were subjected to standard tests and tests using chopped birch firewood. In the tests flue gas temperatures were measured from several points. The mean values of the highest flue gas temperatures at different measurement points in normal heating, overheating and chimney fire tests are presented in Table 3. The chimney used in the tests was a block chimney.

Table 3 *Means of highest flue gas temperatures in the tests by Hansen et al. [12].*

Measuring point	Normal heating		Overheating	
	Standard	Birch	Standard	Birch
Fluegas connector	332 °C	584 °C	879 °C	594 °C
1 m from the fluegas connector	266 °C	441 °C	670 °C	508 °C
4 m from the fluegas connector	240 °C	355 °C	448 °C	379 °C

In the light of Peacock's tests, it is evident that flue gas temperatures can exceed 600°C in fireplaces. In 78% of the tested fireplaces, flue gas temperatures exceeded 600°C. The use of the fireplace is also significant since the difference in flue gas temperatures between normal use and overheating may exceed 300°C. Fireplaces have certainly developed, but the possibility of flue gas temperatures exceeding 600°C cannot be excluded especially under continuous intense heating. However, the highest temperature class of chimneys is T600, which is designed for a maximum flue gas temperature of 600°C [13].

3. Measurement of flue gas in fireplace EN standards

There are many kinds of wood-burning fireplaces: room heaters, inset appliances, residential cookers, slow heat release appliances and sauna stoves. Room heaters are very common in around Europe. Slow heat release appliances and sauna stoves are very common in Finland but less common elsewhere in Europe. Slow heat release appliances and sauna stoves are used differently than other kinds of fireplaces. After a few batches are burned in slow heat release appliances, they release heat into a room space for several hours. Sauna stoves must heat the sauna room quickly to the bathing temperature of 80 to 100°C, after which the temperature has to be maintained. In addition, the sauna stove must keep the temperature of the sauna stove stones at about 300°C.

Fireplaces are subjected to a nominal heat output test and a temperature safety test in accordance with EN standards. The former describes the planned use of the fireplace while the latter is intended to ensure the fire safety of the area around the fireplace. In EN standard tests at nominal heat output, properties such as efficiency, heat output and emissions are determined for fireplaces. Safety distances of fireplaces are determined in a safety test. When testing a room heater at nominal heat output, the fireplace is heated according to the instructions specified in the standard. In the safety test of a room heater, wood batches calculated on the basis of the area of the firebox bottom are burned until the surface temperatures of the adjacent wall have stabilised. The wall structure was made of 20 mm plywood and 40 mm mineral wool insulation. The testing of room heaters and inset appliances according to EN standards is very similar. [14, 15] Burning rate performance test of slow heat release appliances according to the EN standard takes place using the wood batches specified by the manufacturer. The safety test of a slow heat release appliance uses a double batch: a new batch of the same size is burned after a burning rate performance test. [16] The test of a sauna stove at nominal heat output according to the EN standard takes place in the sauna test room specified in the standard. The temperature of the sauna test room must reach 90°C using the batches specified by the manufacturer. The safety test of a sauna stove takes place in the smallest sauna test room by volume specified for the sauna stove. In the test, the temperature of the sauna test room is allowed to stabilise at 60°C, after which draught is increased to 15 Pa $^{+2}_{-0}$ and the firebox is filled to the upper edge of its opening. In the test, the temperature of the sauna test room must reach 110°C, if it is not reached, another batch is added. [17] According to the standard, it is not necessary to measure flue gas temperatures in the temperature safety test of a fireplace.

4. Testing of chimneys according to standards EN 1856 and EN 1859

The thermal resistance of a metal chimney is tested by feeding hot gas into it until equilibrium is reached. Equilibrium is considered to have been reached when the temperature of the test chimney or structure increases by no more than 2°C/30 min. The surface temperature of any combustible material at the safety distance from the chimney must not exceed 85°C when ambient temperature is 20°C. Chimneys designated as soot-fire resistant are also subjected to a chimney fire test. In the test, hot gas temperature must be 1000°C (-20°C/+50°C) for 30 minutes after which the hot gas generator is turned off. The temperatures of the chimney and the surrounding area are monitored until they reach the maximum value and start to fall. The maximum surface temperature of combustible materials must not exceed 100°C when ambient temperature is 20°C. If a metal chimney is designed to withstand a soot fire, its thermal resistance is checked by a thermal resistance test before and after the soot-fire resistance test. [18]

EN standards present 11 temperature classes for chimneys: T80, T100, T120, T140, T160, T200, T250, T300, T400, T450 and T600. The number refers to the maximum nominal operating temperature (°C). The temperature class of a chimney must be higher than the flue gas temperature indicated in the CE marking of fireplace. In the highest temperature classes, T400, T450 and T600, the hot gas temperature used in testing the chimney is 100°C higher than the indicated temperature class. [18] However, a higher test temperature does not ensure the safety of the connection of a fireplace and a chimney since, according to Kaukanen's survey [19], a test temperature higher than the temperature class is intended to cover the different installation variations of chimneys. A metal chimney can be tested as free standing or installed in a corner enclosed or not enclosed. In the tests, the chimney is installed upright and a horizontal pipe is connected to it for feeding hot gas. The temperature of the hot gas is measured from the horizontal pipe. The test corner has two floor structures, the first one 1400 mm above the horizontal pipe. In tests on the chimneys the temperature of the wood is measured at the safety distance from them at the floor structures and 300 mm below the upper one. [20]

5. Experimental

A series of tests was performed in order to determine the flue gas temperatures of fireplaces for use in dimensioning chimneys. Tests were run on two multi-firing wood-burning sauna stoves, one room heater, and two slow heat release appliances, to represent different fireplace types. This article presents the tests and results for one sauna stove, one room heater and one slow heat release appliance. The tests are based on the study that has been performed in Tampere University of Technology (TUT) [21]. A temperature safety test, a nominal heat output test and a bathing test were made with the sauna stove. A nominal heat output test, a temperature safety test, and a test with larger wood batches were made with the room heater and the slow heat release appliances. Draught and flue gas temperature is measured by a Kimo MP 200 micromanometer with a TPL-06-300-T measurement sensor. In addition to the measurements specified in the standard, flue gas temperature is measured from the flue gas connector of the fireplace with a type K thermocouple wire Ø 0.5 mm. Flue gas temperature and composition is measured and recorded at intervals of 1 minute. The flue gas temperature indicated in the CE marking is the average of flue gas temperatures measured during a nominal heat output test. The average is calculated from results measured at intervals of one minute during the test period. The test period for the sauna stove begins at ignition and ends after CO_2 content has fallen to 4.0% [17]. The average for the tested sauna stove was calculated on the basis of the nominal test over 0–94 min. With the room heater, the test period starts after the ignition and pretesting period and ends when the basic firebed is achieved [14]. The average for the tested room heater was calculated on the basis of the nominal test over 62–201 min. The test period for a slow heat release appliance begins at ignition and ends when CO_2 content has fallen to 4.0% or 25% of the previous maximum CO_2 content is achieved. The average for the tested slow heat release appliance was calculated on the basis of a normal use test over 0–66 min. The indicated maximum flue gas temperature is the highest temperature measured during the test. Test arrangement and measurement of temperature, pressure and constituents of flue gases is presented in Figure 1. The fireplaces were common commercial fireplaces. Related information is presented in Table 4.

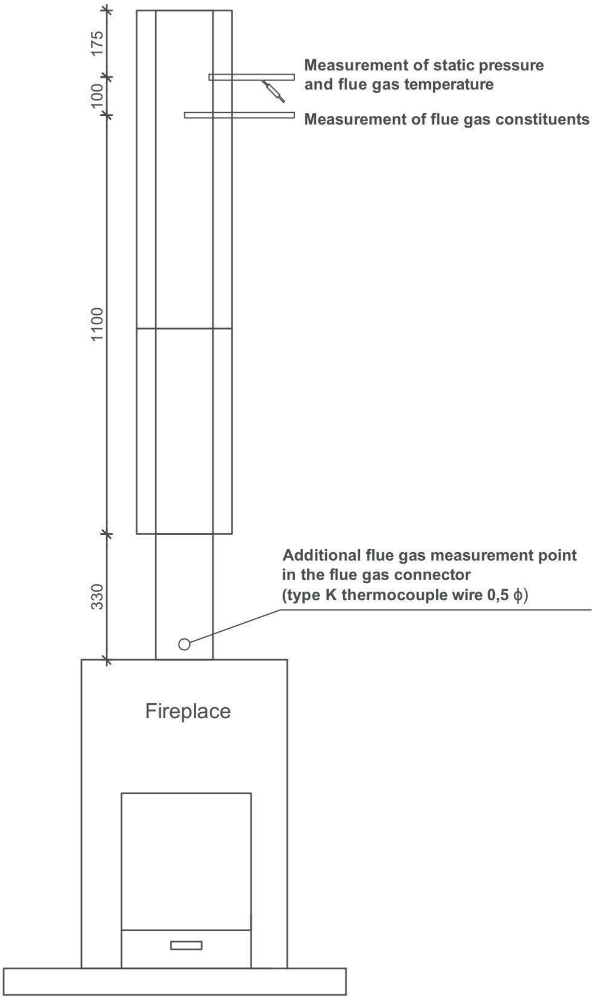

Figure 1 *Test arrangement and measurement of temperature, pressure and constituents of flue gases.*

Table 4 *Information on tested fireplaces.*

	Height	Width	Depth	Weight
Sauna stove	800 mm	540 mm	580 mm	136 kg (incl. Stones 60 kg)
Roomheater	903 mm	450 mm	446 mm	115 kg
Slow heat release appliance	1750 mm	795 mm	585 mm	1300 kg

5.1 Testing of wood-burning sauna stoves

Tests on sauna stoves were made according to standard EN 15821:2010 *Multi-firing sauna stoves fired by natural wood logs. Requirements and test methods*. Tests at nominal heat output used the batch sizes specified by the manufacturer. The fireplace was not CE marked at the time of the tests. Now it bears a CE marking showing an average flue gas temperature of 425°C. The wood batches used in the test for a CE marking were slightly different than in this test (3.5 kg, 3.0 kg and 2.5 kg). The sauna stove was designed for an 8–20 m^3 sauna. The sauna stove that has been used in the tests is presented in Figure 2. Example of the cross section of the sauna stove is presented in Figure 3. The wood batches used in the nominal heat output test of the sauna stove are presented in Table 5. The nominal heat output test of a sauna stove represents a situation where a sauna is heated ready for bathing.

Figure 2 *Sauna stove that has been used in the tests.*

Table 5 *Wood batches in tests of sauna stove at nominal heat output.*

Time	**Ignition**	**24 min**	**48 min**	**75 min**
Batch	3,0 kg	3,0 kg	3,0 kg	
Sauna's temperature				90 °C

In deviation from the standard, the temperature safety test on the sauna stove was performed in a 20 m^3 sauna test room. According to the standard, the test should be performed in the smallest possible sauna test room. A larger sauna was used in test whereby the stove had to heat a larger space requiring a bigger heat output, which may have increased flue gas temperatures. In this temperature safety test, two batch loads were required to raise the temperature of the sauna test room above 110°C. The wood batches used in the temperature safety test on the sauna stove are presented in Table 6.

Table 6 *Wood batches of the temperature safety test on the sauna stove.*

	Preheating of the sauna				**Safety test**		
Time	Ignition	30 min	47 min	61 min	69 min	108 min	136 min
Batch	4,00 kg	0,90 kg	0,85 kg		6,05 kg	5,95 kg	
Sauna's temperature				60 °C		106 °C	137 °C
Draught	12 Pa				15 Pa		

The nominal heat output and temperature safety tests on a sauna stove are short in duration. In reality, a sauna bath may last several hours and a fire burns in the multi-firing stove for the duration. Therefore, in addition to the tests specified in the standard, a bathing test was carried out. In the bathing test, people took a bath in the test sauna during which water was thrown on the sauna stove to produce steam. The bathing test does not correspond to the normal way of taking a sauna bath. Typically, the sauna stove is heated with larger batches and less frequently. In the bathing test batch charges were added in order to keep the temperature of the sauna constant. At the beginning of the bath the temperature of the sauna was about 60 to 70°C, which is lower than normal bathing temperature. At the end of the bathing test, the temperature of the sauna was about 100°C, which is higher than the average bathing temperature. The air exchange rate was 6 times per hour, as specified in the standard. Moreover, the air of the sauna test room exchanged through the chimney due to burning. The air exchange rate was higher than normally in the saunas. The bathing test tried to emulate the Finnish way of using a sauna stove. The bathing tests took place in a 20 m^3 sauna. The draught of the bathing test was set at 15 Pa $^{+2}_{-0}$, which is used in the temperature safety test. Bathing began 33 minutes after the lighting of the sauna stove. Wood batches and sauna temperatures of the test are presented in Table 7.

***Table** 7 Wood batches of the bathing test on the sauna stove.*

Time	Ignition	28 min 30 s	40 min	54 min	70 min	77 min	87 min	102 min
Batch	4,05 kg	1,8 kg	1,6 kg	0,65 kg	1,5 kg	0,7 kg	1,65 kg	1,5 kg
Sauna's temperature	20 °C	52 °C	60 °C	70 °C	64 °C	64 °C	65 °C	70 °C
Time	111 min	118 min	120 min	124 min	132 min	137 min	155 min	183 min
Batch	1,85 kg	1,2 kg	1,05 kg	0,95 kg	0,8 kg	1,0 kg	1,35 kg	2,05 kg
Sauna's temperature	67 °C	79 °C	80 °C	77 °C	86 °C	96 °C	101 °C	90 °C

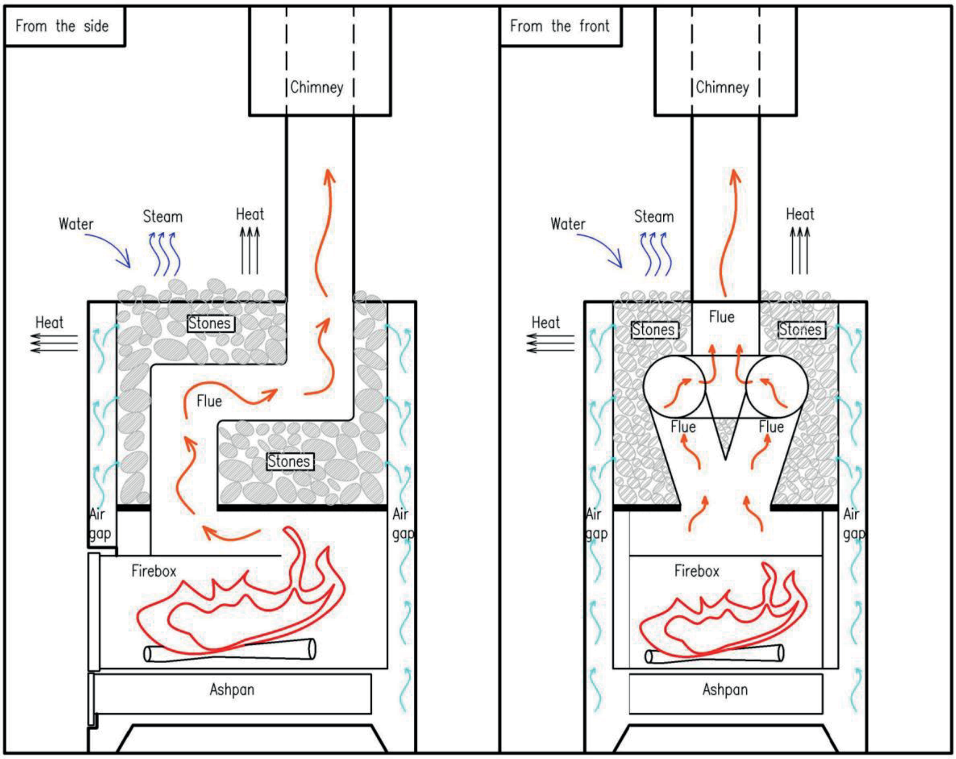

Figure 3 *Example of the cross section of the sauna stove.*

5.2 Testing of the room heater

The room heater was tested according to standard EN 13240:2001/A2:2004/AC:2007 *Room heaters fired by solid fuel. Requirements and test methods*. The room heater was a cast iron commercial room heater with a design nominal heat output of 5 kW. The declared thermal efficiency of the room heater is 5.9 kW at 83% efficiency. The mean flue gas temperature indicated in the CE marking is 260°C. The firewood charging interval recommended by the manufacturer is about 45 minutes. The amount of chopped firewood to be added (2 pieces at a time) is 1.62 kg (nominal heat output). The maximum amount of firewood suggested by the manufacturer is 2.9 kg/h (max. 3 pieces or 2.2 kg/charge). In the temperature safety test, the size of fuel batches is calculated on the basis of the area of the firebox bottom. The standard does not consider the height of the firebox. The large size of the firebox of many room heaters allows using significantly larger wood batches than those of the temperature safety test. Larger wood batches may increase flue gas temperatures. Wood batches used in testing the room heater at nominal heat output and during additional batches are presented in Table 8. Wood batches used in the temperature safety tests of the room heater are presented in Table 9.

Table 8 *Wood batches used in testing the room heater at nominal heat output and with additional batches.*

	Pre-test		**Nominal heat output test**			**Additional batches**			
Time	Ignition	27 min	62 min	107 min	154 min	201 min	241 min	291 min	330 min
Batch	1,6 kg	0,85 kg	1,7 kg	1,7 kg	1,7 kg	3 kg	3 kg	3 kg	3 kg
Draught	12 Pa							15 Pa	

Table 9 *Wood batches used in the temperature safety test of the room heater.*

	Pre-test	**Safety test**			
Time	Ignition	62 min	105 min	150 min	196 min
Batch	3,0 kg	2,5 kg	2,5 kg	2,5 kg	2,5 kg
Draught	12 Pa	15 Pa			

5.3 Testing of slow heat release appliances

Tests on the slow heat release appliance were made according to standard EN 15250:2007 *Slow heat release appliances fired by solid fuel. Requirements and test methods*. The fireplace was not CE marked at the time of the tests. Now it bears a CE marking showing an average flue gas temperature of 174°C. The wood batches used in the test for a CE marking were slightly different than in this test (4.5 kg, 3.0 kg and 3.0 kg). The wood batch sizes used in the test are specified by the manufacturer. After the temperature safety test, another test was conducted using a wood batch twice the size specified by the manufacturer. The fireplace had an ignition damper. During the extra batch the ignition damper was opened to test its effect on flue gas temperatures. When the ignition damper is open, flue gases flow directly into the smoke flue without circulating through the smoke canals of the fireplace. This results in higher flue gas temperatures in the smoke flue. The ignition damper may be kept open for a short time during ignition. Its purpose is to promote the formation of draught in the smoke flue. The wood batches used in the testing of the slow heat release appliance are presented in Table 10.

Table 10 *Wood batches in the testing of the slow heat release appliance.*

	Burning rate performance test			**Safety test**		**Additional batch**	
Time	Ignition	10 min	40 min	66 min	90 min	109 min	133 min
Batch	5,0 kg + 0,5 kg		3,0 kg	5,0 kg	3,0 kg	10,0 kg	
Draught	12 Pa			15 Pa		20 Pa	
Ignition damper	Open	Closed					Open

6. Test results and discussion

Flue gas temperatures of sauna stove tests at nominal heat output, in temperature safety tests and the bathing test are presented in Figures 4 to 6. Flue gas temperatures of tests on the room heater are presented in Figures 7 and 8. Flue gas temperatures of the temperature safety test on the slow heat release appliance and during the additional batch are presented in Figure 9. Flue gas temperature is measured and recorded at intervals of 1 minute. A summary of the flue gas temperatures of fireplaces in the tests is presented in Figure 10.

