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

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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

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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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].
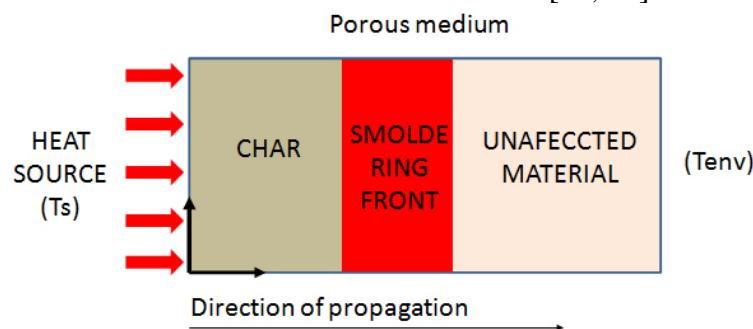

Figure 1. Representation of smouldering process, where Ts is the source temperature and Tenv is environment temperature.

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.
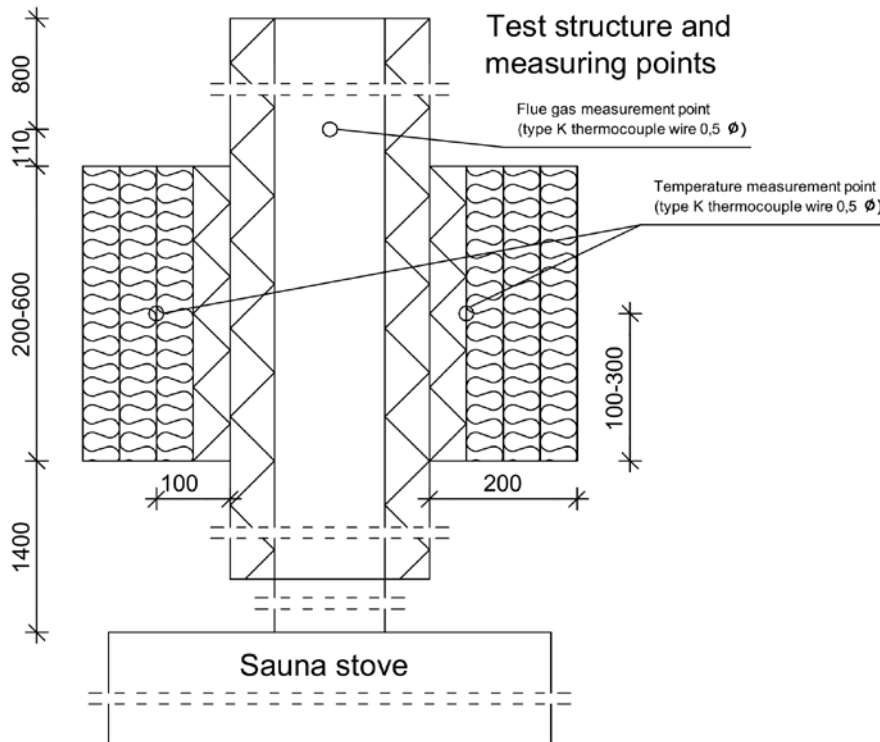

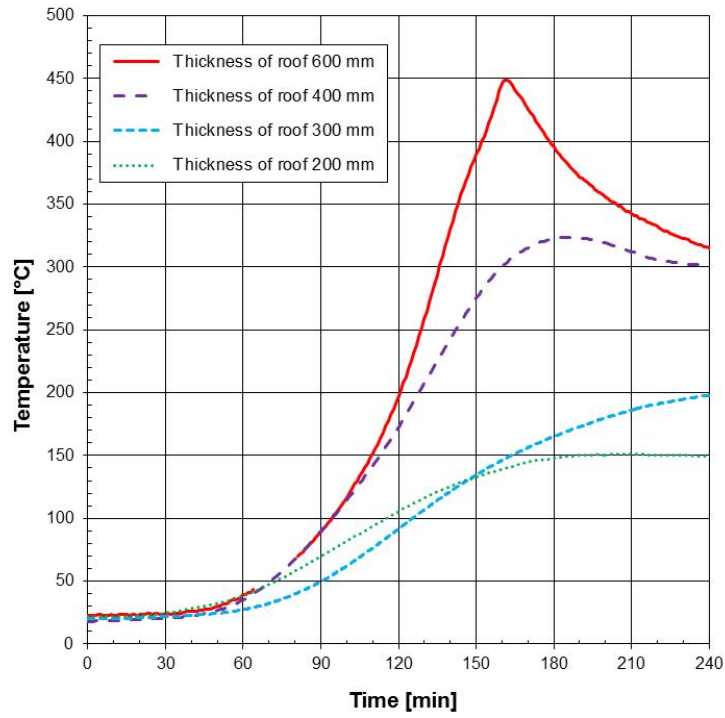Figure 2. Example of the test assembly. Dimensions in millimeters.