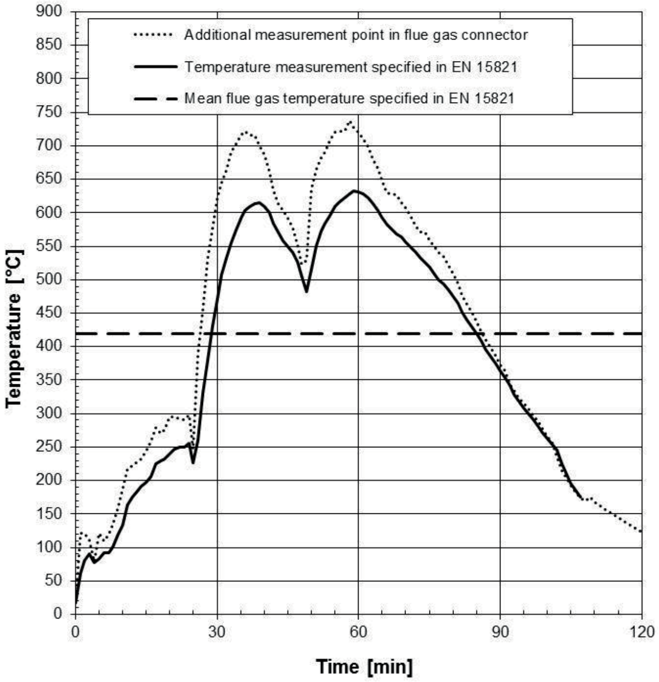

Figure 4 *Flue gas temperatures in testing the sauna stove at nominal heat output.*

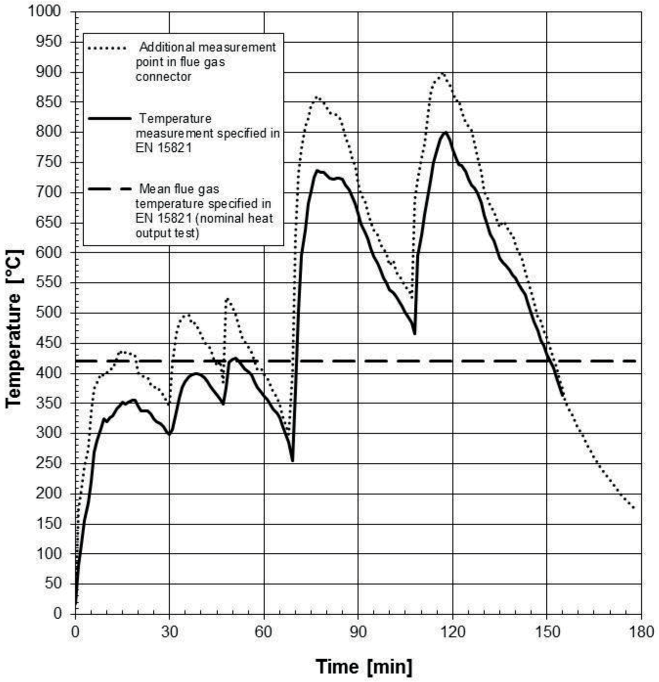

Figure 5 *Flue gas temperatures in the temperature safety test of the sauna stove.*

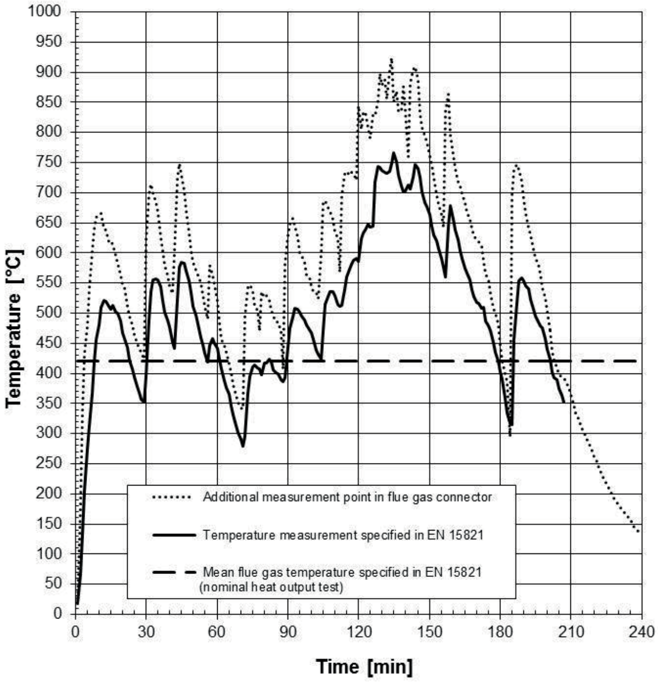

Figure 6 *Flue gas temperatures in the bathing test of the sauna stove.*

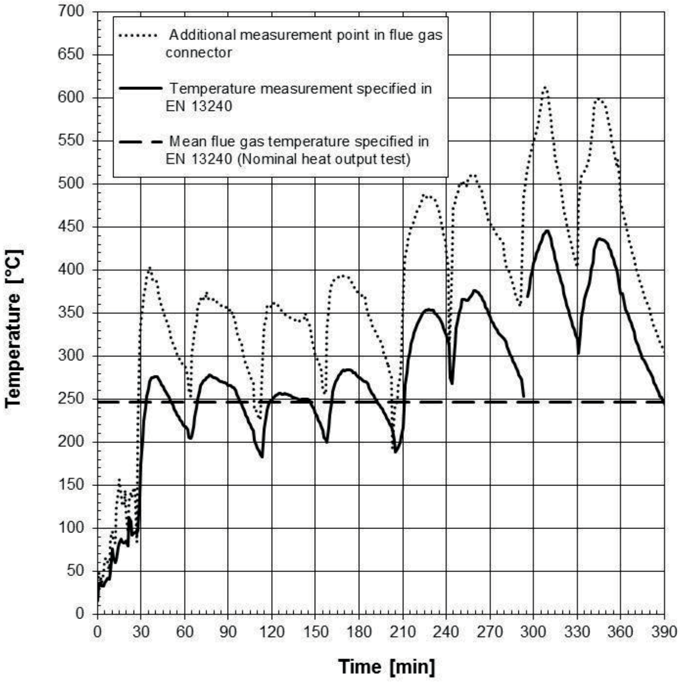

Figure 7 *Flue gas temperatures in room heater tests at nominal heat output and during the additional batch.*

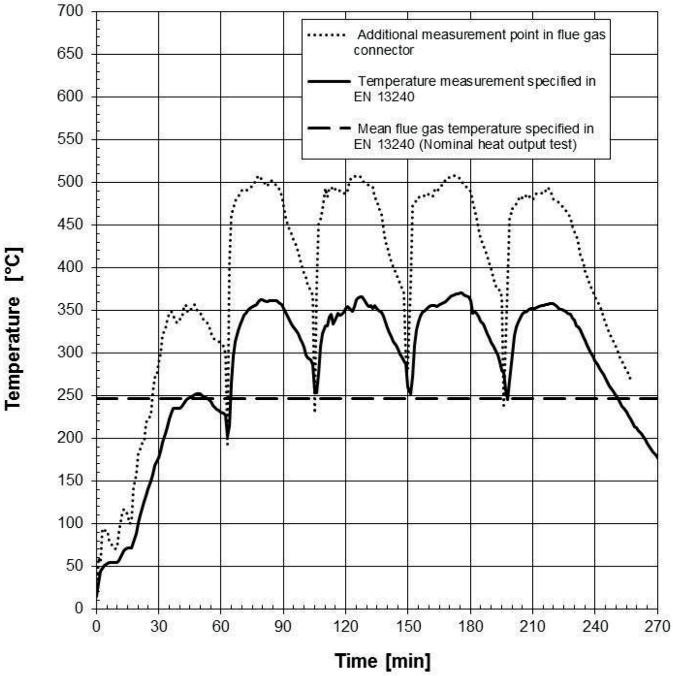

Figure 8 *Flue gas temperatures in the temperature safety test of the room heater.*

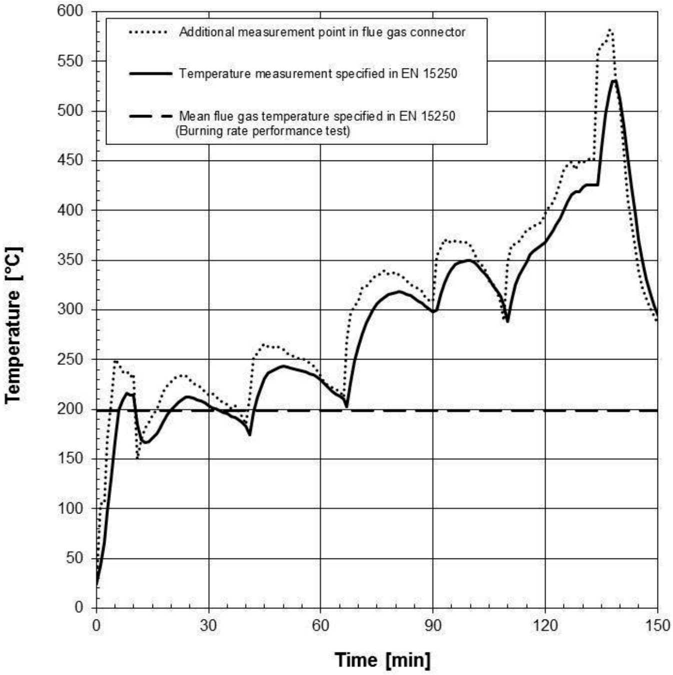

Figure 9 *Flue gas temperatures in the temperature safety test of the slow heat release appliance and during the additional batch.*

The highest flue gas temperature reached in the nominal heat output test of a fireplace was 37 to 212°C above average flue gas temperature. In the case of the tested room heater, the highest flue gas temperature in the nominal heat output test was only 37°C higher than that of the CE marking. This is partly due the fact that the actual testing of the room heaters is preceded by an ignition and pre-testing period. It is evidently intended to produce more favourable emission measurement results by heating the firebox before the test. The highest flue gas temperature in the temperature safety test was 124 to 381°C above the flue gas temperature indicated in the CE marking. The results are in line with those of the test series conducted by Oravainen [22] on a sauna stove, a room heater and a slow heat release appliance, where the highest flue gas temperature in the nominal heat output test was 85 to 212°C higher than the flue gas temperature of the CE marking, and the highest flue gas temperature in the temperature safety test was 230 to 384°C higher than that of the CE marking. A comparison of the flue gas temperatures of fireplaces in different tests is presented in Figure 10.

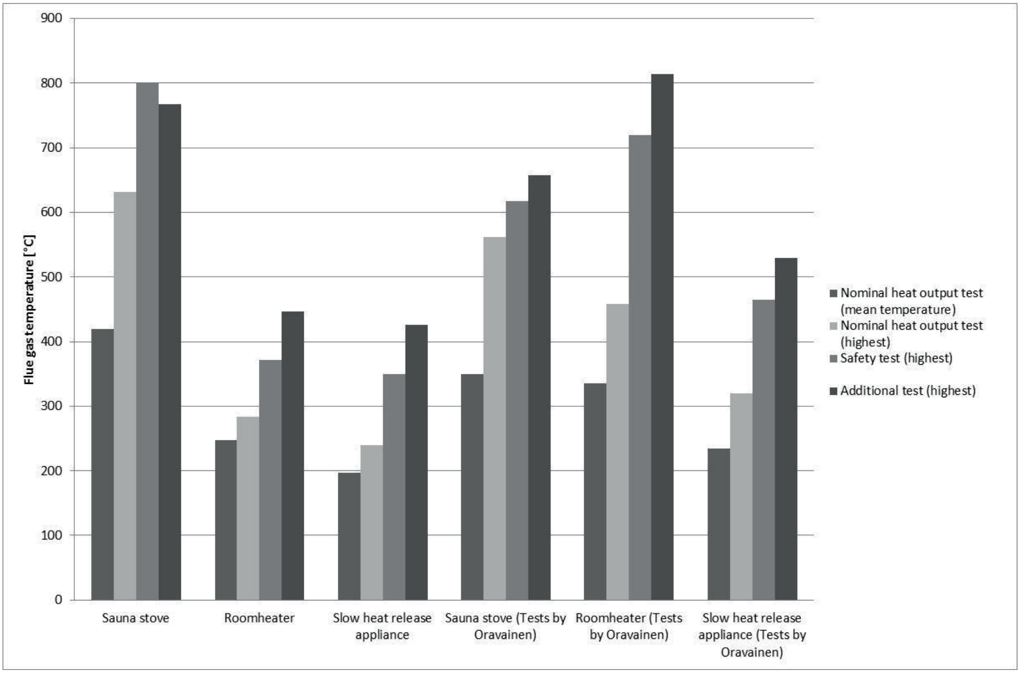

Figure 10 *Flue gas temperatures of the fireplaces in the different tests. (In tests conducted by Oravainen, the draught during additional tests was 20 Pa.)*

The measured flue gas temperatures of the slow heat release appliance can be compared to Oravainen's [23] study on the flue gas temperatures of 45 slow heat release appliances during normal use and temperature safety tests. The purpose of that study was to determine a coefficient with which to multiply mean flue gas temperatures to obtain the temperature of the temperature safety test. The mean coefficient determined for fireplaces was 1.84 ranging from 1.44–2.51. The flue gas temperature indicated in the CE marking for the tested slow heat release appliances was 113–264°C. The mean of the temperatures indicated in the CE marking of the tested fireplaces was 192°C. The highest temperatures measured in the temperature safety test were 225°C to 508°C. The mean of the maximum temperatures measured in the tests was 349°C. In tests that have been performed by TUT the mean flue gas temperature of the tested slow heat release appliance in the nominal heat output test was 199°C, which makes it an average slow heat release appliance as temperature is concerned. The coefficient for multiplying the mean temperature of the nominal heat output test to obtain the temperature of the temperature safety test is 1.78 for the tested slow heat release appliance. It falls within the mid-range of the determined coefficients (1.44–2.51). In the case of the tested sauna stove the coefficient is 1.91 and with the room heater 1.5.

Determination of the design flue gas temperature of fireplaces is problematic with all fireplace types tested according to EN standards. A comparison of the tests on room heaters in Figure 10 reveals that the difference between the mean temperature of the nominal heat output test and the highest temperature of the temperature safety test depends more on each individual fireplace than its type (room heater, sauna stove, slow heat release appliance). In the case of the first room heater, the difference is the smallest of any tested fireplace while in the case of the second one it is the biggest.

The fact that the flue gases generated by a fireplace are hotter than the gases used to test the chimney poses a problem. Higher than assumed flue gas temperatures raise the surface temperatures of the chimney and its surroundings which may ignite surrounding structures. The ignition temperature of wood is not a physical quantity but depends on conditions. Babrauskas et al. [24] found that under short-term exposure (minutes to a few hours) the ignition temperature of wood is about 250°C, but under long-term exposure it can be considerably lower, even as low as 77°C. Matson et al. [25] made a comprehensive study of wood ignition temperatures including tests on different wood species. They presented a compilation of experimental tests where ignition temperatures were around 200°C or higher, but under long-term exposure the ignition temperatures were significantly lower e.g. by steam pipes. Under short-term exposure the 85°C temperature limit would seem to hold, but in longer term exposure certainty decreases. In some instances the exposure times to chimneys may be quite long especially when the chimney passes through efficient thermal insulation.

Using the highest flue gas temperature of the temperature safety test on a fireplace in chimney design is the simplest and a justifiable option. The temperature safety test is designed to emulate continuous intense heating of a fireplace. Therefore, it would also be natural to derive flue gas temperatures for chimney design from the temperature safety test. However, the temperature safety test does not represent actual continuous intense heating of a fireplace in all respects. For example, the sauna stove safety test is based on the principle that firewood is no longer added into the stove when the temperature of the sauna exceeds 110°C. Yet, there are sauna stoves on the market in Finland which allow adding wood batches through the wall from outside the sauna. As the sauna can be heated without entering the sauna room, it is easily possible to overheat the sauna. In addition, some sauna heating instructions suggest starting heating with the door open to prevent temperature from rising too high. In the case of a room heater or a slow heat release appliance, the problem related to the temperature safety test may in some instances lie in the size of wood batches. Moreover, the problem with a slow heat release appliance might be the incorrect use of an ignition damper.

Flue gas temperatures higher than those measured in tests are particularly problematic with metal chimneys because of their light weight. The exterior temperatures of masonry chimneys rise slowly because they retain more heat. The density of brick is more than 10-fold compared to the insulation used in metal chimneys. Peak flue gas temperatures of fireplaces are not dimensioning in terms of the fire safety of a chimney, as the heating of chimney components acts as a buffer. However, using the highest flue gas temperature in the design of a chimney is justified in the absence of more exact research data on the subject. The effect of peak temperatures on the fire safety of chimneys should be studied. The tests showed the major impact of the use mode of a fireplace on flue gas temperatures. Because of the cold winters, it is customary in North Europe to use bigger wood batches and heat up fireplaces longer than in Central Europe.

7. Conclusions

The tests specified in the fireplace standards do not provide the temperature data required for dimensioning chimneys. The temperature specified in the CE marking of fireplaces is measured at nominal heat output when the tested fireplace is heated according to manufacturer's instructions. According to the EN standards, fireplaces are also subjected to a temperature safety test. The test is made to determine the safety distances of a fireplace but, the standard does not require measuring flue gas temperatures. The highest flue gas temperatures of the tested fireplaces measured in the temperature safety test were 124 to 381°C higher than those of the CE marking. Extra heating raised the highest flue gas temperature 199 to 347°C above the flue gas temperature indicated in the CE marking. Based on the tested fireplaces, the flue gas temperature used for dimensioning chimneys is 124 to 381°C too low. To ensure the fire safety of chimneys, the flue gas temperature used in their dimensioning should be the highest temperature measured in the temperature safety test. Light metal chimneys are more sensitive to temperatures higher than the tested ones because they have less heat-retaining mass than masonry chimneys. A masonry chimney requires several hours of heating before its surface temperatures begin to rise.

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PUBLICATION
II

Experimental study on fire safety of chimneys in real use and actual site conditions

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Experimental study on fire safety of chimneys in real use and actual site conditions

Perttu Leppänen*, Mikko Malaska, Timo Inha, Matti Pentti

Tampere University of Technology, Department of Civil Engineering, P.O. Box 600, FI-33101, Tampere, Finland

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ABSTRACT

In recent years, numerous building fires have occurred in Finland where the fire has started due to the ignition of flammable materials in the vicinity of metal chimney penetrations through floors, roofs and walls. Based on onsite observations and experimental studies, one possible reason for the ignition is that the actual flue gas temperatures in real use in buildings are higher than those assumed for chimney design. An experimental study has been conducted in the TUT Fire Laboratory at Tampere University of Technology to determine the actual site conditions, identify the difference between the actual site conditions and the EN standard test conditions and assess whether the differences affect the fire safety of chimney penetrations. This paper describes the results of five site tests conducted in four different residential buildings and a sauna. The results revealed that the actual use of fireplaces and site conditions may differ significantly from the test conditions of EN standards. The site tests demonstrated higher flue gas temperatures and stronger draughts than what specified for the EN standard tests. The flue gas temperatures measured onsite were 134° to 278 °C higher than the mean temperature indicated in the CE marking of the tested fireplaces. The results indicate that the flue gas temperatures given in the CE markings of fireplaces may be too low for the designing of chimneys. This may cause a fire hazard at chimney penetrations.

1. Introduction

Increasing attention has been given to sustainable and energy-efficient buildings which require efficient biomass-fired heating systems, insulation materials with better thermal properties and thicker thermal insulation layers over the building envelope. Sustainable development has also increased the use of biomass fuels, such as firewood and pellets, in the production of warmth energy for the heating and hot water supply of residential one- and multi-dwelling buildings. In advanced systems, biomass installations are a part of a fully integrated system, including solar power and geothermal heating. With this development, interest to fireplaces has increased in many countries. In Finland, for example, approximately one fifth of all detached, semi-detached and terraced houses have wood-fired heating. Almost all new one-family houses have a fireplace that is generally used as a secondary heat source. The use of firewood and pellets has increased 20% in 15 years, and they provided approximately 40% of the heating energy consumed by detached houses in 2007–2008 [1]. In Sweden, biomass fuels have also accounted for a large increase, and consumption was approximately 35% in 2013 [2].

The use of fireplaces affects buildings' fire safety. Despite mandatory certification procedures, a high number of fires due to the presence of chimneys has been reported in some European countries. For example, in Finland, 700–900 building fires caused by fireplaces and chimneys have been reported annually [3–5]. Similar fire-safety problems have been reported in other European countries [6]. In the United States, the majority of residential fires involve solid-fuelled equipment, and fires are caused by the ignition of structural-frame components [7]. Prefabricated metal chimneys are relatively new products in Finland, and the majority of the metal chimneys in Finland are less than 10 years old. Based on a study by Leppänen [8], the number of fires caused by metal chimneys in Finland was high from 2004 to 2009. In 2012, metal chimneys caused over 70% of all chimney-induced fires in residential buildings in Finland [9]. The safety issue with metal chimneys is important, as they represent only 10% of all chimneys in Finland [10,11].

The new energy regulations have increased the thickness of thermal insulation materials in buildings and the air tightness of structures, which has increased the temperatures and risk of overheating the wood framing or other combustible materials adjacent to fireplaces and chimneys. Critical details for fire safety are where chimneys pass through floors, roofs and walls. Several reasons for chimney

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* Corresponding author.
E-mail address: perttu.leppanen@tut.fi (P. Leppänen).

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Fig. 1. Chimney roof penetration after fire.

penetration–induced fires have been identified: higher actual flue gas temperatures onsite than those assumed in chimney design, incomplete or insufficient chimney installations and the smouldering combustion of rockwool insulation [12]. Fig. 1 shows a site-survey picture from a roof space where the heat of a metal chimney has caused a fire. Thermal insulation of this roof consisted of 300 mm thick layer of sawdust overlaid by an additional 100 mm thick layer of blown cellulose insulation. A 100 mm thick penetration insulation of mineral wool was used to isolate flammable materials from the hot surface of the chimney. In this particular case, the penetration insulation was not sufficient and the cellulose insulation ignited and started a fire.

Fireplaces and chimneys are tested in accordance with EN standards. The standard tests are conducted in predefined laboratory conditions. The actual conditions onsite may be very different from the laboratory conditions. Site conditions vary, for example, due to fuel type and chimney-draught conditions, which depend on site, time, draught controls and the chimney's length and installation method. Chimney design based on EN standard tests should lead to a fire-safe solution. However, previous research on fireplaces has demonstrated that the flue gas temperature given in the CE marking of a fireplace may not always lead to a safe solution and should therefore not be used for the designing of a chimney [11]. Studies by Neri [13], Neri et al. [14–17] and Leppänen et al. [18] have shown that the standard test setup and conditions are often different from the site installations.

To improve the fire safety of metal chimneys, an extensive research program was conducted in the TUT Fire Laboratory at Tampere University of Technology between 2010 and 2016. As part of the program, site tests were conducted to obtain better information on the actual flue gas temperatures and draught levels in real use in households. The aim of the research was to measure the actual flue gas temperatures and draught levels onsite, to determine the difference between the site and standard test conditions and to assess whether standard tests always lead to a fire-safe metal chimney penetration. In this paper, the results of five site tests conducted in four different residential buildings and a sauna are reported.

2. Testing in accordance with EN standards

CE marking of fireplaces is mandatory in European countries, and under the regulations, manufacturer's products are required to demonstrate compliance with laboratory tests by a notified test laboratory. Fireplaces are subjected to two different test: a nominal heat-output test and temperature-safety test in accordance with EN standards [19–22]. In the nominal heat-output test, the properties of the fireplace, such as efficiency, heat output, flue gas temperatures and emissions of the fireplace are determined. For the slow heat release appliances the test is called burning rate performance test. The temperature-safety test is used to demonstrate that the temperatures of the surfaces and structures nearby the fireplace do not exceed given limit values or ignition temperatures. Also for chimneys, two tests are required. Metal chimneys are tested in accordance with standard EN 1859 [23], which prescribes the heat stress test and thermal shock test to verify the safety distance between the outer face of the chimney and combustible materials. The purpose of the tests is to avoid overheating the materials in the chimney penetration area. In the chimney design, the temperature class based on the chimney tests must be equal or higher than the mean flue gas temperature recorded in the CE marking of the fireplace connected to the chimney.

The nominal heat-output test is performed at constant flue draught pressure following the manufacturer's recommendations regarding the test fuel, the burning rate and the combustion controls settings to be used to achieve the claimed nominal heat output during the test. The appliance is refuelled in accordance with manufacturer's instructions. Flue gas temperatures are measured during the test. The mean value of the flue gas temperatures measured is recorded to CE-marking to assist chimney design. In the temperature safety test higher draft level and a larger amount of firewood are used. The fire load of the temperature-safety test is specified by the standard either based on the size of the firebox [21,22] or on the fire load used in the nominal heat-output test [19,20]. In the temperature-safety test, a fireplace's flue draught is set to a constant value, 3 Pa higher than in the nominal heat-output test. Flue gas temperatures and draught levels are measured from a point approximately 1.4 m above the fireplace. Flue gas temperatures are not required in the temperature-safety test. The test arrangement is shown in Fig. 2a). The burning rate performance test and temperature-safety test results of a slow heat release appliance are shown in Fig. 3a. Fig. 3b shows the measured flue draught levels in the same tests.

In the heat stress test of metal chimney, hot gas is fed into the chimney. The temperature of hot gas depends on the temperature class specified for the chimney. The test structure consisting of two walls at right angles and two floors through which the test chimney passes. Temperatures within the floor construction are measured during the test and the test is maintain until an equilibrium is reached in the floor temperatures. It must be demonstrated that the surface temperatures at a safety distance specified by the manufacturer do not exceed 85 °C. The safety distance is measured from the outer surface of the chimney. In the thermal shock test, flue gas temperatures are kept at 1000 °C for 30 min. In the test criteria, the maximum surface temperatures measured inside the floor construction are limited to 100 °C. The manufacturer shall declare the minimum distance to combustible material and the performance need to be demonstrated by tests. The heat stress test is repeated after the thermal shock test. Test arrangement for metal chimneys is shown in Fig. 2b).

3. Previous research

3.1. Laboratory tests

Leppänen et al. [11] have studied the flue gas temperatures of fireplaces in laboratory conditions. Their study included a nominal heat-output test, a temperature-safety test, and extra heating, in which firewood batches larger than the recommended size were used to

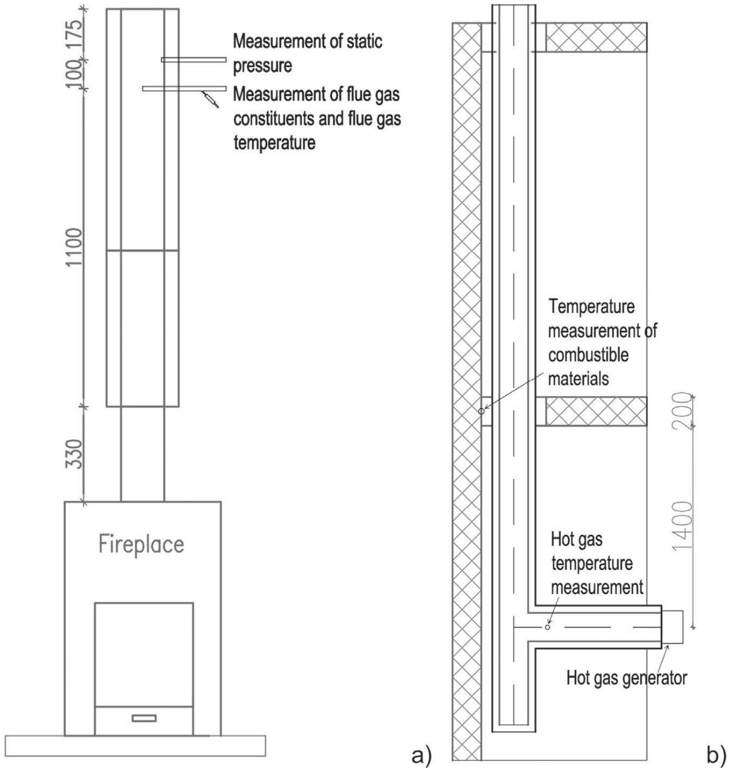


Fig. 2. Test arrangements according EN standards for: a) Fireplaces; b) Metal chimneys.

demonstrate misuse. The highest measured flue gas temperatures in the temperature-safety tests were 124 °C to 381 °C above the flue gas temperature indicated in the CE marking. The study concluded that the mean flue gas temperature measured in the nominal heat-output test of EN standards should not be used for the designing of a chimney; instead, the highest flue gas temperature of the temperature-safety test should be used. Furthermore, they also tested how higher fuel loading than that given in the manufacturer's instructions affects flue gas temperatures. Higher loading is possible if the occupant does not read the manufacturer's instructions. When a room heater was fuelled with 1.3-

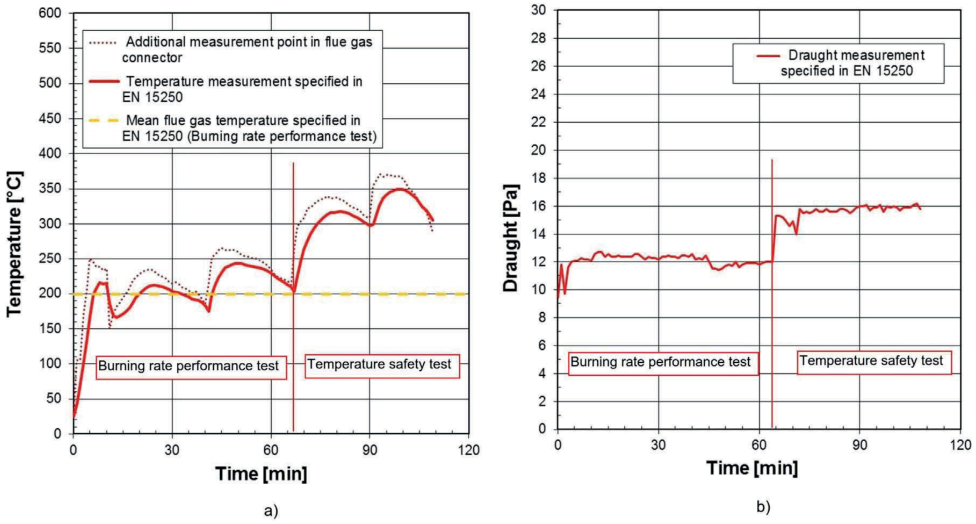


Fig. 3. Typical a) temperature and b) draught measurements from a burning rate performance test and a temperature safety test of a slow heat release appliance. Horizontal dashed line represents the mean temperature recorded to CE-marking.

kg larger wood batches (3.0 kg), the highest flue gas temperature was approximately 90 °C higher than in normal use when the wood batches were 1.7 kg. When the heating of the room heater was continued with the same size of wood batches (3 kg) and the flue draught was increased to 15 Pa, the flue gas temperature increased and was 160 °C higher than the temperature in normal use.

Oravainen [24] have studied the flue gas temperatures of a room heater, sauna stove and a slow heat-release appliance by conducting a nominal heat-output test, temperature-safety test, and overheating test on the fireplaces. In the overheating tests, the highest flue gas temperatures were 295 °C to 478 °C above those indicated in the in CE marking. In a couple of tests, the flue gas temperatures exceeded 600 °C. Mitchell performed fire hazard tests with masonry chimneys [25]. In the tests, the flue gas temperature of a stove exceeded 900 °C in five minutes and were nearly 1000 °C in 10 min. The flue gas temperatures of different fireplaces have also been studied by Peacock [26]. The study included 18 typical commercial fireplace in the USA. In 14 tests flue gas temperatures were 600 °C or higher. In another study by Peacock [27], the measured flue gas temperatures varied between 426 °C and 519 °C for normal heating conditions and between 574 °C and 855 °C for overheating conditions. In tests conducted by Hansen et al. [28] the flue gas temperatures measured were 240 °C to 584 °C and 379 °C to 879 °C in normal and overheating conditions, respectively. In tests conducted by Inha et al. [29] on sauna stoves temperatures up to 1000 °C were measured. Loftus et al. [30] tested 17 different wall pass-through systems (thimble-chimney connector) connected to a chimney flue gas connector and a stove. In these tests, the ability of the pass-through systems to provide thermal protection at chimney-wall penetration area was studied. In the tests, the three temperatures of flue gases were used, 538 °C, 593 °C and 649 °C. Hansen et al. [31] studied damage to block chimneys. Their tests simulated possible intense heating. In intense heating, the highest flue gas temperature at the flue-gas connector exceeded 900 °C. During intense heating, the chimney draught was as strong as 45 Pa. Even during the ignition load, the chimney draught was approximately 20 Pa. Achenbach et al. [32] studied the performance of masonry chimneys under steady state conditions. In the tests, they used three different gas temperatures and three different gas flow rates. The results demonstrated that higher inlet gas temperatures increased the flue draught. Type of masonry material and liner, and treatment of air space affected the flue draught very little. Even if the above test evidence clearly demonstrate flue gas temperatures exceeding 600 °C, the highest temperature class recognized by the standards is T600 with a maximum allowable flue gas temperature of 600 °C [33].

In a chimney fire, residue deposits referred to as soot or creosote, on the inner surfaces of chimney flue ignites and starts burning which increase the flue temperatures significantly. Peacock [34] has studied the critical conditions of soot fires in masonry chimneys by means of 12 tests. In these tests, the peak gas temperatures in chimney flues and connectors were studied. The maximum temperatures measured during the tests were 908 °C to 1370 °C. The soot fires had relatively short duration and the entire exposure time, during which the flue gas temperatures were over 600 °C, lasted 5–44 min, the average being 19 min.

Inha et al. [35] performed two tests using a slow heat release appliance with an ignition damper. Ignition dampers are used in slow heat release appliances where the flue gas channels inside the appliance are long and it is difficult to provide sufficient flue draught for ignition. A shorter access is therefore provided for the flue gasses from firebox into the chimney through a damper temporarily open during the ignition. This damper is different from the normal flue damper typically located above the fireplace and used to control the removal of gasses. The ignition damper is illustrated in Fig. 4. The aim of the tests was to demonstrate the effect of the ignition damper on flue gas temperatures. The measured flue gas temperatures were 120 °C higher when the ignition damper was left open after ignition. In normal use, the ignition damper is open during the ignition only and closed when the fire has strongly ignited. The test demonstrated that if the damper is left open for a long time, the risk of fire increases.

3.2. Field tests

Little information is available on actual flue gas temperatures in residential buildings. Hansen et al. [36] have studied the use of fireplaces in Norway. The study included a questionnaire on the use of fireplaces, and they also measured flue gas temperatures in the field and laboratory. The tested fireplaces were room heaters. In the tests, flue gas temperatures were measured from three different locations: the flue-gas connector, the chimney 1 m above the flue-gas connector and the chimney 1 m below its top. Chimneys used in the tests were block or masonry chimneys. In the field tests, the highest flue gas temperatures measured in the connector were approximately 350–700 °C, and the mean flue gas temperatures in the connector were approximately 260–450 °C. The highest flue gas temperatures measured from the chimney 1 m above the connector were only approximately 100–430 °C. The study found a contradiction between the testing of fireplaces and their actual use in Norway. However, the difference was not considered significant enough to require changes in the testing procedures of fireplaces. It was found that the occupant is refuelling the fireplace at longer intervals and larger batches than in standard testing. After ignition, the occupant normally uses 2–3 larger batches before switching to normal heating. The study also revealed that heating periods are longer than in tests, but it is uncertain whether that leads to higher thermal stresses. According to the measurements, fireplace draughts are weaker in actual use than in tests. That may cause soot build up in a chimney. According to the study, temperatures in prefabricated block chimneys are considerably higher than in masonry chimneys.

The use of fireplaces in Finland differs somewhat from what is customary in Norway. The biggest difference lies in the type of fireplaces used. The most common types in Finland are slow heat-release appliances and wood-burning sauna stoves. Sauna stoves are intended to heat the indoor air in a sauna rapidly to a temperature suitable for bathing at approximately 70–100 °C. Moreover, the stones must stay hot enough for the duration of the bath, which can take several hours.

4. Experimental field study

4.1. Test programme

The previous research [11,24–29,31] reported in Chapter 3 demonstrated that flue gas temperatures can be significantly higher than specified in the CE marking used for chimney design. A series of field tests was performed to study flue gas temperatures and flue draughts in fireplaces and chimneys in their real environment and conditions in people's homes [37]. The aim of the field tests reported here was to study if the flue gas temperatures onsite exceed the allowable levels to better understand the reasons for the high temperatures and estimate the actual risk of fire in buildings. Test sites were found through agreements with home owners and construction companies.

In this article, tests on five fireplaces are introduced, including three similar room heaters (free standing wood stove), one slow heat-release appliance, and one wood-burning sauna stove. The definitions of the three type of heaters are given in EN standards. Room heater is an appliance having a fully enclosed firebox with a firedoor which is normally closed. The appliance distributes heat by radiation and/or convection. Slow heat release appliance is an intermittent burning appliance having thermal storage capacity to accumulate heat into its own mass such that it provides heat for a period of hours after the fire has gone out. Sauna stove distributes heat by radiation and/or convection and it is fitted with stones or other heat retaining material onto which water is poured to produce hot steam/vapour that rises from the hot sauna stones. The tested fireplaces are shown in Fig. 5, and their

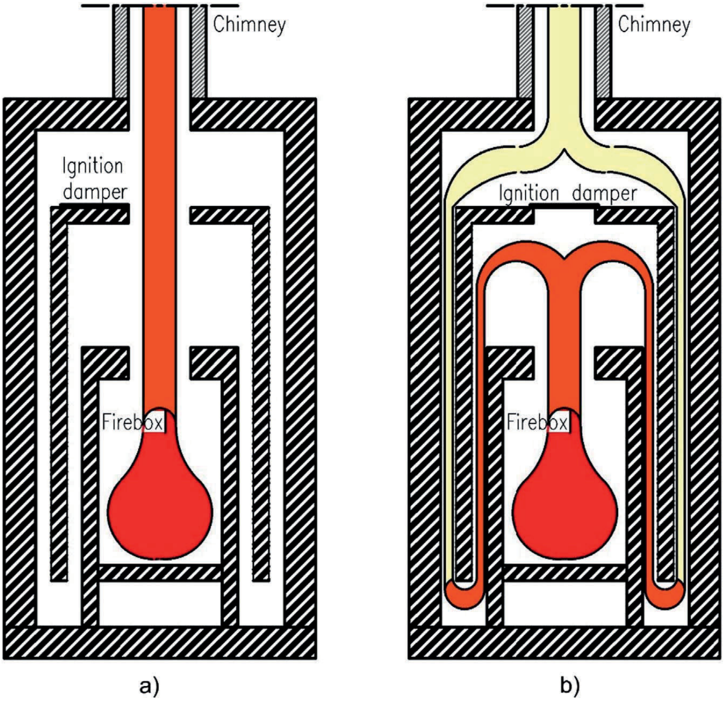


Fig. 4. Illustration of an ignition damper; a) Ignition damper open, b) ignition damper closed.

technical information is presented in Table 1. All fireplaces were CE-marked, and in the tests, they were operated in accordance with the manufacturer's instructions. The use and operation of the three type of fireplaces differ significantly from each other.

Room heaters 1 and 2 were located on the first floor of two-story residential buildings. Room heater 3 was located in a single-story residential building, and the metal chimney was semi-insulated for the first 0.95 m of its length and thereafter fully insulated, extending from the top of the room heater. In all room heaters, the metal chimney was connected from the top. The fully insulated section consisted of a 60 mm thick layer of mineral wool and in the semi-insulated section, the layer was 30 mm thick.

The tested slow heat-release appliance was located on the first floor of a two-story residential building. The metal chimney was connected from the top of the fireplace.

The tested sauna stove was installed in a lakeside log sauna building. The inside floor dimensions of the building were 2.8 m × 2.75 m. The floor-to-ceiling height was 2.25 m at the eaves and 2.75 m

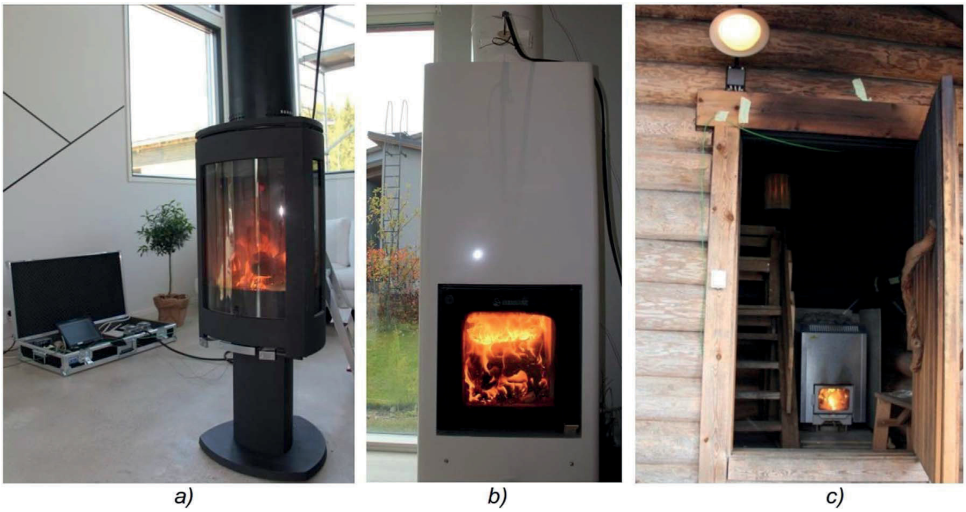


Fig. 5. Tested fireplaces: a) Room heater 1 and site measurement equipment, b) Slow heat release appliance, c) Exterior view of lakeside sauna and sauna stove.

Table 1
Technical information on the tested Fireplaces.

	Height [mm]	Width [mm]	Depth [mm]	Weight [kg]	Thermal output [kW]
Room heater 1, 2, 3	1150	442	452	156	5.5
Slow heat release appliance	1650	594	514	495	–
Sauna stove	700	520	620	200 (incl. Stones 110)	25

Table 2
Test program.

Fireplaces	Field test(s)	Laboratory test(s)
Room heater 1, 2, 3	Nominal heat output test	Lab test 1, 2 and 3
Slow heat release appliance	Burning rate performance test[a]	Earlier laboratory tests [35]
Sauna stove	Actual use of the lakeside sauna	Values informed by the manufacturer

[a] Burning rate performance test of slow heat release appliance corresponding nominal heat output test.

at the ridge. The volume of the sauna was approximately 19 m^3. The sauna stove was designed for an 8–20 m^3 sauna. The sauna stove was connected with a rear flue connection, and the chimney penetrated an external log wall behind the sauna stove.

In all the field tests, the standard methods of fire tests were followed as much as possible without damaging the equipment or affecting the fire safety of the building. The test programme is concluded in Table 2.

For the three room heaters, nominal heat-output tests were conducted in accordance with standard EN 13240 [19]. The temperature measurement points of room heaters 2 and 3 deviated from the points specified in standard EN 13240; therefore, the same type of room heater was also tested in the laboratory to determine flue gas temperatures at the point specified by standard EN 13240 and at the flue-gas connector located 50 mm above the fireplace. First, a standard nominal heat-output test (lab test 1) was conducted, followed by a test in which the originally uninsulated flue was insulated using mineral wool (lab test 2).

In the standard test assembly of EN 13240, the appliance is connected to the chimney flue through an uninsulated flue-gas connector. The measurement section above the connector is fully lagged with 40-mm thick thermal insulation to provide a thermal conductivity of 0.04 W/mK at an average temperature of 20 °C. In all tested room heaters, the chimney flues were insulated. To better understand how much the insulated chimney flue affects gas temperatures, an additional laboratory test (lab test 2) was undertaken. By comparing the temperatures of lab tests 1 and 2, the possible increase in gas temperature can be determined.

In the third laboratory test (lab test 3), the flue draught at the flue-gas connector was set to a value equal to the draught measured onsite.

The slow heat-release appliance was subject to a burning rate performance test, and the approach of standard EN 15250 [22] was followed as closely as possible. In previous research, Inha et al. [35] conducted laboratory tests with a similar type of fireplace.

The sauna stove was tested for conditions which correspond to normal use in Finland, as the site conditions were very different from those specified in standard EN 15821. The sauna stove was first heated so that the temperature of the air in the sauna was 100 °C. Afterwards, people bathed in the sauna. A total of 169 min from the beginning of the test, the measuring was interrupted by a power failure. The measured temperatures and draught levels represent real winter conditions. The manufacturer of the sauna stove also gave the highest flue gas temperature of the temperature-safety test.

4.2. Test set-up and measurement points

Flue gas temperatures and flue draughts were measured and recorded during the tests. The flue gas temperature and draught are dependent upon the location of the measurement point along the chimney flue. Onsite conditions, it is impossible to install the sensors exactly in the locations the EN test standards specify. As the measurement point locations deviated from the standard, additional laboratory tests were performed to derive the relationship between the temperatures and draughts measured at different locations. The structural sections of the fireplaces and chimneys and the measurement points of the flue gas temperatures and draught are shown in Fig. 6. In the test of room heater 1, measurements were taken from a measurement point located 1.19 m

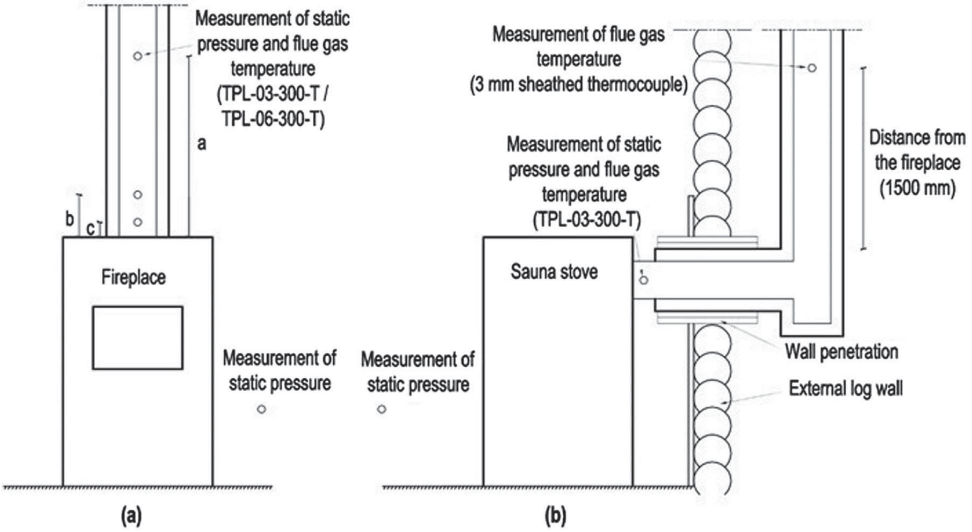


Fig. 6. Measurement point locations for (a) room heaters and slow heat release appliances and (b) sauna stove. Site dimensions a, b and c are given in Table 3.