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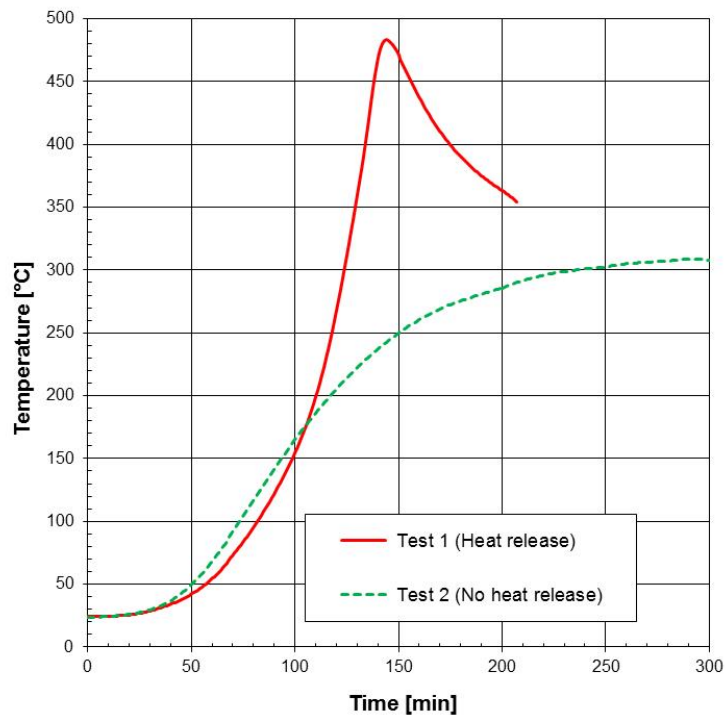and roof thicknesses of 200 mm to 600 mm.

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.
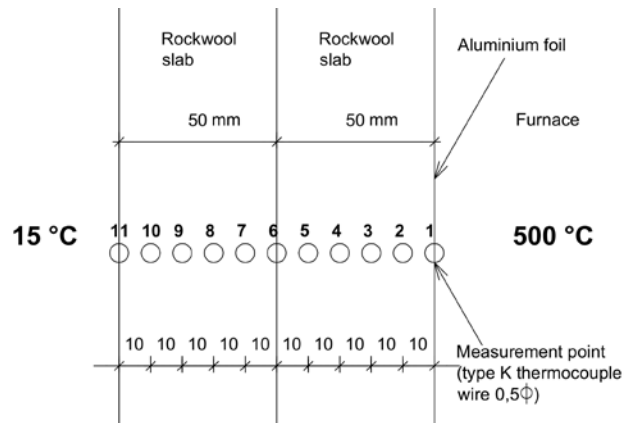

Figure 5. Test specimen before the tests.