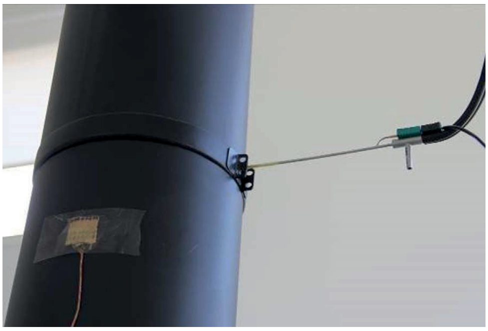


Fig. 7. Flue gas temperatures and draught of Room heater 1 were measured through a 3 mm hole drilled through a collar plate of a chimney element joint which located 1.19 m above the fireplace.

above the fireplace, which is relatively close to the measurement section of the test standards. The measurement sensor was installed through a 3-mm hole drilled through a collar plate of a chimney element joint. The installation shown in Fig. 7 included both the temperature and pressure sensors. The measurement points of room heaters 2 and 3 were located at the flue-gas connector 50 mm above the fireplaces. For the slow heat-release appliance, measurements were taken at the ignition damper located 160 mm above the top of the fireplace.

In the test of the sauna stove, gas temperatures and draught levels were measured at two points. One point was at the flue-gas connector. The other one was installed following the instructions of EN 15821, and the point was located outside of the building envelope 1500 mm above the top of the sauna stove. In addition, the surface temperatures of the chimney and external log wall were measured at the wall penetration. The temperature of the sauna was measured in the middle of the room 300 mm below the ceiling, as has been presented in standard EN 15821.

The measurement point locations for all tests are shown in Fig. 6. Chimney dimensions and the outdoor air temperatures at the time of testing are reported in Table 3. These site conditions are different from the standard test specifications and have an effect on the flue-draught levels.

4.3. Site-measurement system and sensors

Temperatures were measured with an NI 9213 thermocouple module. Pressure differences were measured with Huba Control 699 differential pressure transmitters. The sensor used for flue gas temperature and draught measurements in the room heater and sauna stove tests was Kimo TPL-03-300-T. The sensor used to test the slow heat-release appliance was Kimo TPL-06-300-T. In the sauna stove test, flue gas temperatures were also measured using a shielded thermocouple wire (Ø 3 mm) to a standard's measuring section. Measurements were recorded at intervals of 15 s.

Table 4
Wood batches and charging intervals in the room heater tests. Lab. tests are described in clause 4.1. CE test refers to the interval specified in the manufacturer's instructions and CE marking.

	Batch [kg]	1.4	1.4	1.4	1.4	1.4	2.8
Time [min]	Room heater 1	0	15	51	81		
	Room heater 2	0	15	58	95		
	Room heater 3	0	27	57	87		
	Lab. test 1	0	40	85	130		
	Lab. test 2	0	40	85	130		
	Lab. test 3	0	30	65	100	135	176
	CE test	0	45	90	135	180	

5. Testing and results

5.1. Room heater tests

Birch logs, the moisture content of which was approximately 8 wt%, were used as firewood. The amount of firewood was based on the operating instructions of the room heater. The charging intervals are different from the operating instructions because the flue draught was not controlled during the field tests. As the draught levels onsite were higher than in the standard test, the flue gas temperature was higher, and the firewood burned faster than in standard test conditions. The wood batches and charging intervals used in the room heater tests are presented in Table 4.

The test results are presented in Figs. 8–10. The first graph in each Figure represents the flue gas temperature, and the second is the draught. The solid line represents the data recorded during the test, and the dotted line represents the mean value of the recorded temperatures. The dashed lines represent the mean flue gas temperature the manufacturer has given based on nominal heat-output tests. In the three tests, the mean flue gas temperatures were approximately 100 °C higher than those indicated in the CE marking. The main reason for the higher temperatures is assumed to be the flue draught, which was considerably stronger during the field tests than in the standard nominal heat-output test. Due to the stronger draught, wood batches had to be fed more often than in the standard nominal heat-output test. It is obvious that a user will also follow this shorter charging interval. As described in Section 4.3, the location of the temperature and draught-measurement points of all three field tests were closer to the fireplace than the measurement point specified in the standard. The effects of these variations on the flue gas temperatures were studied in more detail by conducting three laboratory tests. The results of these tests are introduced and discussed next.

5.1.1. Lab test 1

In the tests of room heaters 2 and 3, the flue gas temperatures were measured from the flue connectors located 50 mm above the appliances. Lab test 1 was conducted to determine the temperature difference between the flue-gas connector and standard measurement point 1.4 m above the appliance. Based on the results of lab test 1, the mean gas temperature in the connector was 44 °C higher than that measured from the standard measurement point. The mean gas temperature

Table 3
Locations of flue gas temperature and pressure measurement points and chimney dimensions, refer to Fig. 6.

	Distance between the top of the fireplace and the measurement point [mm]:	Height of the chimney [m]	Diameter of the flue [mm]	Outdoor air temperature [°C]
Room heater 1	a = 1190	7.5	134	26
Room heater 2	c = 50	4.6	150	22
Room heater 3	c = 50	4	150	7
Slow heat release appliance	b = 160	8	150	10
Sauna stove	1500	3.5	114	0

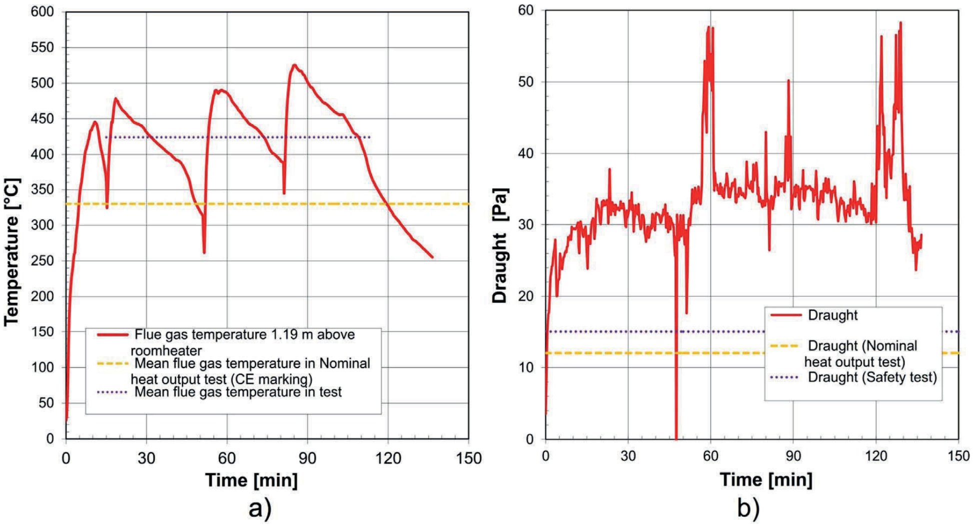


Fig. 8. Flue gas temperatures and flue draught of test on Room heater 1.

measured from the standard point in lab test 1 was 284 °C. Based on this information, it can be assumed that the mean flue gas temperatures at the standard measurement point locations were around 400 °C and 450 °C for room heaters 2 and 3, respectively. The temperatures are 70–100 °C higher than the values recorded in the CE markings of the appliances.

5.1.2. Lab test 2

As all chimney flues onsite were insulated and the standard nominal heat-output test was undertaken with an uninsulated flue-gas connector, lab test 2 was conducted to study the effects of the insulation on flue gas temperatures. Based on the test results, the insulation had only a small effect on flue gas temperatures.

5.1.3. Lab test 3

As the flue draught was measured from the flue connectors located 50 mm above room heaters 2 and 3, lab test 3 was conducted to determine the difference in draught values measured from the connectors and standard measurement point 1.4 m above the appliances. Laboratory tests revealed that when the flue draught was 12 Pa at the point specified in the standard, the measured draught value at the flue connector was approximately 22 Pa. When the draught increased to 15 Pa, the draught at the flue connector was approximately 25 Pa. When the draught at the flue connector was set to 32 Pa, corresponding to the field measurements, the draught at the point specified in the standard was approximately 19 Pa. The difference in pressure between the two measurement points was approximately 10 Pa. Based on these results, the draught values at the standard measurement point locations were approximately 20–25 Pa for room heaters 2 and 3. By comparing Figs. 11 and 12, it can be seen that by increasing the draught from 12 Pa to 20 Pa, the mean flue gas temperature increased by approximately 50 °C. To study the effects of overloading the fireplace, the firewood

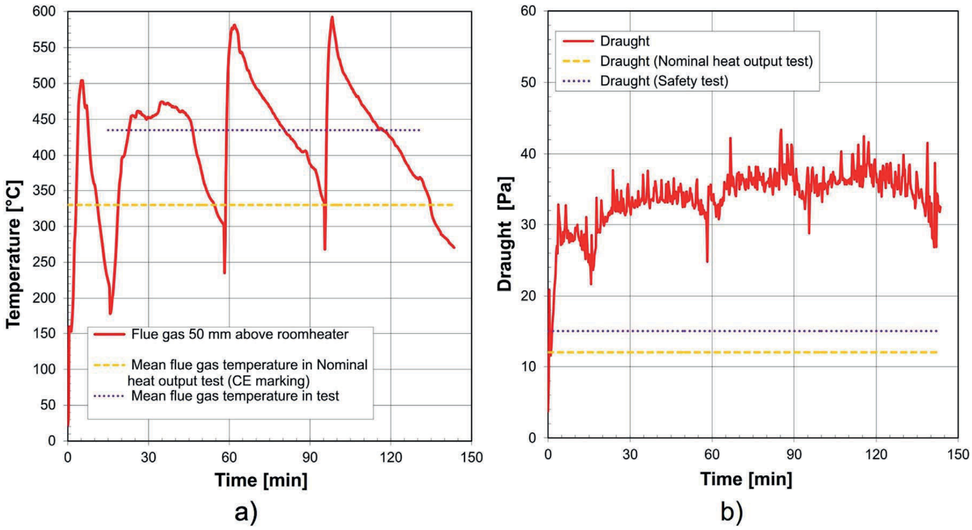


Fig. 9. Flue gas temperatures and flue draught of test on Room heater 2.

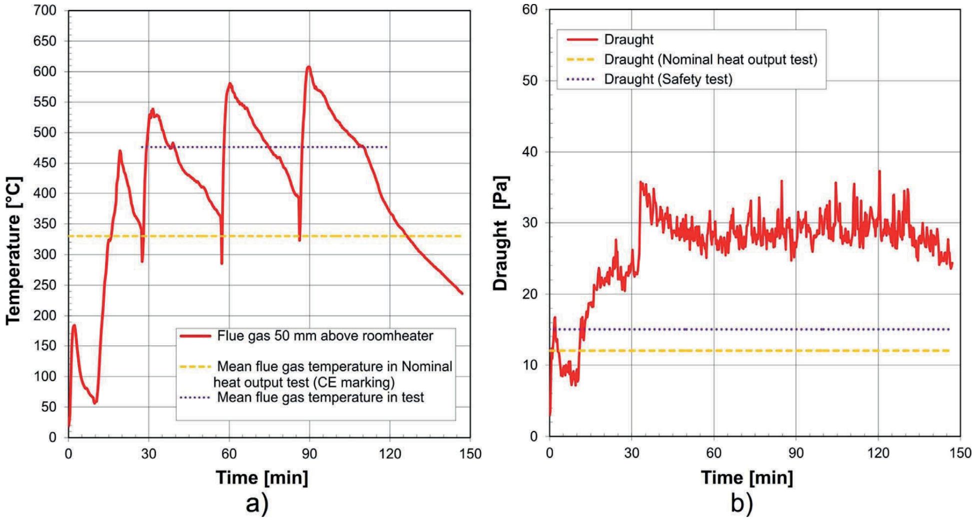


Fig. 10. Flue gas temperatures and flue draught of test on Room heater 3.

batch was increased from 1.4kg to 2.8 kg 180 min after the beginning of the test. As can be seen in Fig. 13b), the bigger firewood batch can be easy fitted in the firebox, and it is possible that a user accidentally misuses the appliance if he or she does not check the mass of the wood batches. A bigger load batch increased the flue gas temperature by approximately 100 °C.

The above test results demonstrate that the flue gas temperatures measured from room heaters operating in actual field conditions can be significantly higher than temperatures given in the manufacturers' instructions and CE markings. Temperature differences as high as 100 °C were recorded. Lab test 3 also showed that the misuse of the fireplace can further increase the flue gas temperature by 100 °C.

5.2. Test of slow heat-release appliance

The mass of the fuel load and refuelling intervals declared by the manufacturer were used in the test. Birch logs, of which the moisture content was approximately 8 wt%, were used as firewood. The wood batches and charging intervals are presented in Table 5.

The flue gas temperatures and flue draught of the tested slow heat-release appliance are shown in Fig. 14. The field-measured flue gas temperatures were higher than what was reported in previous laboratory tests Inha et al. [35] performed on the same appliance. In the previous laboratory test, flue gas temperatures were measured from the point specified in standard EN 15250 and from the flue-gas connector. In the burning rate performance test of the fireplace, the mean flue gas temperature was only 11 °C higher in the connector than that measured from the point specified in standard EN 15250. In the laboratory test, the mean temperature measured from the point specified in the standard was 250 °C, which is more than 40 °C higher than the flue gas temperature specified in CE marking. It can be seen from Fig. 14 that the mean flue gas temperature of the field test 160 mm above the appliance was 275 °C. Based on previous laboratory tests [35], it can be assumed that the temperature at the standard measurement location is approximately 10 °C lower, i.e., 265 °C. This is 65 °C higher than the temperature given by the manufacturer. The reason for the higher flue

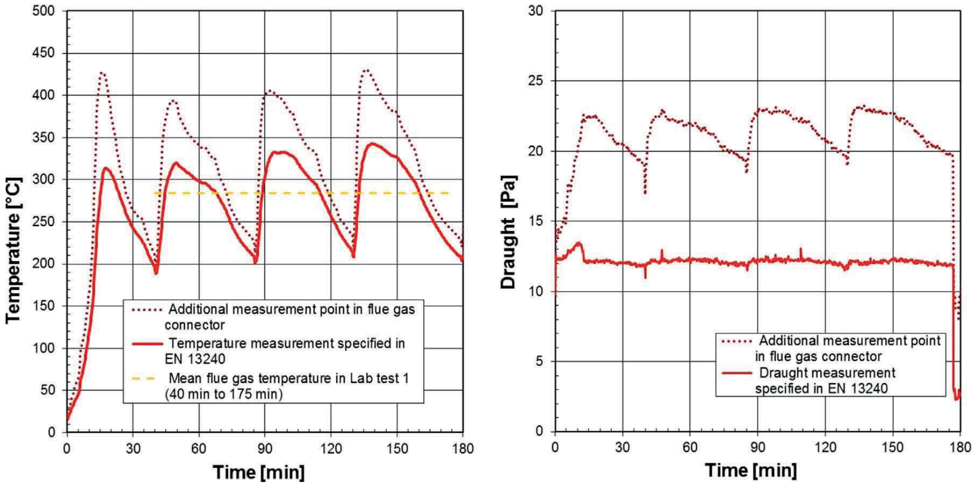


Fig. 11. Flue gas temperatures and flue draught of Lab test 1 on Room heater.

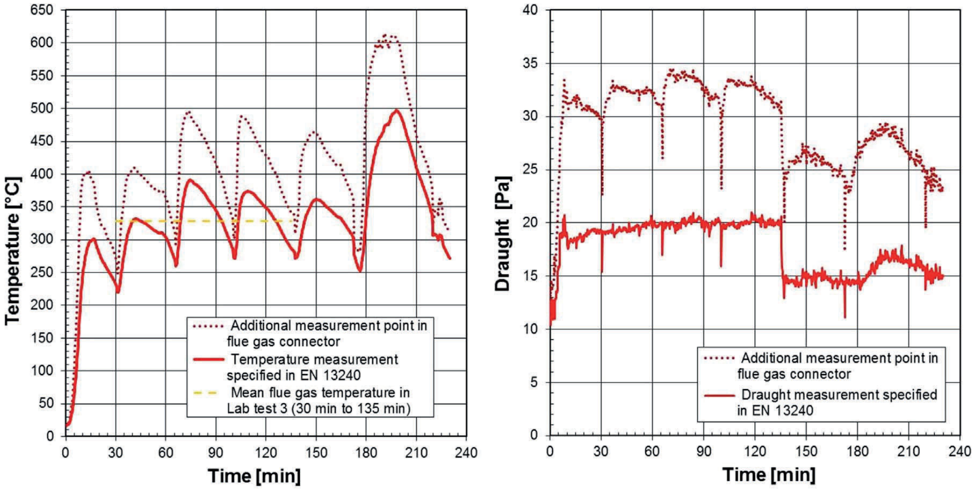


Fig. 12. Flue gas temperatures and flue draught of Lab test 3 on Room heater.

Fig. 13. a) The 1.4 kg wood batch used in field test. b) The bigger 2.8 kg wood batch in Lab. test 3.

Table 5
Wood batches in test of slow heat release appliance.

Time [min]	0	19	49	81
Batch [kg]	2.5	2.5	2.5	2.5

gas temperatures can be the considerably stronger flue draught than that used in the standard nominal heat-output test. The instructions for the fireplace recommend that the damper be used to control the flue draught. In this field test, that was not possible; the damper had to be removed to allow the installation of temperature and flue-draught sensors. This faulty situation can also occur if the occupant operating the fireplace does not use the damper properly and leaves it open.

5.3. Test on a sauna stove

The amounts of firewood, firewood-charging intervals and draught controls were recorded during the test. In accordance with the manufacturer's instructions and CE markings, the initial charge was 4 kg, and the additional batches were 2.8 kg each. In the temperature-safety test, the batch size was 4.3 kg. In this field test, the wood batches were approximately the same size as the additional batch of the nominal heat-output test. Birch wood with a moisture content of approximately 14 wt% was used as firewood. The wood batches used in the test are presented in Table 6. The outdoor air temperature during the test was 0 °C, which was also the temperature of the lakeside sauna at the beginning of the test. The test was interrupted due to a power failure 169 min from the beginning of the test.

The flue gas temperatures of the tested sauna stove and the sauna temperatures are presented in Fig. 15a) and flue draught in Fig. 15b). In the Figures, the flue gas temperatures recorded during the field test are

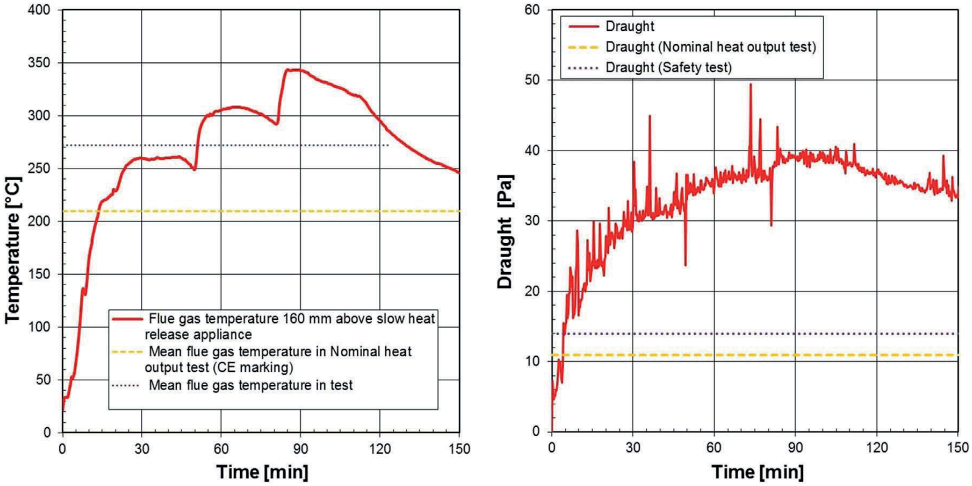


Fig. 14. Flue gas temperatures and flue draught of test on slow heat release appliance.

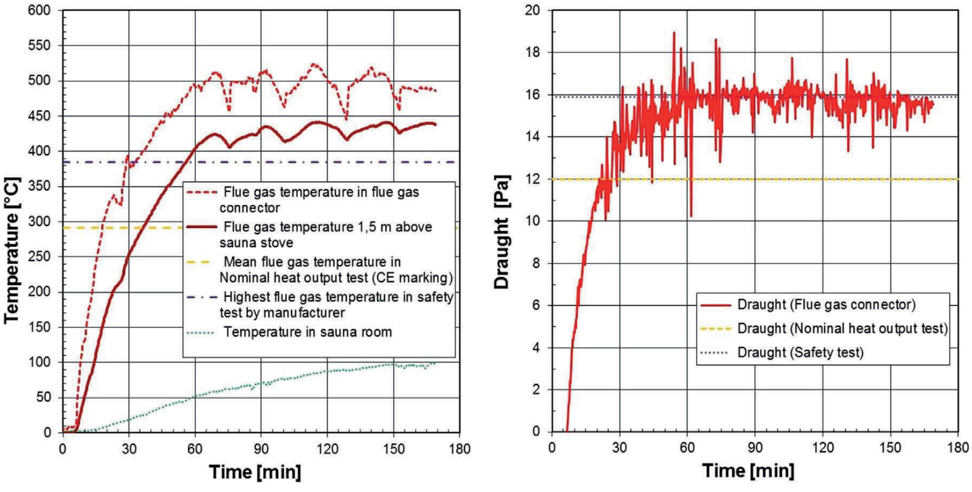
Table 6
Wood batches in test of sauna stove.