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.
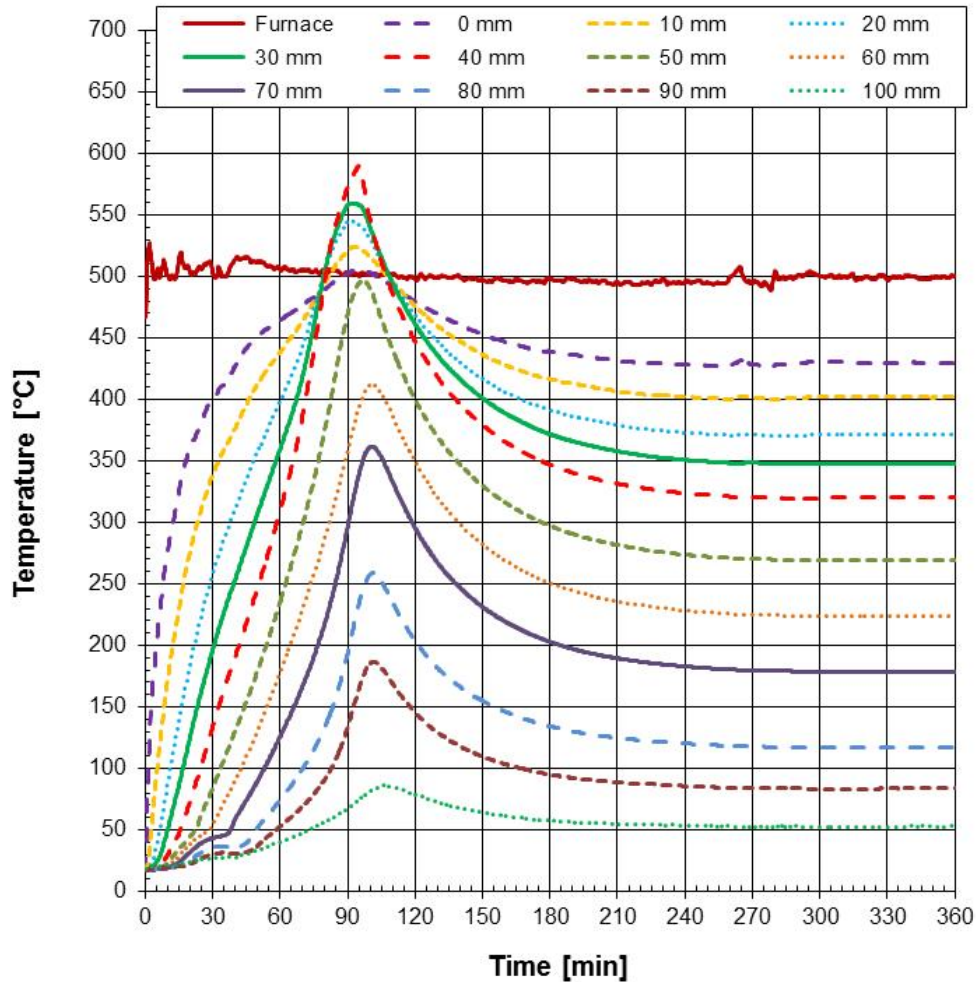

Figure 8. The charring of the binder of rockwool causes a momentary temperature rise inside the rockwool.
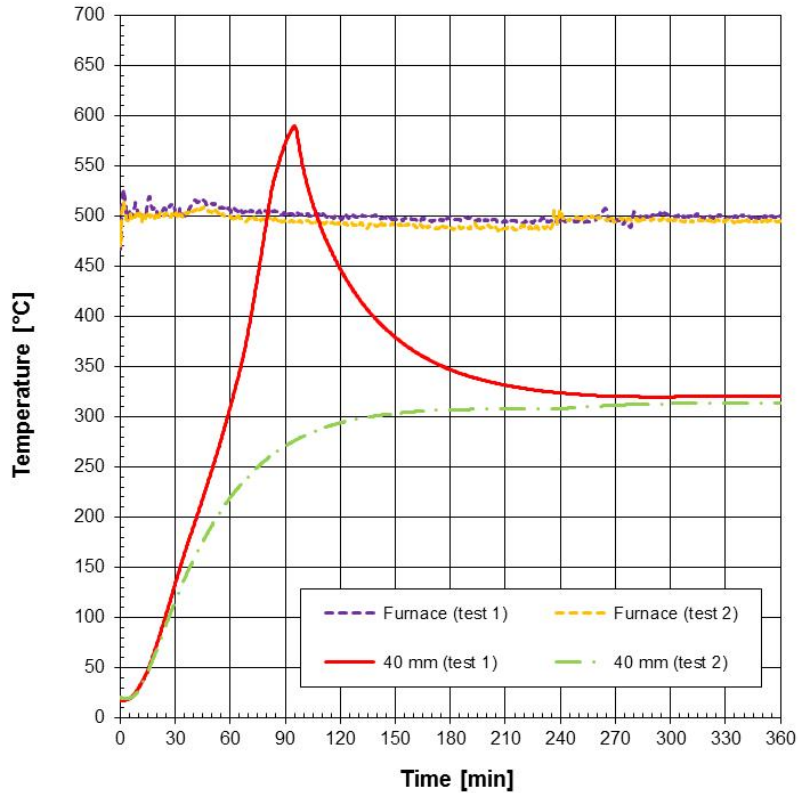
Figure 9. Differences in the temperatures observed within the insulator 40 mm from the furnace between the first and second test when the temperature of the furnace was 500 °C.

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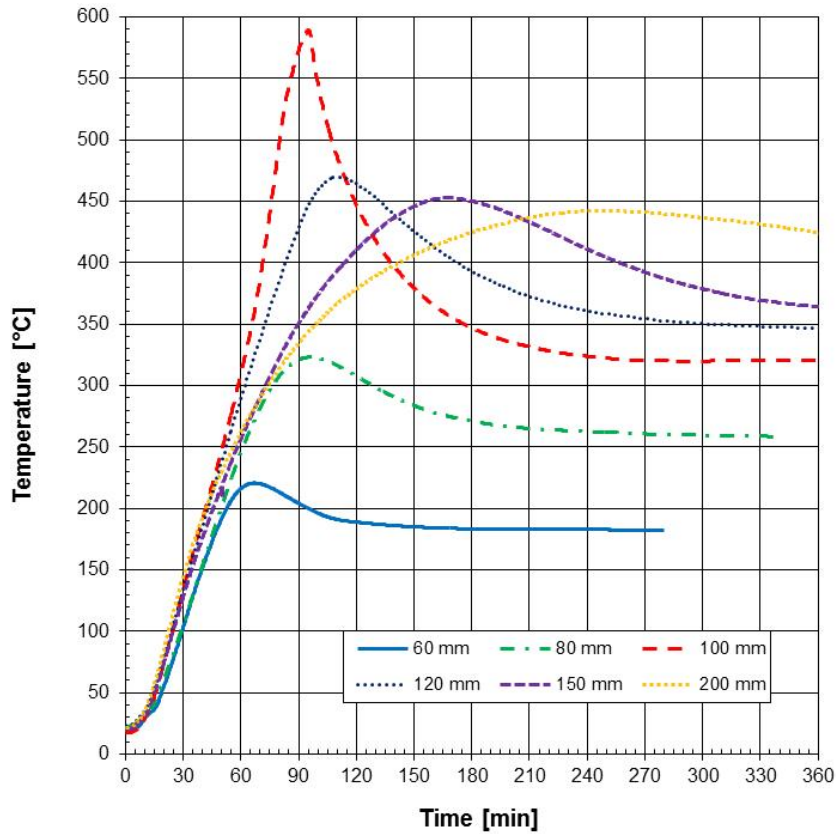
Figure 10. Temperatures in rockwool measured 40 mm from the furnace. Specimen thickness was 60 mm to 200 mm and furnace temperature 500 °C.

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 rockwool	Distance from the furnace [mm]																
	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 $T(t,x=0)=500\,°C$ and $T(t,x=100\,\mathrm{mm})=15\,°C$. 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.
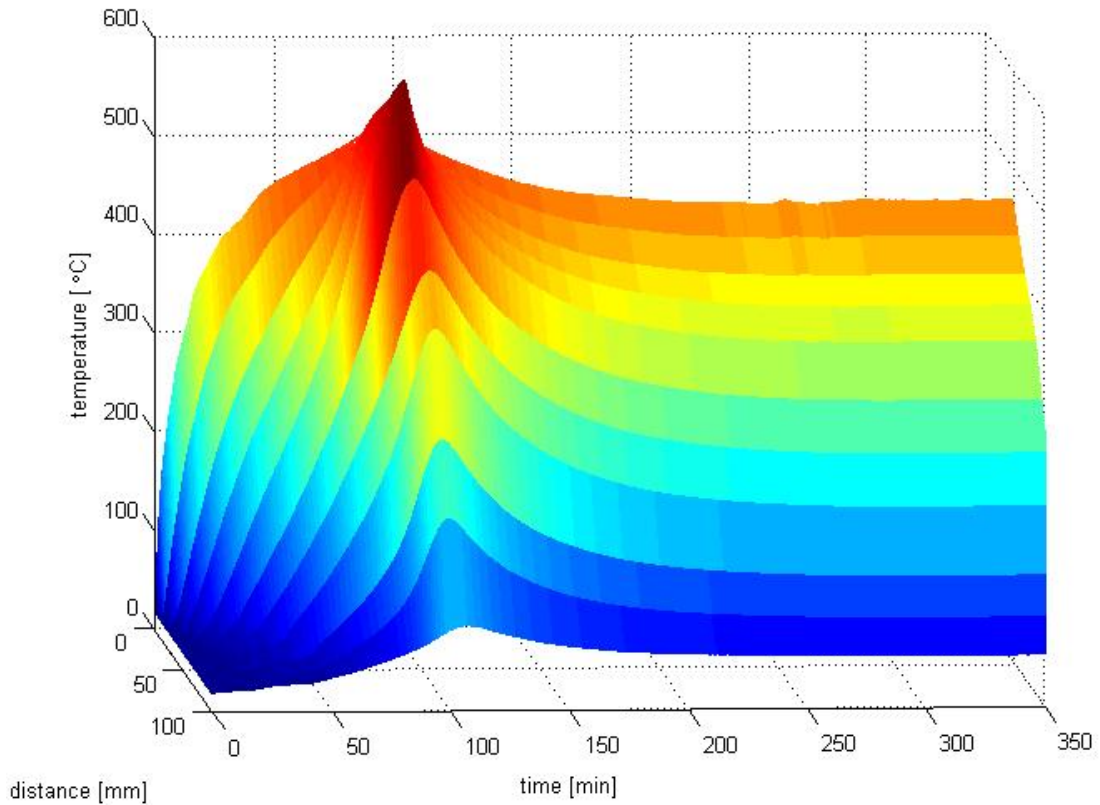
Figure 11. Measured temperature field of the rockwool, the wool width is 100 mm, and the
temperature of the furnace was 500 °C