Time [min]	0	29	52	77	102	131	154
Batch [kg]	2.6	2	2.1	2.8	2.8	2.4	2.4

compared against the nominal heat-output test and temperature-safety test results given in the manufacturer's instructions. During the heating of the sauna stove, flue gas temperatures remained for a long time above the highest temperature of the temperature-safety test conducted by the manufacturer (dashed-dotted line). Flue gas temperatures measured from the flue-gas connector were approximately 100 °C higher than those measured from the chimney flue 1.5 m above the appliance. For fire safety, the flue-gas connector location represented the critical design condition in this building, as the horizontal flue outlet penetrated the wall immediately after the flue-gas connector. The mean flue gas temperature measured 1.5 m above the sauna stove was 355 °C. The mean flue gas temperature the manufacturer declared for the nominal heat-output test is 291 °C, which is significantly lower than the field-measured value. The field measurements also exceed the highest flue gas temperature of 384 °C the manufacturer has given for the safety test. The test results demonstrate that the flue gas temperatures in the actual field conditions can be significantly higher than those measured during a standard laboratory test. In this sauna-stove test, the temperature difference was approximately 100 °C.

5.4. Evaluation of measured temperatures

Flue gas temperature and flue draught are dependent on the location they are measured from along the chimney flue. The measured values cannot be directly compared with the value that has been given in the CE marking if the measuring location is different. The temperatures of flue gases and flue draught measured in the field tests has been compared with values measured in the laboratory from the same



a)

b)

Fig. 15. Flue gas and sauna temperatures and chimney draught of the sauna stove test.

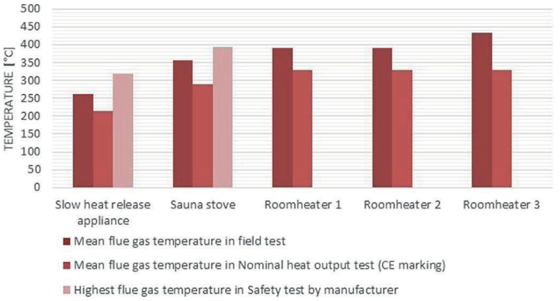


Fig. 16. Summaries of the flue gas temperatures of the tested fireplaces at the standard measurement point location.

location. Summaries of the flue gas temperatures of the tested fireplaces are presented in Fig. 16. If the values in the field tests have not been measured from the standard measurement point location, calculatory values have been used.

Differences also exist between the laboratory tests. The informed mean flue gas temperature of the slow heat-release appliance is 215 °C, and the highest flue gas temperature of the safety test is 320 °C. However, Inha et al. [35] measured temperatures, respectively, of 250 °C and 368 °C. The informed mean flue gas temperature of the room heater is 330 °C. Even so, the mean flue gas temperature was only approximately 290 °C in lab test 1.

6. Discussion

6.1. *The effects of field conditions on the flue gas temperature*

In all field tests, flue gas temperatures higher than specified in the manufacturer's instructions were measured. For the room heaters and sauna stove, the temperatures were approximately 100 °C higher. Temperatures measured for the slow heat-release appliance were 50 °C higher.

The tests aimed to use the fireplaces according to the operating instructions. This was done to assess the effect of different conditions on flue gas temperatures and fireplace draught. Using a fireplace contrary to the operating instructions increases fire hazard. However, the exact recommended wood batch sizes are not normally used when heating a fireplace, nor is draught control always done properly.

A higher flue draught raises the flue gas temperature of fireplace. In this study, the effect was approximately 50 °C when the flue draught was 8 Pa higher than standard test. In addition, a higher draught guide adds wood batches often, which raises flue gas temperature even more. Too high of a draught can be restricted with a chimney-draught limiter. The problem is that the value for a draught that is too high is not known.

6.2. *The effects of the misuse of the fireplace on the flue gas temperatures*

The way a fireplace is operated has a significant impact on the flue gas temperatures. As fireplaces are often considered seemingly simple and easy to operate appliances, the users often do not read manufacturer's instructions or follow them accurately. The instructions of more complicated and dangerous equipment are typically studied much more carefully and obeyed. It is difficult to distinguish visually when the flue gas temperatures are too high and to prevent the user from overheating the fireplace.

One solution to avoid overloading is to design the firebox such that there is no room for an oversized batch. For example, the sauna stove tested in this research was equipped with a fireplace door, which limited the loading of the firebox up to the top level of the doorframe. Even when the stove was fully loaded, it was not overloaded and the solution provided sufficient space above the firewood for effective burning process. However, many sauna stoves on the market have a firebox twice as big as the maximum wood batch given in the manufacturer's instructions. Thus, a potential risk exists of flue gas temperatures to exceed the temperatures used in the chimney design.

The effects of misuse were also studied by doubling the firewood batch in a room heater test, refer to Fig. 13b). For the most efficient visual experience, the size of the glass door is often maximized and, as can be seen from the figure, the double batch was easy to fit into the fireplace and the loading is not visually alarming. However, the double batch increased the flue gas temperature by approximately 100 °C causing a potential fire risk if the chimney attached to this fireplace is not designed for the higher temperature level. In this firebox with full size glass door, it is very difficult to restrict the use of the firebox without affecting the visual appearance of the fireplace. In this type of designs, the potential risk of misuse should be considered in the testing procedures at least to some extent.

Previous study on a slow heat release appliance demonstrated that defective use of an ignition damper of the fireplace can increases the flue gas temperatures over 100 °C. It is important that the ignition damper is kept open during the ignition only.

The results of this experimental study demonstrate that it is of great importance that the user is familiar with the operating instructions, and that the maximum allowable batch sizes and charging intervals specified by the manufacturer are somehow controlled and not exceeded. Methods to overcome these issues can include end-user training, detailing of the firebox, and amendments to test standards and procedures. As it is impossible to remove and control all the uncertainties related to the behaviour of the end users, the main responsibility for fire safety should always lie with manufacturers and standardization.

6.3. *The effects of higher flue gas temperatures on the fire safety of chimneys and chimney penetration*

Chimneys are dimensioned in accordance with the instructions of the fireplace manufacturer. The temperature class of the chimney should be equal to or higher than the mean flue gas temperature given in the CE marking of the fireplace. The standard chimney test method of EN 1859 [23] limits the maximum temperatures of structures adjacent to the chimney to 85 °C. Higher flue gas temperatures will increase the temperatures of the chimney construction and the temperatures of building structures and materials adjacent to the chimney penetration. Metal chimneys have low thermal inertia, and, thus, the temperatures around the chimney rise faster than in the case of masonry chimney construction.

The effects of different exhaust-gas temperatures on the temperatures of combustible materials adjacent to chimneys have been investigated by means of numerical simulations [18] performed with a 2D numerical model. In the simulations, metal-chimney constructions insulated with 25-mm and 65-mm-thick layers of non-combustible mineral wool were considered. The simulations demonstrated that when the exhaust gas temperature increased by 150 °C, the surface temperatures of combustible material increased by approximately 70 °C and 50 °C for the 25-mm and 65-mm-thick insulation layers, respectively. In the field tests, the flue gas temperatures exceeded the temperatures given in the CE marking by approximately 130 °C. As the test method of EN 1859 [23] limits the maximum surface temperature of combustible materials to 85 °C, it is possible that temperatures have been as high as 130–150 °C in the structures adjacent to the tested chimneys. In addition, many other factors can raise temperatures in structures adjacent to chimneys [18].

Exposure to high temperatures at the chimney penetrations is usually short term (minutes to a few hours). According to Babrauskas et al. [38], the ignition temperature of wood-based materials in these conditions is approximately 250 °C. However, it is possible in residential use that the exposure is longer, particularly for sauna stoves and room heaters. After 20 h of exposure, lower ignition temperatures can be as low as 120 °C [39]. Based on the results of this research, a potential for fire risk exists.

Ongoing research is occurring at Tampere University of Technology to study the combustion of organic material, e.g., binders, of the thermal insulation materials used in chimneys and penetration constructions. Preliminary results have indicated that this phenomenon can increase temperatures in penetration construction by 100–200 °C. The duration of the phenomena is typically less than 2 h, and the combustion of the organic material occurs during the first heating operation. This can affect fire safety when a fireplace is used for the first time and the heating operation occurs for a long period of time.

6.4. *Fire safe flue gas temperature for the designing of a chimney*

The temperature safety test for fireplaces is designed to emulate continuous intense heating of a fireplace. Therefore, it would be natural to use the same condition and results also for chimney design. Currently the chimney design is, however, based on the results of the nominal heat output test, which is designed to emulate normal effective use of a fireplace and, where flue gas temperatures appear to be lower than in the temperature safety test. Experimental research by Leppänen et al. [11] also support the idea of using the temperatures from the temperature safety test. In their tests, the highest measured flue gas temperatures in the temperature safety tests were about 120 °C to 380 °C higher than the mean flue gas temperatures measured in the nominal heat-output test. The results indicate that the actual temperatures can exceed the level of the current design temperatures. In European standardization, it has recently been proposed that the mean temperature of the temperature-safety test is to be used for the designing of chimneys [40]. In Finland, the current guidelines require that the maximum temperature of the temperature safety test is to be used [41], based on the results of Leppänen et al. [11]. The justification for the maximum temperature is that, even if more conservative than the mean temperature, the solution provides some level of safety margin. Also, the tests carried out in real use and actual site conditions, refer to Chapter 5, demonstrate that the conditions can vary a lot and a sufficient safety margin is needed.

7. Conclusions

Site conditions and the way fireplaces are operated have a significant impact on flue gas temperatures. In the field tests, the mean flue gas temperatures measured during the room heater and sauna-stove tests were approximately 100 °C higher than the flue gas temperatures given by the manufacturers in the CE marking of the fireplaces. The highest measured flue gas temperatures were 300 °C above the temperatures given in the CE marking. For the slow heat-release appliance, the temperature difference was significantly lower. When the chimney and chimney-penetration details are designed for temperatures, which are significantly lower than the actual gas temperatures, a potential risk of fire will occur. The laboratory tests demonstrated that the misuse of fireplaces and oversized batches can further increase temperatures, as much as 100 °C. In the standard heat stress test of metal chimneys to EN 1859 [23] the maximum surface temperatures of combustible materials adjacent to the chimney penetration are limited to 85 °C. When the actual flue gas temperatures are 100 °C to 150 °C higher than the temperature class of the chimney given in the CE marking, the ignition of the combustible materials and structures adjacent to the chimney creates a potential fire risk.

The results of this experimental study demonstrate that it is of great importance that the user is familiar with the operating instructions, and that the maximum allowable batch sizes and charging intervals specified by the manufacturer are somehow controlled and not exceeded. Methods to overcome these issues can include end-user training, detailing and size of the firebox, and amendments to test standards and procedures. As it is impossible to remove and control all the uncertainties related to the behaviour of the end users, the main responsibility for fire safety should always lie with manufacturers and standardization.

The field tests conducted in this research show that the use of current EN standards for fireplaces do not always lead to fire-safe chimney dimensioning. The standards [19–22] do not sufficiently take into account the effects of site conditions and user performance on flue gas temperatures and fire safety of the chimney penetration. The mean flue gas temperature of the nominal heat-output test is too low in comparison with the mean flue gas temperatures measured during the field tests of this study. Based on the observations made, the maximum temperature of the temperature-safety test would provide a fire-safe solution. However, these criteria are applied in Finland only. In standard FprEN 16510-1:2016 [40], it has been proposed that the mean temperature of the temperature-safety test should be used for dimensioning chimneys. The field measurements show that these criteria do not always lead to a fire-safe solution. Further research is required to determine the correct design temperature.

Acknowledgements

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III

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Comparison between European chimney test results and actual installations

Perttu Leppänen[1], Manuela Neri[2], Davide Luscietti[2], Sandro Bani[3], Matti Pentti[1] and Mariagrazia Pilotelli[2]

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Abstract

European standards regulate the certification procedure for determining chimney class temperature and the distance at which to install chimneys from combustible materials. These standards prescribe the heat stress test and the thermal shock test. The high number of roof fires due to the presence of a chimney that have recently occurred in European countries seems to be due to a weak certification procedure. In this article, experimental tests and numerical simulations have been performed to highlight the major differences between real and test conditions to identify critical aspects of the current certification procedure. The influence of the position of the chimney in the test structure, the thermocouples' positioning and the thermal shock test initial condition have been investigated. It has been shown that flammable materials' temperatures measured in the certification procedure can be lower than those in real installations, and this is mainly due to the fact that exhaust gas temperature in the certification procedure of chimneys can be even 350°C lower than in real installations. Then, real installations represent a more severe condition.

Keywords

Flue gas temperature, combustible materials, thermal shock test, heat stress test, chimney, fire safety

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[1]Department of Civil Engineering, Tampere University of Technology, Tampere, Finland
[2]Department of Mechanical and Industrial Engineering, University of Brescia, Brescia, Italy
[3]ANFUS, Brescia, Italy

Corresponding author:
Perttu Leppänen, Department of Civil Engineering, Tampere University of Technology, P.O. Box 600, FI-33101 Tampere, Finland.
Email: perttu.leppanen@tut.fi

Introduction

In Europe, metal chimneys are certified according to the EN 1859[1] standard, whose aim is the determination of the minimum safety distance between chimney and nearby combustible structure and the chimney class temperature. The minimum safety distance is the distance at which chimneys must be installed from combustible materials to avoid overheating and consequent fires. Combustible material can be, for example, wood or thermal insulation materials. The chimney temperature class gives information about the maximum temperature at which exhaust gas can flow in the chimney; this information is reported on a label on certified chimneys and respecting these prescriptions should guarantee safe installations.

Despite the certification, roof fires seem to be a problem in different countries such as Finland, Italy and Great Britain. In Finland, according to the reports[2,3] of years 2002–2004, about 500 fires broke out from fireplaces and chimneys every year, and their share was about 14%–15% of all the building fires in Finland. Every year between 2008 and 2014, about 700–900 fires involved fireplaces and chimneys, and about 300–400 soot fires ignited.[4–6] According to Leppänen,[7] metal chimneys caused about 500 building fires during the years 2004 and 2009. Possible causes of these fires are listed in Table 1. Although damaged metal chimneys have not caused a very significant number of the fires, the fires involve CE-marked metal chimneys. The fireplace was a sauna stove in over half of the cases. Hakala[8] performed an investigation in the Finnish rescue services about fires caused by fireplaces and chimneys in 2012. Tables 2 and 3 show that 36% of fires started from fireplaces, 64% from chimneys and despite metal chimneys accounting for only about 10% of the chimneys in the country,[9,10] 73% of fires that involved chimneys started from metal chimneys, of which 68% had roof penetration and 32% wall penetration. In the Italian province of Brescia, about 300 fires occurred in 2007,[11,12] most caused by incorrect installations followed by lack of maintenance. Every year between 2000 and 2014, 8000–14,000 fires involved chimneys in Great Britain.[13] Heat transfer between chimneys and combustible

Table 1. Factors influencing the fires partly caused by metal chimneys in Finland.[7]

Factor	Share of fires (%)
Defective insulation	30
Defective minimum safety distance	29
Overheated chimney	19
Rust away	5
Joint of chimney	4
Chimney fire	1

Table 2. Fires caused by fireplaces in Finland during the year 2012 according to reason.[8]

Fires from fireplaces	Amount of fires	Share of fires (%)
Spark from a fireplace	21	47
Damage of a fireplace	9	20
Minimum safety distance of a fireplace	9	20
Fault of a fireplace	4	9
Flue gas of a smoke sauna	2	4

Table 3. Fires caused by chimneys in Finland during the year 2012 according to reason.[8]

Fires from chimneys	Amount of fires	Share of fires (%)
Metal chimney (roof penetration)	38	48
Metal chimney (wall penetration)	18	23
Masonry chimney (minimum safety distance)	12	15
Masonry chimney (damage)	9	11
Spark from a chimney	2	3
Masonry chimney (connection)	1	1

materials has been studied for a long time and from different points of view. According to some studies, the auto-ignition temperature of wood is considered in the range of 250°C–300°C,[14] but it can be much lower depending on time exposure[15,16] and the chemical processes that take place in it.[17] Other studies have shown auto-ignition of wood as possible even at 32°C above the ambient temperature under long-time exposure,[18] at 66°C,[19,20] at 100°C[21] and charring of wood occurred at 93°C.[19] To this day, the maximum acceptable temperature exposure of wood is controversial.

Chimney safety tests by the standard 1859

To guarantee safe installations, chimneys have to be certified according to the European standard EN 1859.[1] The standard prescribes the thermal performance test, consisting of the heat stress test that reproduces the conditions of chimneys' normal functioning and the thermal shock test, which reproduces conditions of soot fires. The tested chimneys are installed in a test structure similar to that shown in Figure 1(a) composed of two walls at a right angle and two roofs at different heights connected to an exhaust gas generator. Chimneys must be installed according to the manufacturer's prescription regarding the distance from combustible materials and the method of sealing this space (clearance sealing mode). In the test procedure, the clearance can be left open or can be sealed; however, this information is not reported on the label of certified chimneys. In both tests, temperatures are measured by means of thermocouples installed horizontally at the centre height of the clearance on the walls of the test structure, that is, in correspondence with the chimney roof penetration, while on the roof no thermocouples are provided. In the heat stress test, exhaust gas is conveyed into the chimney until the increase in temperature on the test structure is less than 2°C in 30 min, and these temperatures must not exceed 85°C. As regards the thermal shock test, exhaust gas is supplied at 1000°C for 30 min, and temperatures of the test structure are monitored until they reach the maximum value and start to fall; the maximum temperature on combustible materials must not exceed 100°C when the ambient temperature is 20°C.

Previous studies on the subject and objective of the research

In previous studies, the certification procedure[1] and, in particular, the heat stress test were called into question by the authors of this article on the previous studies.[22–25] Experimental studies showed that fires can be due to the fact that real installations can cause more severe conditions than the standard tests. In Inha et al.,[26] it was shown that the tests of EN standards[27–31] for fireplaces and chimneys are not compatible because their flue gas temperature

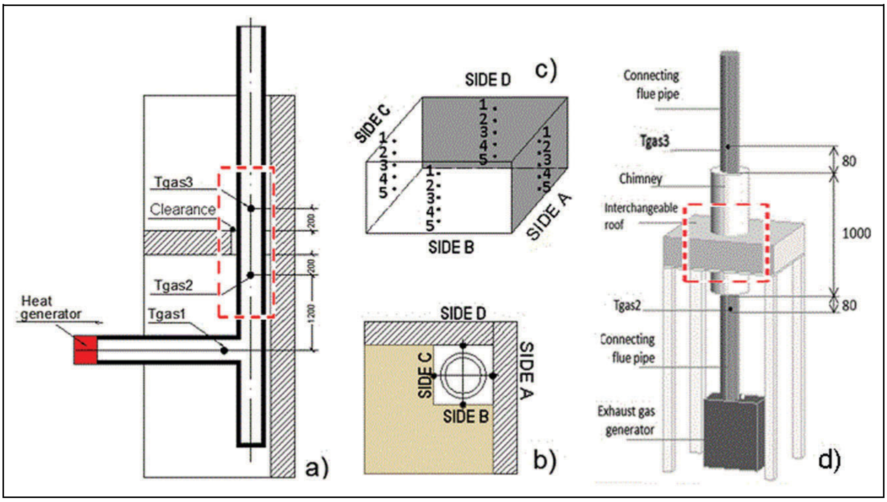

Figure 1. Test structure: (a) cross-section of the corner test structure, (b) top view of the corner test structure, (c) thermocouples positioning in the clearance in the corner test structure, (d) axisymmetric test structure. Dimensions are in millimetres. Dashed lines point out details represented in Figures 2 and 6.

measurement ranges are different. The exhaust gas temperature is measured near the intersection between vertical and horizontal pipes (T_{gas1} in Figure 1(a)) and not in the vicinity of the critical chimney roof penetration. The thermocouples' positioning on the test structure was questioned by Neri et al.:[23,24] it was shown that higher temperatures are usually measured on the roof of the test structure, and temperature varies along the vertical direction depending on the roof layers' position and the clearance sealing mode.

Although it clearly affects the temperature in the chimney roof penetration,[23,24] the clearance sealing mode to be adopted in the installation of a chimney is not specified. Therefore, in real installations, the temperature in the roof penetration can be higher than that measured during the certification test. Temperature–time curves measured in experimental tests[23,24] show that the final condition of the heat stress test does not allow approach of the steady-state temperature; for this, the steady-state temperature should be estimated by means of the *heating curve model* presented in Neri et al.[25] How to choose data to be analysed by means of the heating curve model is explained in Neri et al.,[25] while the accuracy of the model was investigated in Neri et al.[32] Two numerical models were proposed for calculating heat transfer between chimney and roof: the condition in the standard tests was reproduced by means of a three-dimensional (3D) numerical model,[25] while the condition in real installations was reproduced by means of a two-dimensional (2D) numerical model.[32]

The critical condition of soot fires, in which deposit of soot on the inner surface ignites, was studied by Peacock[33] by means of 12 tests. Some of the results of the tests are shown in Table 4. Accumulation of soot was highest when 2733 kg of wood was burned in 1752 h at an average ambient temperature of −6°C. As can be seen in Table 5, the soot fires had relatively short duration and the entire exposure time over which the temperature was over 200°C lasted 11–90 min, the average being 36 min.

This article investigates the certification procedure in order to supplement the analysis in the literature, focusing on some aspects that still have not been treated, to identify the worst condition in which a chimney may operate.