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.

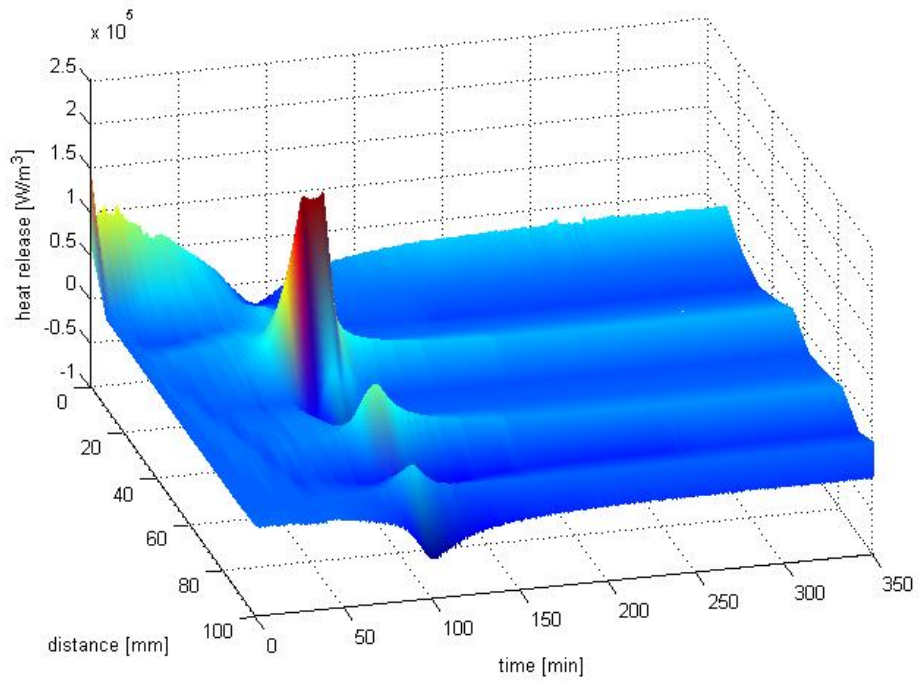| ρ	140 kg/m^3
c_p	840 J/kg°C
$\lambda(10\,°C)$	0,037 W/m°C
$\lambda(100\,°C)$	0,043 W/m°C
$\lambda(200\,°C)$	0,057 W/m°C
$\lambda(300\,°C)$	0,077 W/m°C
$\lambda(400\,°C)$	0,104 W/m°C
$\lambda(500\,°C)$	0,138 W/m°C
$\lambda(600\,°C)$	0,179 W/m°C
$\lambda(700\,°C)$	0,226 W/m°C