Table 4. Minimum, average and maximum values of Peacock's soot fire tests.[33]

	Total wood burned (kg)	Duration of build-up (h)	Thickness of deposit (mm)	Peak gas temperature in chimney and chimney connector (°C)	Peak gas temperature in chimney (°C)
Minimum	115	76	3–13	908	754
Average	940	605	9–21	1042	952
Maximum	2733	1752	13–64	1370	1370

Table 5. Duration (minutes) of soot fires in tests performed by Peacock.[33]

Temperature in chimney (°C)	Minimum	Maximum	Average
$\geq$200	11	90	36
$\geq$400	8	82	28
$\geq$600	5	44	19
$\geq$800	2	18	10
$\geq$1000	0	8	2
$\geq$1200	0	3	0

Roofs can be made of several layers, such as wooden layer, insulating layer and water proof layers: their presence and their position in roofs, in the following called roof layers position, depend on several factors such as the energy class to which the building aspires. The influence of the position of the layers in the roof and the effect of the clearance sealing mode, that is, the way of sealing the space between chimney and flammable structure, were investigated for the condition reproduced in the certification procedure[23] and for the condition that may occur in real installations.[24] A direct comparison between these two conditions has not been proposed yet because the experimental tests presented in the two studies[23,24] were performed in different conditions. To complete this analysis, two tests have been performed to investigate the influence of the position of the chimney in the roof: one test has been performed on the test structure shown in Figure 1(a) representing the one prescribed by the standard,[1] and another test has been performed on the test structure shown in Figure 1(d) that reproduces real installation conditions where chimneys are installed completely surrounded by a roof or, however, in a position where they are not affected by the presence of walls. The dashed lines in Figure 1 surround chimney roof penetrations that are represented in detail in Figures 2 and 6. Experiments have shown that the exhaust gas temperature drops along the chimney and temperatures measured in the roof penetration are related to a temperature lower than those measured in the certification.[23] To do this, the tests were performed on a test structure slightly different from that prescribed by the standard[1] because the flue pipe between the heat generator and the chimney in the roof penetration was made up of a vertical tube, while the standard[1] prescribes to install a horizontal flue pipe between them and measure the exhaust gas temperature near the intersection point. To complete this analysis, exhaust gas temperature has been measured in tests performed on the structure shown in Figure 1, where exhaust gas is conveyed into the chimney by means of horizontal and vertical flue pipes. The exhaust gas temperature has been measured near the intersection of the flue pipes, that is, in the position prescribed in the previous study[1] and

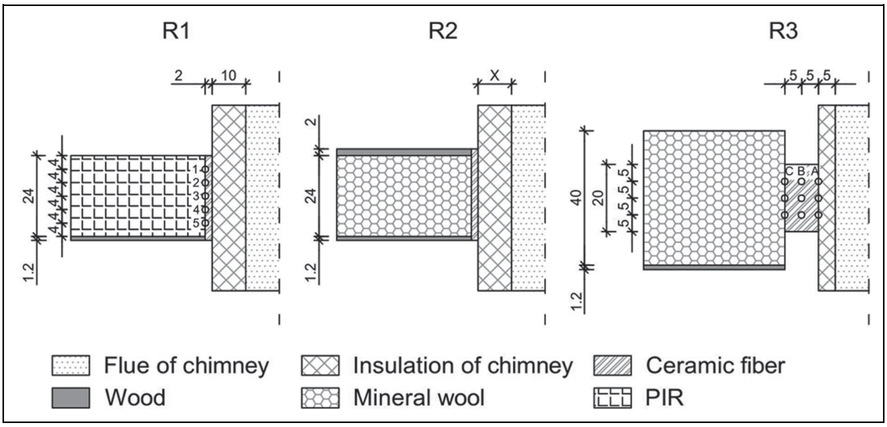

Figure 2. Roofs and chimneys installed in the test structures. Configuration R1 has been adopted to investigate the influence of the chimney position in the roof, R2 the drop in temperature along the chimney and R3 the thermal shock test initial condition. In the configuration R3, in the clearance an accessory has also been installed whose characteristics are not shown here. Dimensions are in centimetres.
PIR: polyisocyanurate.

near the roof penetration point. The difference in exhaust gas temperature measured in the experiments has been used to simulate how it affects the temperature in the roof. Because the literature does not explain how to use the heating curve model, this article describes the steps for estimating the steady-state temperature.

Given that in the literature the majority of the studies analysed the condition in the heat stress test, in this article, the thermal shock test conditions are analysed: this latter determines a special fire risk in the case of metal chimneys due to their low thermal capacity. According to the standard,[1] the thermal shock test must be performed from ambient temperature, but in real installations, a soot fire may occur after an extended period of heating, that is, when combustible materials' temperature can be much higher than the ambient temperature. To investigate this aspect, a soot fire test has been performed from the ambient temperature and another test has been performed immediately after the heat stress test to ensure a pre-heating of combustible materials. Also, the exhaust gas temperature measurement point has been analysed to determine whether the certification procedure is able to ensure an exhaust gas temperature of 1000°C in the penetration point.

Approach to the problem

By means of experimental tests and numerical simulations performed with the numerical models presented in the previous studies,[25,32] the certification procedure has been investigated. The tests were performed mainly according to the standard EN 1859. The tests studied how the actual installation of the chimneys affects the temperature of combustible materials. In standard tests, the chimney is tested at a corner. In addition, axisymmetric tests were performed to get better correspondence to the actual installation.

Experimental configuration

The tests consisted of installing a chimney in a test structure, connecting it to an exhaust gas generator and measuring the temperature of combustible materials in the vicinity of the chimney. The exhaust gas temperature has been measured in the vicinity of chimney roof penetration. Two types of tests have been performed. The heat stress test used exhaust gas at a predetermined temperature until the increase in temperature on the test structure was lower than 2°C in 30 min, while in the thermal shock test, the temperature of exhaust gas rose to 1000°C in 10 min and was maintained for 30 min. The tests deviated from the EN 1859[1] standard tests on the positions of the thermocouples and installation of the chimneys. The characteristics of the experimental tests are listed in Table 6, and each test is identified by an acronym. The first letter identifies the test structure in which the chimney has been installed: *C* states for corner test structure and *A* for axisymmetric test structure. Then, the type of test is indicated: *HS* refers to the heat stress test, *SF* to the thermal shock test and *HSF* to a heat stress test followed by a thermal shock test. The first number in the acronym, when indicated, indicates the exhaust gas temperature in the chimney during the experiments. All the tests were stopped when the final test conditions defined by the standard[1] for the heat stress test and the thermal shock test were achieved. Four chimneys with an internal diameter of 200 mm were installed in one of the test structures shown in Figure 1, and their characteristics are summarised in Table 6 and in Figure 2. The corner test structure in Figure 1(a) reproduces the condition in the tests performed according to the EN 1859[1] standard, where chimneys are installed in a corner of two roofs and in the vicinity of two walls at right angle, while the axisymmetric test structure in Figure 1(d) reproduces the conditions that usually occur in real installations, where chimneys are installed in a position where they are completely surrounded by a roof and not affected by the presence of vertical walls.

Tests C-HS500 and A-HS500 were performed to highlight the effect of test structure on the temperatures, and their configuration is identified with R1 in Figure 2. The roof is made of polyisocyanurate (PIR) with thermal conductivity of 0.025 W/m K, the clearance is 20 mm wide and it has been completely filled with ceramic fibre (128 kg/m^3). Tests C-SF1000-1, C-SF1000-2 and C-HS700 were performed to investigate the influence of the exhaust gas temperature measurement point in the heat stress test and in the thermal shock test, and their configuration is identified with R2 in Figure 2. Because the drop in temperature along the chimney can be affected by the chimney characteristics, the analysis has been done with two different chimneys installed in a roof similar to the thicker roof prescribed by the standard.[1] In these tests, the temperature of exhaust gas was measured also in the vicinity of the penetration of the roof. Because the aim of these tests is the determination of the drop in temperature along the chimney, the clearance has been sealed in the same way in order not to change the conditions of the tests. Tests A-SF and A-HSF were performed to investigate the influence of the initial condition of the thermal shock tests, and their configuration is indicated with R3 in Figure 2. In the clearance, a layer of ceramic fibre and an accessory, whose aim is to reduce the temperature of flammable materials in the vicinity of a chimney, has been installed. The features of the accessory cannot be specified in detail because it is under study: the accessory can be described as a metallic casing filled with ceramic fibre, and it occupies half clearance, while the other half of the clearance, that is, the space between the accessory and the roof, is occupied by ceramic fibre. The test was also used in the development of the accessory. This article does not study the function of the accessory but does study the effect of the actual installation of chimneys. Because in both tests the accessory has been installed between chimney and roof, its presence has not affected the results of the analysis.

The temperatures measured in both tests are lower than the temperatures that would have been measured without the accessory. A-SF has been performed according to standard,[1] that

Table 6. Test arrangements.

Test	Type of installation (test structure)	Exhaust gas temperature (°C)	Configuration	Insulation thickness of the chimney (mm)	Material and thickness of the insulation in the clearance	Aspect investigated
C-HS500	Corner installation	500	R1	100	Ceramic fibre (20 mm)	Position of the chimney in the roof
A-HS500	Axisymmetric	500	R1	100	Ceramic fibre (20 mm)	
C-HS700	Corner installation	700	R2	25	–	Exhaust gas temperature measurement point
C-SF1000-1	Corner installation	1015.8 ± 8.3	R2	25	–	
C-SF1000-2	Corner installation	1008.7 ± 14.7	R2	65	–	
A-SF	Axisymmetric	986.5 ± 7.3	R3	50	Ceramic fibre (100 mm) + accessory	Thermal shock test initial condition
A-HSF	Axisymmetric	703 ± 6.8 followed by 996.2 ± 8.4	R3	50	Ceramic fibre (100 mm) + accessory	

C: corner test structure; A: axisymmetric test structure; HS: heat stress test; SF: thermal shock test; HSF: heat stress test followed by thermal shock test.

is, from the ambient temperature, while A-HSF consisted of an heat stress test with exhaust gas at 700°C followed by a thermal shock test in which the temperature has been raised to 1000°C (measured in the roof penetration point) in 10 min and maintained for 30 min.

Temperature measurement and elaboration. In the tests, exhaust gas temperatures and combustible material temperatures have been measured every 10 s by means of thermocouples of type K and two data loggers connected to a personal computer (PC). Exhaust gas temperatures have been measured with a 3-mm sheathed thermocouple. Combustible material temperatures have been measured with a thermocouple wire of 0.5 mm. Type K thermocouples have an uncertainty of ±2.8°C for temperatures ranging between 0°C and 350°C and of ±0.75% for temperatures ranging between 350°C and 1260°C. The uncertainty of the data logger is ±0.02°C. Periodic checks performed with heat source at a known temperature guaranteed the correct functioning of the instrumentation. The uncertainty of the temperatures was determined as the sum of the uncertainty related to the measuring instruments plus the uncertainty related to the data elaboration. The temperatures were determined as an average of data recorded for a certain time interval. The uncertainty has then been calculated as the sum of the uncertainties of measured data, uncertainty of the data logger and the uncertainty of the thermocouples. Final combustible material temperatures have been determined as an average of several measurement points, and the related variability has been determined as the difference between maximum and minimum values. Also, the exhaust gas temperature in the chimney (T_{ch}) was determined as the average of two values, but in this case, the variability was calculated as the sum of the two values' variability.

In the tests performed with the corner test structure, combustible material temperatures have been measured in the clearance according to the scheme in Figure 1(b) and (c), that is, by means of thermocouples positioned vertically on the roof and the wall structures. In the tests performed with the axisymmetric test structure, temperatures have been measured according to the scheme in Figure 2. The temperature has been measured from the four sides of the chimney. Final temperatures have been obtained by averaging temperatures related to homologous points. In this way, five temperatures have been calculated for the axisymmetric test structure, while for the corner test structure, five temperatures have been obtained for the roof (sides B and C), and five temperatures for the walls (sides A and D). In tests C-HS700, C-SF1000-1 and C-SF1000-2, performed to investigate the influence of the exhaust gas measurement point, the exhaust gas temperature has been measured before and after the roof penetration (T_{gas2} and T_{gas3} in Figure 1(a) and (d) and in corner test structure also at the point prescribed by the standard,[1] that is, near the intersection of the horizontal and the vertical flue pipes (T_{gas1} in Figure 1(a)). In tests A-SF and A-HSF, performed to assess the influence of the thermal shock test initial condition, temperatures have been measured according to the configuration R3 in Figure 2, that is, at several distances from the chimney: two rows of thermocouples have been installed on the external surface of the chimney (line A), at the centre of the insulation in the clearance (line B) and on the roof (line C). Disassembling the setup made it clear that the positioning of the thermocouples was not precise: for each line, one value has been obtained by averaging these six values.

Heating curve model

The steady-state temperatures reported in the following have been estimated by means of the heating curve model presented by Neri et al.[25] In previous works,[24,25,32] this model has also been called the *lumped element model*, but given the condition taken into account in the computing, the former name is more correct. Indeed, thermocouples positioned on combustible materials are not immersed in a constant ambient temperature because the temperature of the roof is not uniform or constant in time. In the vicinity of a thermocouple, the temperature of the roof can be considered as the driving system of the thermocouple temperature.

The temperature does not necessarily reach steady-state temperatures at the penetration during the tests performed according to the EN 1859 standard.[1] The model can be used to estimate the steady-state temperatures on the basis of the results of the test which have not yet reached the steady-state temperatures. The advantage of using estimated steady-state temperatures is that numerical simulations are faster and simpler in steady-state conditions.

Results and discussion

The analysis performed focuses on the influence of the position of the chimney in the roof, the exhaust gas measurement point and the thermal shock test initial condition, and it has been done on the basis of data obtained by means of simulations and in the experimental tests.

Position of the chimney in the roof

The steady-state temperatures estimated in the tests C-HS500 and A-HS500 are compared in Figure 3: the tests reproduced the conditions in the heat stress test. The estimated temperatures have been used because then it has been possible to compare steady-state temperatures. The temperature does not reach steady-state temperatures at the penetration of the chimney during the test. Given that test C-HS500 has been performed on the corner test structure (Figure 1(a)), temperatures on the walls and the roof are reported for it. It can be noted that on the walls the temperature is more uniform with respect to those measured on the roof, and this result is in accordance with Neri et al.:[23,24] on the walls, thermocouples have been installed on the same material. Higher temperatures have been measured on the roof where they can be 40°C higher than those measured on the walls. The difference in

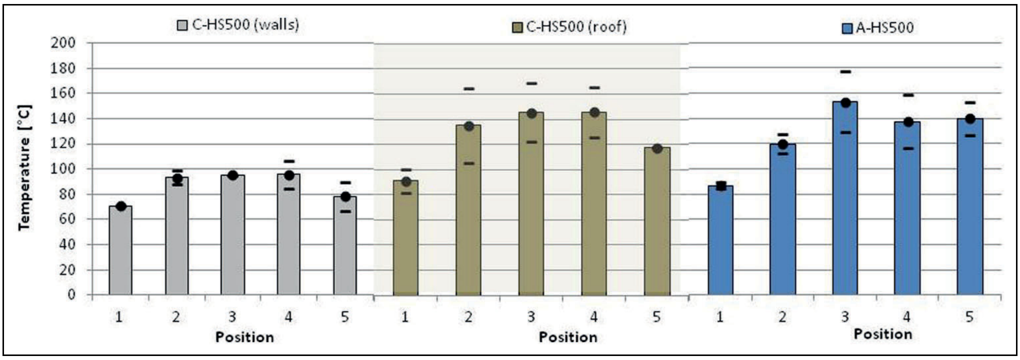

Figure 3. Comparison of maximum temperatures estimated with the heating curve model for the tests C-HS500 and A-HS500. The numbers 1 to 5 represent the thermocouple positions (Figure 2), where 1 is the top one.

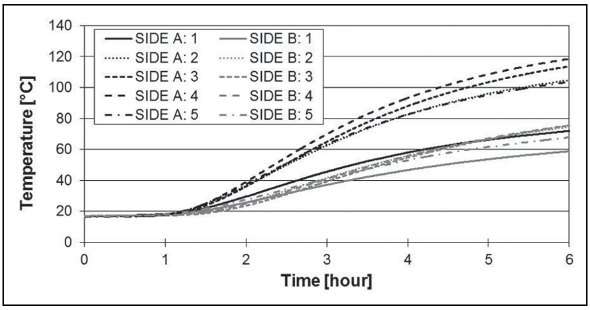

Figure 4. Temperature–time curves measured on the walls (side B) and the roof (side A) in heat stress test C-HS500. The positions of thermocouples are shown in Figure 1(c).

temperature is due to the fact that the walls offer a lower thermal resistance to heat flow than the roof. This aspect is confirmed also by the temperature–time curves shown in Figure 4: the curves related to the walls seem to reach the final test condition before those measured in the roof given that the slope is lower in the first case. Then, to assess the achievement of the final test condition, temperatures measured on the roof should be considered or steady-state temperatures should be estimated with the heating curve model.

By comparing the temperatures estimated with the heating curve model and reported in Figure 3, and those measured according to the standard[1] and reported in Figure 4, the difference between the temperatures related to the two conditions can be noted: the temperatures measured at the end of the heat stress test range between 60°C and 80°C on the walls, and between 100°C and 130°C in the roof (except the curve referred to position 1, where the thermocouple was likely not completely covered by insulating material), while the temperatures estimated by means of the heating curve model range between 70°C and 100°C on the wall and between 90°C and 150°C in the roof. This shows the weaknesses of the final test condition. The final test condition should be changed, but this would imply long tests; otherwise, the steady-state temperature should be estimated by means of the heating curve model.

By comparing the temperatures estimated for the corner test structure (C-HS500) and those for the axisymmetric test structure (A-HS500) in Figure 3, the highest temperature has been obtained for this latter. This is due to the fact that a chimney completely surrounded by an insulating slab is a more severe condition than that in the test structure where heat finds a way out. The difference in temperature between the certification condition and real installations can be up to 50°C and, because self-ignition of wood was recorded also for low exposure temperature,[16–21] this can be a possible cause of the high number of roof fires.

Exhaust gas temperature measurement point

In this section, the tests C-HS700, C-SF1000-1 and C-SF1000-2 have been analysed to investigate the influence of the exhaust gas temperature measurement point in the certification procedure. The exhaust gas temperature measured in the point prescribed by the standard,[1] that is, near the intersection of the horizontal and the vertical flue pipes (T_{gas1} in Figure 1(a)) and T_{ch} obtained as the average of the temperatures measured in the vicinity of the penetration point (T_{gas2} and T_{gas3} in Figure 1) are compared.

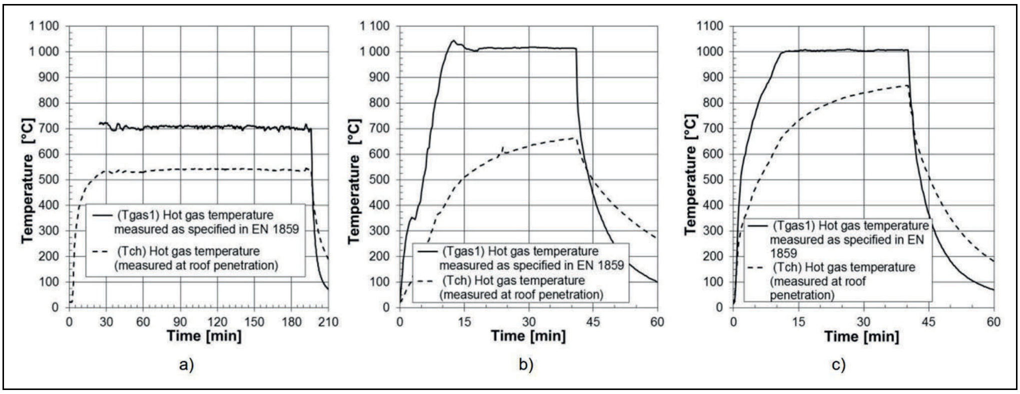

Figure 5. Comparison between exhaust gas temperatures measured according to the EN 1859 and in the vicinity of the roof penetration: (a) C-HS700, (b) C-SF1000-1 and (c) C-SF1000-2. Tests C-HS700 and C-SF1000-1 have been performed on a 25-mm-thick chimney, and test C-SF1000-2 has been performed on a 65-mm-thick chimney.

In Figure 5(a), which refers to the heat stress test C-HS700, the exhaust gas temperature at the chimney roof penetration is between 150°C and 200°C lower than that measured according to the standard[1] and used to declare the chimney class temperature. The same occurs in the thermal shock tests: in test C-SF1000-1 shown in Figure 5(b), the maximum exhaust gas temperature at the chimney roof penetration is about 350°C lower than that measured in the point prescribed by the standard,[1] while in test C-SF1000-2 shown in Figure 5(c), the temperature is 150°C lower. It can be stated that the way of measuring the exhaust gas temperature prescribed by the standard[1] does not allow to know the actual temperature in chimney roof penetration during the certification, especially in the thermal shock test. When the fire safety of the chimney is determined, the essential matter is the temperature of exhaust gas at the penetration. The standard determined the minimum safety distance at the penetration. It is not possible to be sure about results of the thermal shock test because the temperature of exhaust gas in the test can be hundreds of degrees lower than in the real soot fires. Figure 5(b) and (c) relates to two different chimneys, and a lower drop in temperature along the chimney has occurred in the second case, that is, for the better-insulated chimney. This implies that for less-insulated chimneys, the exhaust gas temperature in the penetration point is lower than in better-insulated chimneys, and this could lead to lower combustible material temperatures. For all these reasons, the performance of different chimneys cannot be compared on the basis of the heat stress test and the thermal shock test. Rather, the exhaust gas temperature should be measured as closely as possible to the roof penetration, especially in the thermal shock test in which, given the rapidity of execution of the test, the system is not able to reach a steady-state condition, and the temperature is much lower than that prescribed by the standard.[1]

Numerical simulations. The effect of a difference in the exhaust gas temperature on combustible material temperature has been investigated by means of simulations performed with the 2D numerical model[32] because only the exhaust gas temperature has been measured in test C-HS700. Two sets of simulations have been performed: in one set, the exhaust gas temperature has been set equal to the value prescribed by the standard,[1] that is, 700°C in the

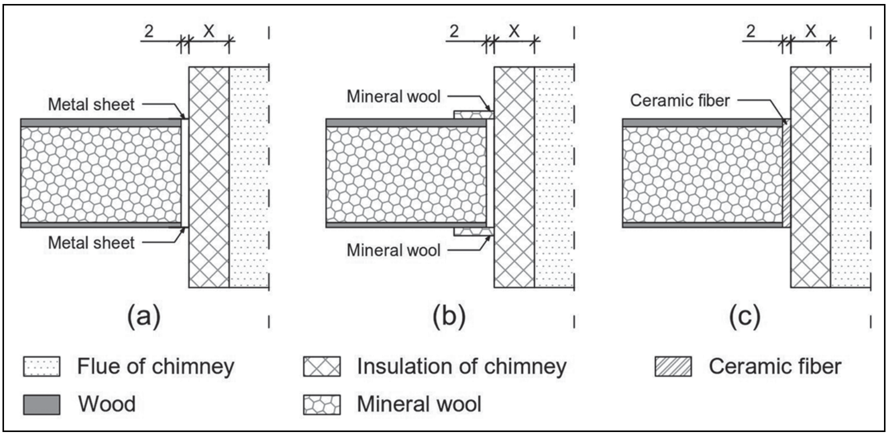

Figure 6. Clearance sealing modes: (a) sealed with metal sheets, (b) sealed adiabatically and (c) filled with insulating material.

Table 7. Mineral wool thermal conductivity (W/m K) as function of the temperature (°C).[34]

Temperature (°C)	50	100	200	300	400	700
Thermal conductivity (W/m K)	0.035	0.043	0.069	0.079	0.104	0.22

penetration, and in the other, the exhaust gas temperature has been set equal to 550°C, that is, the temperature measured in the penetration point in the test C-HS700. In the simulations, 25- and 65-mm-thick chimneys made up of mineral wool have been considered. The simulations have been performed on the configuration R2 in Figure 2, and the 20-mm-width clearance has been sealed in three different ways: sealed adiabatically, sealed with metal sheets and filled with insulating material. Clearance sealing modes are shown in Figure 6. A constant value of the thermal conductivity has been set for the wood ($\lambda = 0.013$ W/m K) and steel ($\lambda = 15$ W/m K), while for the mineral wool in the roof, in the chimney and in the filling of the clearance, the values reported in Table 7 have been set.

Impact on the temperature in the roof. It has been shown that the exhaust gas temperature measurement point prescribed by the standard[1] does not allow correct declaration of the chimney class temperature, then, by means of simulations, and the effect of this difference on the temperature measured in the penetration point has been investigated.

The maximum temperatures estimated numerically in the penetration point are shown in Figures 7 and 8. It can be noted that despite the exhaust gas temperature difference of only 150°C, the difference in the combustible material temperature is up to 70°C for less-insulated chimneys (Figure 7), while for more-insulated chimneys, the difference in temperature is about 50°C (Figure 8) and 10°C (Figure 8). The difference in temperature does not seem to be affected strongly by the clearance sealing mode.

Thermal shock test initial condition

To investigate the influence of the initial condition of the thermal shock test, the temperatures measured in tests A-SF and A-HSF are compared in Figure 9: test A-SF has been

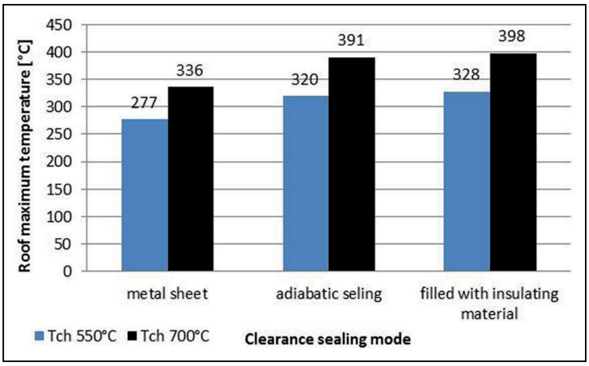

Figure 7. Maximum temperature estimated in the roof for different exhaust gas temperature and clearance sealing mode and 25-mm-thick chimney. T_{ch} is exhaust gas temperature in the roof penetration.

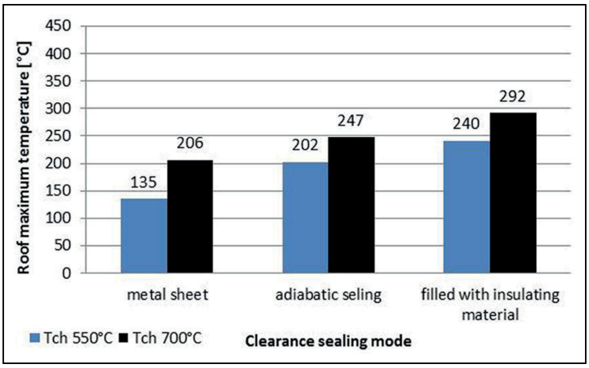

Figure 8. Maximum temperature estimated in the roof for different exhaust gas temperature and clearance sealing mode and 65-mm-thick chimney. T_{ch} is exhaust gas temperature in the roof penetration.

performed according to the standard,[1] that is, from ambient temperature, while test A-HSF has been performed immediately after the heat stress test, that is, when combustible materials had been already heated. As a reminder, in both tests, in the clearance, an accessory was installed, and this has probably lowered the temperature of combustible materials. For test A-HSF, in which the exhaust gas temperature has been raised to 1000°C after a heat stress test, temperature on combustible materials is 10°C higher with respect to those measured in the test performed according to the standard.[1] The difference is limited to a few degrees because the chimney is well-insulated; when performing the test for a less-insulated chimney, the difference in temperature may be higher. Then, it is recommended to perform the thermal shock test immediately after the heat stress test. This procedure would lead to faster certification procedure and the outcome of the test would be safer.

Proposal for the new chimney tests

Different European countries have very different building customs. A Finnish house, for instance, has an insulated ceiling below a ridge roof. In Italy, it is typical that the roof has

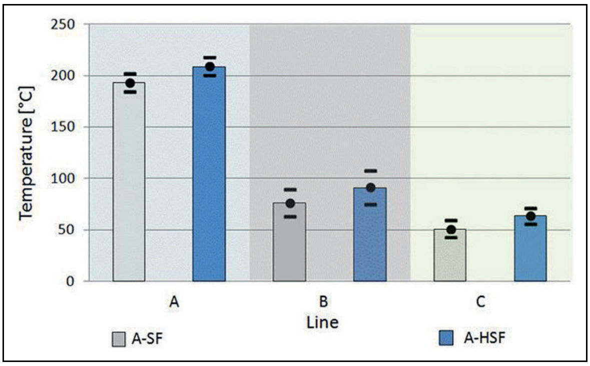

Figure 9. Temperatures measured in the thermal shock test performed according to the EN 1859 standard (A-SF) and after the heat stress test (A-HSF), at several distances from the chimney. Line A is on the external surface of the chimney, line B is 5 cm from the chimney (at the centre of the insulation in the clearance) and line C is between the insulation in the clearance and the roof, according to configuration R3 in Figure 2.

been insulated. Furthermore, the insulation thicknesses vary considerably. In Finland, it is typical to use insulating layers which are even 600-mm high and may be still higher in energy-saving buildings.

The chimney test should be performed with axisymmetric structure. Temperature measurement should be in the insulation material, not in the wood construction. The insulating layer of the roof should be higher than 200 mm in the chimney test. The exhaust gas temperature measurement point should be situated in the roof penetration. The thermal shock test should be performed directly after the heat stress test.

Conclusion

The study highlighted the differences between the conditions in real installations and those in the thermal performance test prescribed by the standard[1] for the certification of chimneys. It showed that the temperatures measured in the tests performed according to the standard[1] can be lower than the maximum temperature that may occur in real installations. This is mainly due to a weak certification procedure.

Its weaknesses concern the position of the chimney in the test structure, the exhaust gas measurement point, the maximum temperature measured in the tests and the initial condition of the thermal shock test. The position of the chimney in test structure, that is, in a corner of the roof and near two walls, does not represent the worst condition in which a chimney may operate. In real installations, chimneys are usually completely surrounded by a roof that offers higher thermal resistance than the walls of the test structure. Then, the chimney should be installed at the centre of the roof.

The thermocouple's positioning for the exhaust gas temperature measurement in the thermal performance test does not allow a guarantee of the temperatures prescribed by the standard[1] because exhaust gas temperature is measured far from the chimney roof penetration: in this latter point, temperatures can be much lower than those prescribed in Standard.[1] The difference in temperature measured according to the standard[1] and that measured in the vicinity of the chimney roof penetration depends on the chimney characteristics; then, the thermal performance of different chimneys cannot be assessed by means of tests performed according to the standard.[1] The difference in temperature depends also on the way of performing the test. It has been shown that in the thermal shock test, the temperature in the chimney roof penetration can be about 350°C lower than those recommended, while for the heat stress test the difference was about 150°C. Simulations have investigated the effect of the difference in the exhaust gas temperature on the combustible material temperature. A difference of 150°C in the exhaust gas temperature can vary the temperature of combustible materials about 70°C, and the difference depends on the characteristics of the chimney. For this, in the certification procedure, the exhaust gas temperature should be measured as closely as possible to the chimney roof penetration to determine the class temperature of the chimney correctly, and this is in agreement with Peacock.[33]

Experimental tests have shown that the initial condition of the thermal shock test does not reproduce the worst condition in which a chimney may operate. Given that a soot fire may occur after a certain period of functioning of the heating system, that is, when combustible materials have already been heated, the thermal shock test should be performed immediately after the heat stress test. This new way of performing the certification procedure would be safer and faster. Peacock[33] stated that the position where the actual burning of soot occurs affects the temperatures: by measuring exhaust gas temperatures in the chimney roof penetration, the worst condition that may occur in real installations is taken into account, that is, a soot fire where chimneys are surrounded by flammable materials.

In this article, the steps to estimate the steady-state temperature with the heating curve model presented in Neri et al.[25] have been reported, and the importance of estimating the steady-state temperature from temperature–time curves measured in the tests has been remarked upon.

In conclusion, it has been shown also that a certified chimney could cause a dangerous overheating of combustible materials in its vicinity. Thus, a new and more stringent chimney certification procedure should be proposed, and all the aspects raised in this article should be taken into account. However, a deeper analysis of the thermal shock test should be performed. The influence of the roof characteristics should be investigated to identify the roofs in the new test structure. For example, the certification procedure should prescribe different roofs to test chimneys in view of the structure where they will be installed. In this way, better performance will be required for chimneys to be installed in energy-saving buildings.

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Declaration of conflicting interests

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Author biographies

Perttu Leppänen, MSc of civil engineering. He is a doctoral student in the Tampere University of technology. His particular interest is the fire safety of fireplaces and metal chimneys.

Manuela Neri is a PhD of University of Brescia. She is specialized in thermal science.

Davide Luscietti is a PhD of University of Brescia. He is specialized in Thermal Science.

Sandro Bani is the President of the ANFUS (chimney installers and sweepers association) of Brescia. He is interested in problems of roof fires.

Matti Pentti, DSc, professor of Structural Engineering. He is head of the Department of Civil Engineering.

Mariagrazia Pilotelli is a researcher of University of Brescia. She teaches Thermal Science.

PUBLICATION
IV

Heat release caused by the smouldering combustion of the binder of rockwool

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Heat release caused by the smouldering combustion of the binder of rockwool

Perttu Leppänen[1], Manuela Neri and Jari Mäkinen

Summary. Recently, numerous fires have started in Finland around roof penetrations of metal chimneys. One reason for the fires is the smouldering combustion of the binder of rockwool used at the roof penetrations of metal chimneys. The charring of the binder produces heat which can increase the temperature in the penetration to over 100 °C. Tests which were performed on rockwool demonstrate the heat release.

Key words: smouldering combustion, heat release

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Introduction

Many fires in Finland have started around metal chimney roof penetrations. According to Leppänen’s study [1], metal chimneys caused an average of 87 fires in Finland during 2004–2009. A thematic investigation of fires started from fireplaces and chimneys by Hakala [2] at Finnish fire and rescue stations in 2012. Of the fires, 36% had started from fireplaces and 64 % from chimneys. Of the fires started from chimneys 73 % involved metal chimneys. In 47 % of the cases involving chimneys, the fire had started from a roof penetration and in 22 % from a wall penetration of a metal chimney. The problem is really significant because according to Murtokare [3] the share of metal chimneys in Finland is about 6 %. In addition, an inquiry targeting chimney sweeps by Leppänen at al [4], to which 25 chimney sweeps from different parts of Finland responded, asked about the prevalence and fire hazards related to metal chimneys. Due to the small sample, the results were only indicative but clear enough. The results of the inquiry are shown in Table 1. In new buildings the share of metal chimneys was about 34 %. The majority of metal chimneys in Finland are less than ten years old. It is alarming that in 2012 approximately 10 % of chimneys caused over 70 % of all chimney-induced fires in Finland. The problem is made even more significant by the fact that all metal chimneys in Finland are relatively new. Fire safety problems with

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[1] Corresponding author. perttu.leppanen@tut.fi

brick masonry chimneys are mainly due to degradation with age. In a study by Inha at al [5] on the fire safety of light-weight metal chimneys, high flue gas temperatures of sauna stoves were found to be one cause of fires. Other causes of fires are the high thickness of roof penetration of the chimney and the smouldering combustion of the binder of rockwool used as an insulator for the chimney itself and as an insulator for the roof penetration of the chimney.

Table 1. Shares of different chimney types of all the chimneys of the residential buildings of the whole building stock in Finland at different periods [4].

		1980's	**1990's**	**2000's**	**2010's**
Metal chimney	**Range**	1 to 13 %	3 to 13 %	4 to 20 %	4 to 20 %
	Average	5 %	7 %	10 %	11 %
Block chimney	**Range**	0 to 10 %	0 to 15 %	1 to 25 %	1 to 50 %
	Average	3 %	7 %	12 %	16 %
Masonry chimney	**Range**	85 to 99 %	80 to 95 %	60 to 92 %	40 to 90 %
	Average	92 %	87 %	77 %	73 %

The objective of the study was to allocate the heat released from the charring of the binder of rockwool and to create a model of heat release. Furthermore, the objective was to estimate if fire safety of chimney roof penetration could be ensured by applying the model produced.

Smouldering combustion and heat release

Smouldering is a flameless combustion that spreads at very low velocity in porous medium or in fiberboards and it is characterized by heat release. It has been widely investigated because it is one of the causes of fire deaths [6]; indeed, as it occurs flameless, it is not promptly identified. This leads to further propagation of combustion and the production of toxic gas. Heat and mass transfer, fluid flow and chemical reaction have to be taken into account in the study of the smouldering process.

Smouldering process is characterized by two phenomena: pyrolysis, an endothermic reaction that requires low oxygen concentration and begins at about 250 °C; and oxidation, an exothermic reaction. In smouldering processes, temperatures ranging between 400 and 750 °C were measured in the reaction area. The medium has to be porous to allow the flow of oxygen toward the reaction zone by diffusion and convection. The smouldering process is affected by heat losses and oxygen supply rates [7, 8, 9]. The initiation of smouldering process is dominated by the oxidation of the medium and can occur when enough energy is available; for example, supplied by external burning.

Once started, the smouldering process is characterized by the three zones represented in Figure 1: a zone near to the heat source which has already undergone the smouldering process and char has been formed; a zone in which the process is being developed; and a third zone far from the heat source in which the process has not yet occurred. The fact that a smouldering process begins does not guarantee that the process will continue.

Stable process occurs for particular rates of air/flue ratio [10] and a minimum thickness of the porous material [11]. Indeed, the material must serve as a heat insulator to prevent heat release from the reaction to the environment. [12, 13].

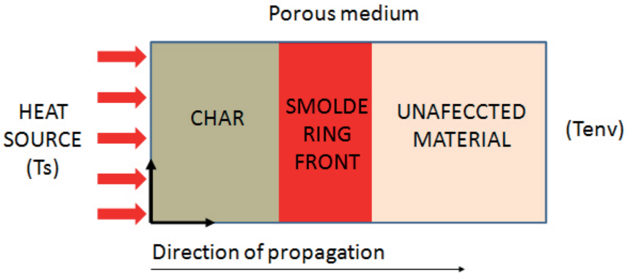

Figure 1. Representation of smouldering process, where Ts is the source temperature and Tenv is environment temperature.

Depending on the direction of oxygen flow, two kinds of smouldering process have been identified: the forward one, and backward one. Even though they can coexist, one is always predominant. It is important to understand the smouldering process type because each one undergo different heat and mass transfer processes [14].

In forward smouldering, the reaction front moves in the same direction of the oxygen flow and many studies have been performed on it. For example, [15] investigated on which condition the process begins, [16] investigated the conditions that allow a constant process, [15] analyzed smouldering with ignition and smouldering without ignition separately. This process was also modeled numerically by some authors, among which [17].

In backward smouldering the oxygen moves through the unburned zone to the reaction zone. Dosanjh at al [16] stated that steady propagation of the phenomenon occurs if the heat release is enough to heat the air entering the medium. A relation between the velocity of propagation and the medium thickness was found by [11], while [12,18,19] found a relation correlation between the heat release and the oxygen rate. Studies were performed to compare the two kinds of processes [12,20].

In addition to experimental tests, models of the smouldering process can be found in the literature [13,15,21,22,23].

Despite smouldering being widely investigated, the European fire classification does not define constant smouldering combustion. For this, the Institut fur Brandtechnolgie GmbH investigated the phenomenon on building materials using the SBI test method [24]. In the study, edited SBI tests were performed. Hemp, rockwool insulators, melamine resin foam ”Basotect”, polyurethane foam and glasswool were used as test materials in the tests performed. The SBI test was chosen as a test method because in other European test methods, the size of the specimen is so small that it is difficult to perceive constant smouldering combustion. In the test performed, constant smouldering combustion was not identified in the rockwool insulator ”Tervol PTP” which had a binder content of 3.2 %. Constant smouldering combustion was located in a small area on the surface of the specimen of rockwool insulator ”Rhinox” which had the highest binder content (4.6 %). However, constant smouldering combustion did not occur in a wider area on the part surface. Constant smouldering combustion was not observed in the rockwool insulator (Kortff) which had an average binder content of 3.7 %.

Inha at al study fire safety of metal chimneys [5]. They carried out tests to the metal chimneys. In the tests a metal chimney was connected to a sauna stove. The sauna stove was heated strongly to produce hot flue gases. Rockwool insulator was installed around the metal chimney in effort to represent the penetration of a roof. The tests were performed with different thicknesses of roof. The thicknesses used in the tests were 200 mm, 300 mm, 400 mm and 600 mm. A diagram of the test structure is shown in Figure 2. During the study, it was noticed that a higher roof thickness led to heat being accumulated in the middle part of the penetration. Temperatures in the penetration with different thicknesses of roof at a distance of 100 mm from the chimney are demonstrated in Figure 3. Momentary rise of temperature can be noticed in the 400 mm and 600 mm roof thicknesses. The rise of the temperature is due to heat being released from the combustion of the binder of rockwool. Heat release occurred especially in high roof thicknesses. Heat release ceases to appear after all of the binder of rockwool has been burnt. Heat release was clearly recognized when two tests were carried out on the same structure. In the second test the temperatures at the penetration were considerably lower than in the first test. The temperatures during the tests 1 and 2 are shown in Figure 4.

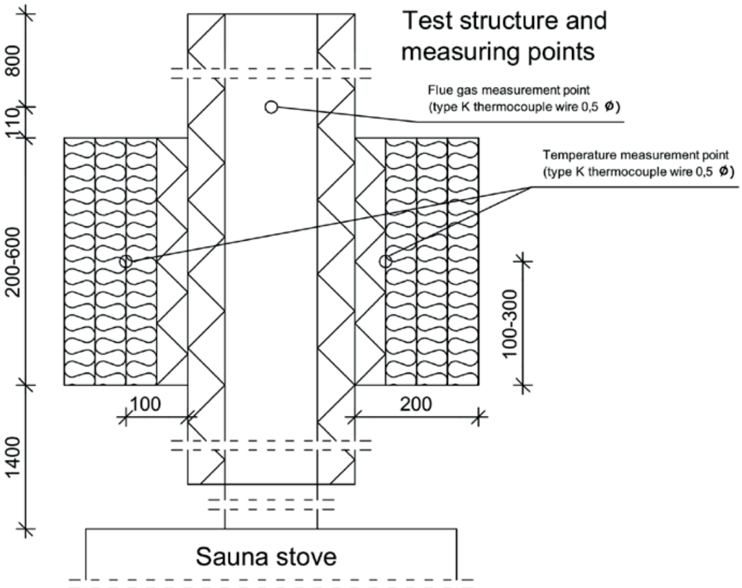

Figure 2. Example of the test assembly. Dimensions in millimeters.

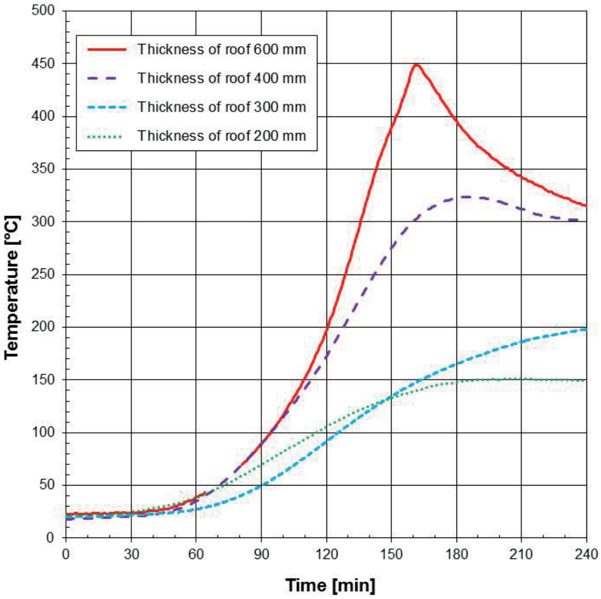

Figure 3. Temperatures at penetration with 100 mm distance from the surface of the chimney and roof thicknesses of 200 mm to 600 mm.

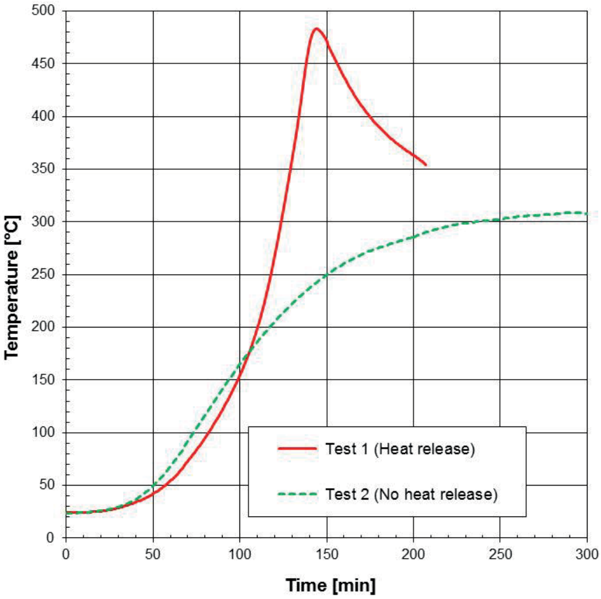

Figure 4. Temperatures at penetration with 100 mm distance from the surface of the chimney in tests 1 and 2.