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 ($q_{max} = 205\,\text{kW/m}^3$) is at the time span 83…95 min at 40 mm from the furnace surface.
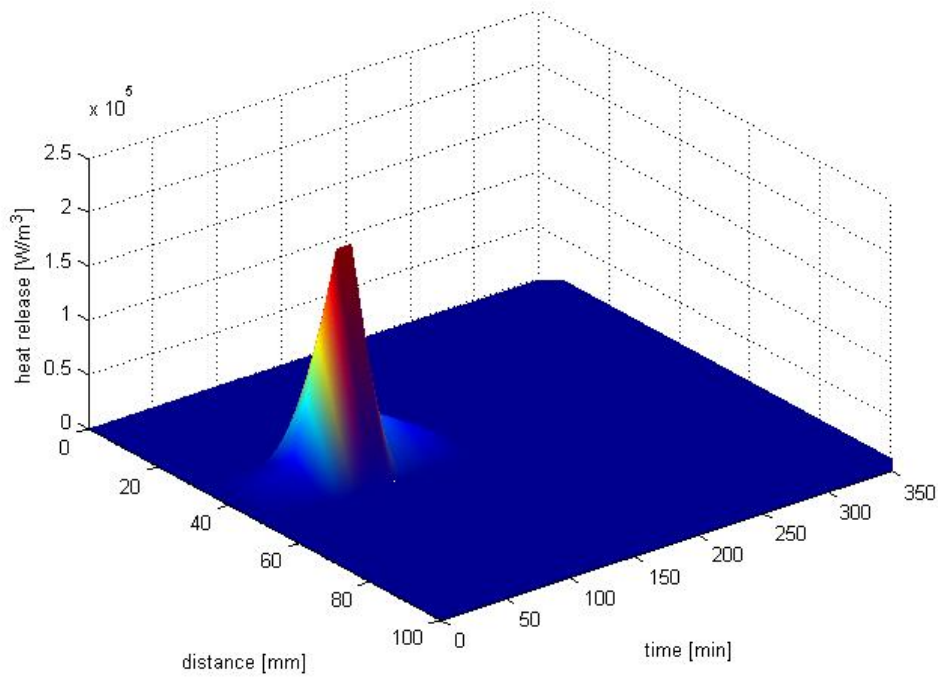

Figure 13. Heat release simplification

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.

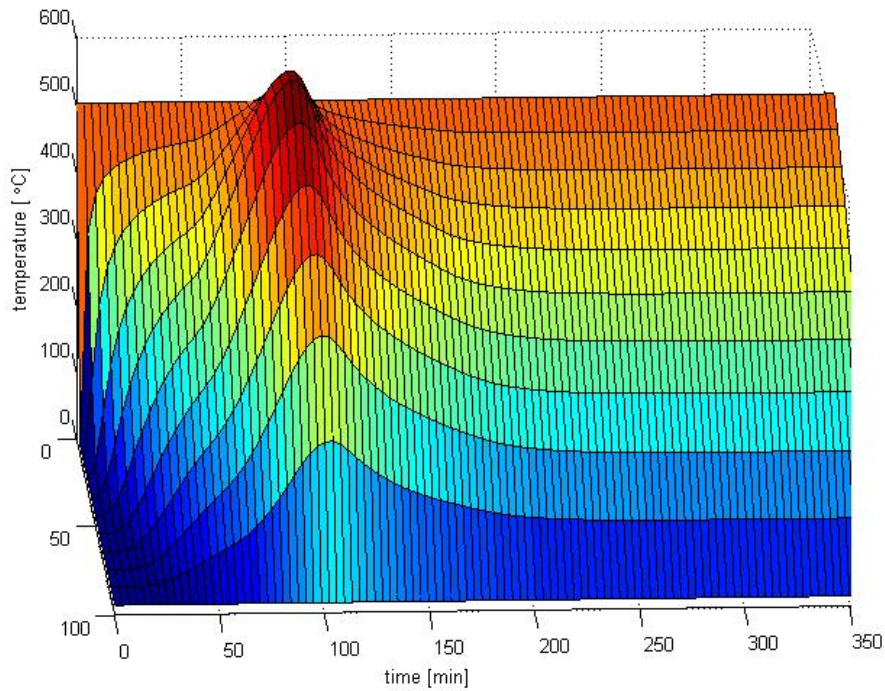Figure 14. Computed temperature of the rockwool $T(t,x)$ with the heat release approximation according to Figure 13

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.

Financing

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