Experimental Results

A test series was performed in the study, which studied the heat release caused by the charring of the binder of rockwool. When the temperature of the electric furnace was stabilized at the desired temperature, a rockwool slab (thickness 2x50mm) was installed in a hole in the wall of the furnace. The temperature of the rockwool slab was measured from the cross section with 10 mm spaces between measurement points. The face of rockwool slab facing the furnace was covered with aluminum foil to prevent convection and radiation. The specimen before testing is shown in Figure 5. Test arrangement and measurement of temperature is shown in Figure 6. The test specimen installed in the wall of the furnace is shown in Figure 7. The tests were performed with furnace temperatures of 300 °C, 350 °C, 400 °C, 500 °C and 600 °C. A second test was performed on the specimens at the same temperatures. The development of temperatures without heat release from the burning binder of rockwool was observed during the second test.

Figure 5. Test specimen before the tests.

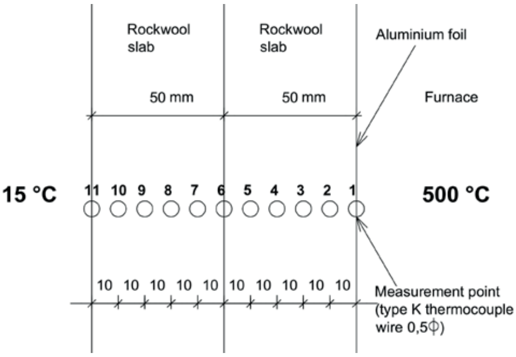

Figure 6. Test arrangement and measurement of temperature. Dimensions in millimeters.

Figure 7. Test specimen installed in the wall of the furnace.

Heat release from the burning of the binder of rockwool was observed clearly during the tests. When the temperature of the furnace was 500 °C, the highest temperatures were reached for about 90 minutes. After this, the temperatures decrease. Inside the specimen, temperatures reached were higher than in the furnace. The temperatures within the cross section of rockwool are shown in Figure 8. The difference between temperatures measured in tests 1 and 2 was nearly 270 °C at the highest. The temperatures were measured 40 mm from the furnace. The differences in temperatures within the insulator 40 mm from the furnace measured between the first and second tests, with furnace temperature at 500 °C is shown in Figure 9.

The highest temperatures observed at different distances in tests, and the differences of the highest temperatures with the furnace temperature at 300 °C to 600 °C are shown in the Table 2. It can be concluded from Table 2 that the heat release is not very high at furnace temperatures below 400 °C.

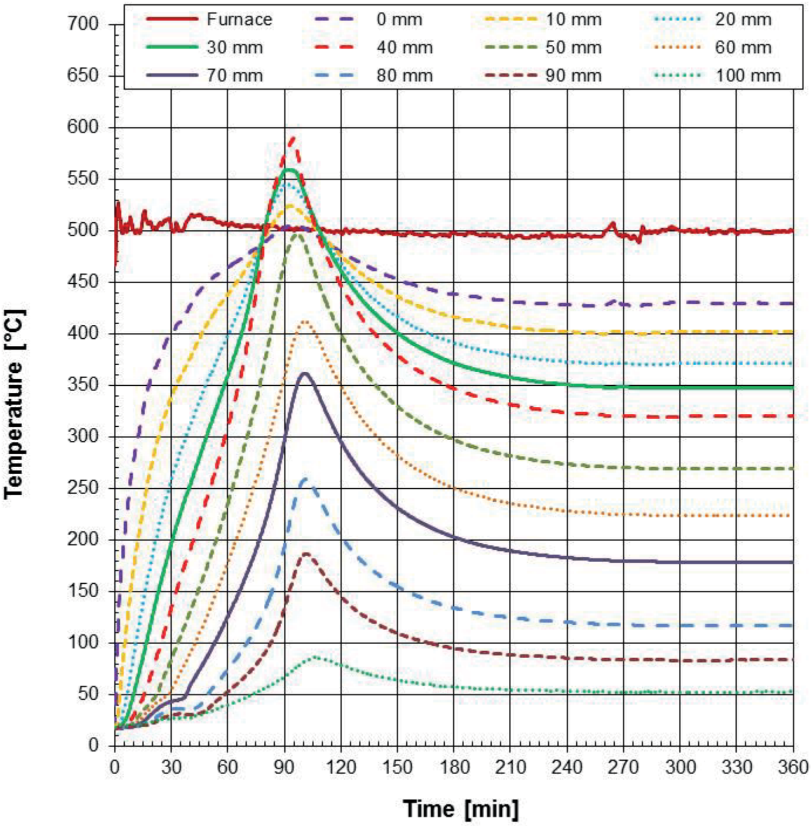

Figure 8. The charring of the binder of rockwool causes a momentary temperature rise inside the rockwool.

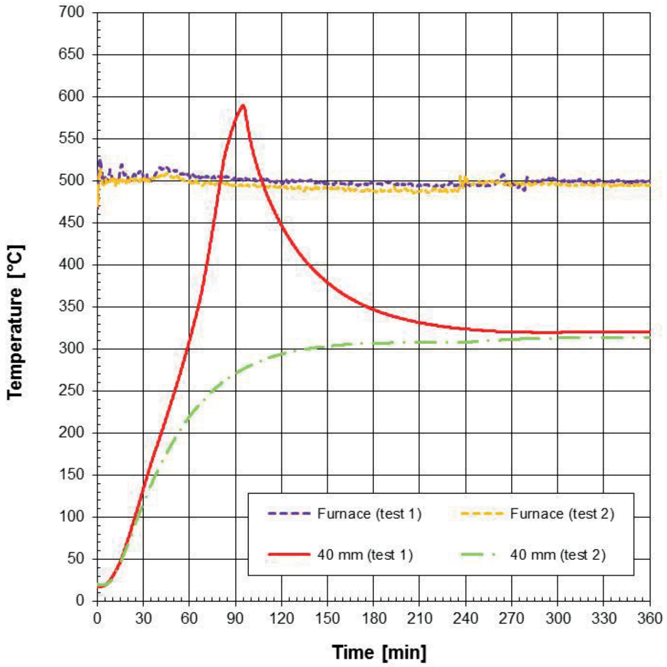

Figure 9. Differences in the temperatures observed within the insulator 40 mm from the furnace between the first and second test when the temperature of the furnace was 500 °C.

Table 2. The highest temperatures at different distances in tests, and differences of the highest temperatures when furnace temperature was 300 °C to 600 °C. In test 1 heat is released and in test 2 heat is not released.

Furnace	600 °C			500 °C			400 °C			350 °C			300 °C		
	Test1	Test2	T1-T2	Test1	Test2	T1-T2	Test1	Test2	T1-T2	Test1	Test2	T1-T2	Test1	Test2	T1-T2
0 mm	583	517	66	505	420	85	340	321	19	304	281	23	253	251	2
10 mm	591	491	100	524	392	132	329	307	22	287	263	24	239	236	3
20 mm	599	466	133	545	363	182	306	281	25	268	243	25	221	220	1
30 mm	599	422	177	560	340	220	286	260	26	248	224	24	206	204	2
40 mm	584	378	206	590	314	276	262	237	25	223	200	23	181	180	1
50 mm	574	352	222	497	262	235	226	200	26	191	171	20	154	153	1
60 mm	536	284	252	412	215	197	187	166	21	155	139	16	129	129	0
70 mm	456	220	236	362	173	189	151	134	17	127	113	14	103	103	0
80 mm	358	167	191	259	115	144	103	91	12	92	83	9	75	74	1
90 mm	200	97	103	187	85	103	64	57	7	49	45	4	41	39	2
100 mm	139	73	66	86	54	32	55	49	6	41	38	3	41	41	0

The tests were also performed on different thicknesses of rockwool layers (60 mm, 80 mm, 100 mm, 120 mm, 150 mm and 200 mm). The temperatures within the rockwool 40 mm from the furnace during different tests are shown in Figure 10. During the tests the temperature of the furnace was 500 °C. The highest temperatures measured in the tests at different distances from the furnace are shown in Table 3.

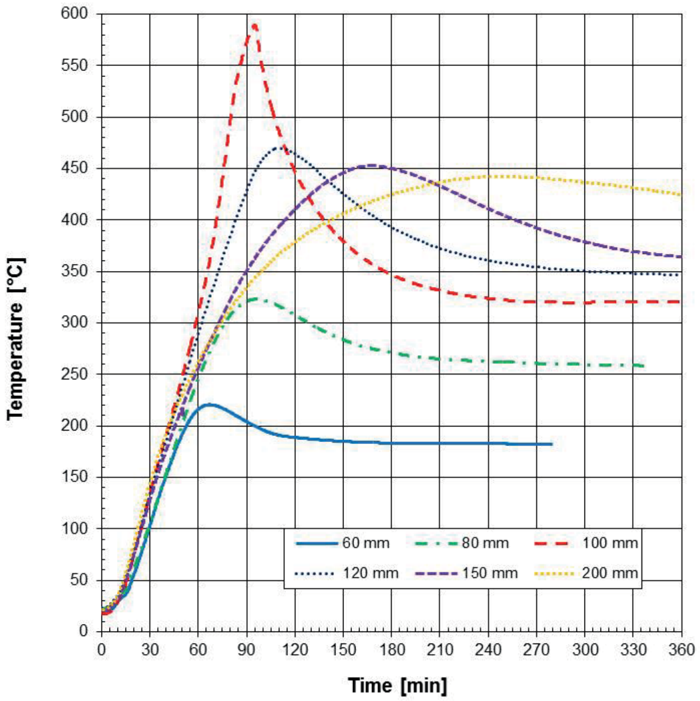

Figure 10. Temperatures in rockwool measured 40 mm from the furnace. Specimen thickness was 60 mm to 200 mm and furnace temperature 500 °C.

It can be noticed from Figure 10, that heat release has the highest effect with 100 mm thickness of rockwool. The binder burns more slowly in thicker rockwool layers. The fact that the amount of air required for combustion does not effectively penetrate the thicker insulator layer is probably an explanation here. However with thinner insulation than 100 mm, the amount of heat required for combustion does not accumulate in the rockwool.

Table 3. The highest temperatures at different distances in tests when the thickness of rockwool was 60 mm to 200 mm.

Thickness of	**Distance from the furnace [mm]**																
rockwool	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**120**	**130**	**150**	**160**	**180**	**200**
60 mm	415	384	352	262	221	111	70										
80 mm	434	423	399	362	323	265	190	91	79								
100 mm	505	524	545	560	590	497	412	362	259	187	86						
120 mm	488	487	488	479	470	453	428	377	330	262	195	63					
150 mm	466	466	463	459	453	441	424	402	366	338	282	186	136	55			
200 mm	465	460	456	450	442	432	421	411	396	378	357	318	284	221	172	108	49

Higher than assumed temperatures in the roof penetration for the chimney may ignite surrounding structures. The ignition temperature of wood is not a physical quantity but depends on conditions. Babrauskas at al [25] found that under short-term exposure (minutes to a few hours) the ignition temperature of wood is about 250 °C, but under long-term exposure it can be considerably lower, as low as 77 °C. Matson at al [26] made a comprehensive study of wood ignition temperatures including tests on different wood species. They presented a compilation of experimental tests where ignition temperatures were around 200 °C or higher, but under long-term exposure the ignition temperatures were significantly lower e.g. by steam pipes. Under short-term exposure the 85 °C temperature limit would seem to hold, but in longer exposure times certainty decreases. In some instances the exposure times of chimneys may be quite long, especially when the chimney passes through efficient thermal insulation

Computational Modeling

In this section the heat release model is generated. Measurement is key factor when constructing the heat release model. Time-dependent, one-dimensional heat conduction equation for the rockwool reads

$$\rho c_p \frac{\partial T(t,x)}{\partial t} = \lambda(T) \frac{\partial^2 T(t,x)}{\partial x^2} + q(t,x) . \tag{1}$$

where ρ is density of rockwool, (kg/m^3), c_p is the specific heat (J/kg°C), $T(t,x)$ is temperature depending on the spatial co-ordinate x (m) and time t (s), $\lambda(T)$ is the temperature-dependent thermal conductivity (W/m°C), and $q(t,x)$ is the rate of internal heat generation (W/m^3). In computations, as the initial condition the temperature field $T(t=0,x)$ was set to constant value 15 °C and the boundary conditions was $T(t,x=0)=500\,°\mathrm{C}$ and $T(t,x=100\text{ mm})=15\,°\mathrm{C}$. The temperature field $T(t,x)$ of rockwool is shown in Figure 11. Radiation heat transfer is modeled in the so called optically thick limit, where the radiative flux is proportional to the temperature gradient [27]. Exploited values of conductivity $\lambda(T)$ are shown in Table 4.

When temperature field $T(t, x)$ is known by measurements, the heat release can be solved, giving

$$q(t,x) = -\lambda(T) \frac{\partial^2 T(t,x)}{\partial x^2} + \rho c_p \frac{\partial T(t,x)}{\partial t} . \tag{2}$$

where derivatives can be approximated by difference formulas. The heat release $q(t,x)$ of the rockwool during the first heating is illustrated in the Figure 12 showing typical numerical oscillations due to the difference formulas. However, the biggest peak indicates heat release caused by smouldering combustion.

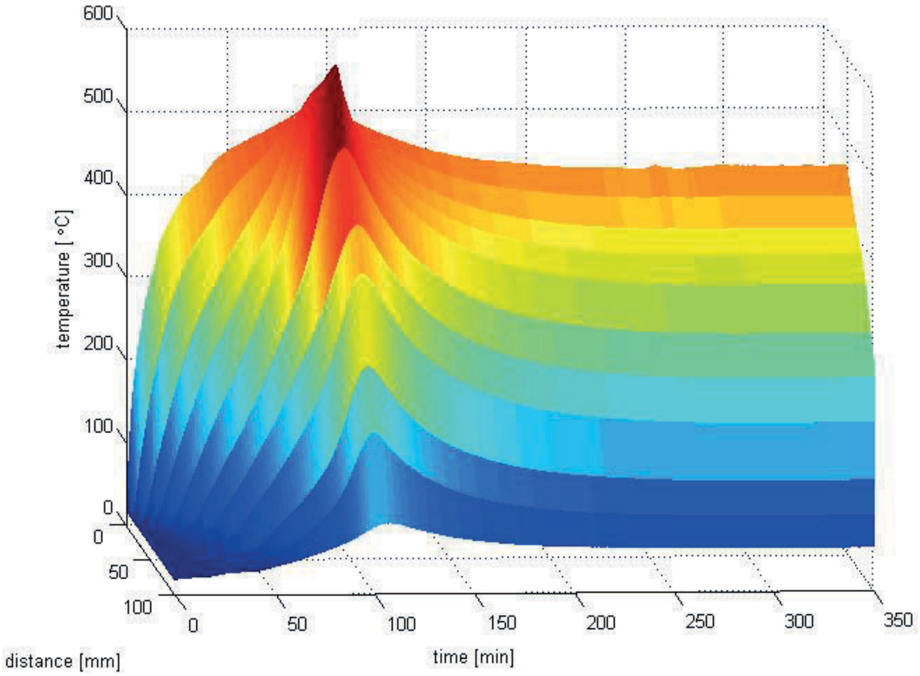

Figure 11. Measured temperature field of the rockwool, the wool width is 100 mm, and the temperature of the furnace was 500 °C

Table 4. Properties of rockwool: ρ is density, c_p is the specific heat capacity, the conductivity $\lambda(T)$ is linearly interpolated between given points.

ρ	140 kg/m^3
c_p	840 J/kg°C
λ(10˚C)	0,037 W/m°C
λ(100˚C)	0,043 W/m°C
λ(200˚C)	0,057 W/m°C
λ(300˚C)	0,077 W/m°C
λ(400˚C)	0,104 W/m°C
λ(500˚C)	0,138 W/m°C
λ(600˚C)	0,179 W/m°C
λ(700˚C)	0,226 W/m°C

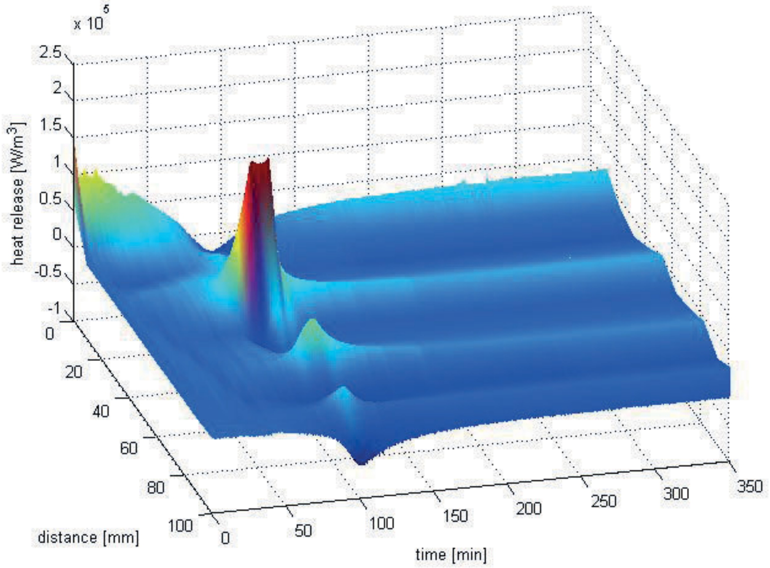

Figure 12. Heat release of rockwool under the first heating after equation (2)

Heat release $q(t,x)$ can be estimated by piece-wise approximation given in Figure 13. The maximum value of the heat release ($q_{\max} = 205\ \mathrm{kW/m^3}$) is at the time span 83…95 min at 40 mm from the furnace surface.

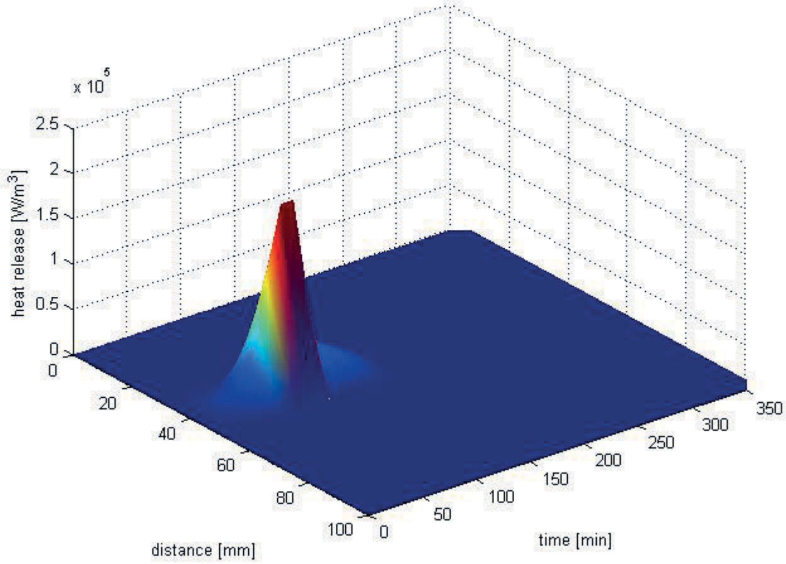

Figure 13. Heat release simplification

Afterwards when the heat release approximation is known (Figure 13), the heat equation (1) can be solved numerically by MATLAB with pdepe-function. The temperature field of the rockwool $T(t,x)$ is shown in Figure 14 indicating relatively good fitting to measurements. The fitting can be improved by including the possible endothermic reaction (negative heat release) in front of smouldering combustion area; the distance from 55…65 mm.

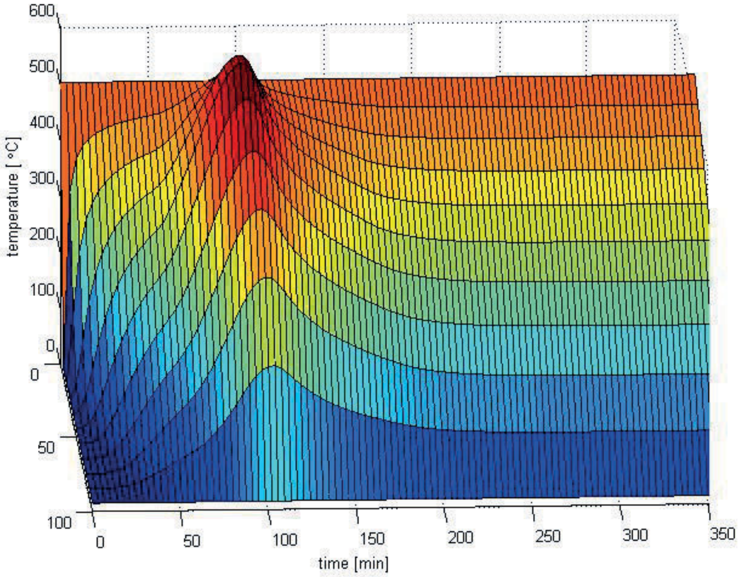

Figure 14. Computed temperature of the rockwool $T(t,x)$ with the heat release approximation according to Figure 13

Conclusions

The temperature in the chimneys roof penetration is significantly affected by the smouldering combustion of rockwool binder. The phenomenon is at its worst when it is been at the risk limits in the temperatures. At the roof penetration, even a small rise in temperature can cause ignition if the temperature is already near ignition temperature. Because the burning of the binder releases heat and raises temperature, it essentially causes the situation to get worse. The consequence may be an escalation of temperatures.

Numerical study of the heat equation discovers the location and time moment where the heat release has a significant effect on the temperature field. The result of numerical modeling provides the heat release function on time and position. However, a more involved smouldering combustion model need to be studied in order to predict temperature peak in rockwool in general case.

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Perttu Leppänen, Jari Mäkinen
Department of Civil Engineering
Tampere University of Technology
P.O. Box 600, 33101 Tampere
perttu.leppanen@tut.fi,
jari.m.makinen@tut.fi

Manuela Neri
Department of Industrial and
Mechanical Engineering
Universita Degli Studi di Brescia
Via Branze 38, 25123 Brescia Italy
m.neri001@unibs.it