SAFETY ISSUES IN SOLID FUEL HEATING INSTALLED IN CLOSED SYSTEMS WITHOUT HEAT DISSIPATION DEVICES

by

Borivoj Lj. STEPANOV, Momčilo Dj. SPASOJEVIĆ, Željko D. VLAOVIĆ, Kalman B. BABKOVIĆ, Djordjije D. DODER, and Vladimir M. RAJS**

Faculty of Technical Sciences, Novi Sad, Srbija

Original scientific paper
https://doi.org/10.2298/TSCI170623298S

The objective of this paper is to raise awareness of the risk of boiling liquid expanding vapor explosions (steam explosions) in heating systems in Serbia caused by a combination of the following factors: solid fuel burning, older boiler design, closed systems, and non-installation of heat dissipation devices. The practice is in accordance with neither Standard SRPS EN 303-5:2012 nor subject literature, which both demand that this type of heating be installed in open systems. Explosions do occur; there was one in 2014 in Futog, Serbia, with fatal consequences. The main protection element, safety valve, is designed for temperatures up to 110 °C. Its operation above 110 °C is unknown. The experiment physically simulated the worst case scenario, where there is no circulation in the heating system. It used a 90 L water-filled vessel with six 3 kW electric heaters installed and safety valves attached. This paper presents the first results for the case where the set pressure of the safety valve was 1.5 bar and one heater of 3 kW was in operation. The results showed that the safety valve did not prevent boiling. The recorded pressure peaks were at 2.2 bar and the lows were at 0.8 bar, so its operation intensified boiling. Therefore, the system cannot be considered safe even with a brand new safety valve and at low overheating rates. Better air removal in the system is to be solved in future experiments. Tests will be done with different safety valves and overheating rates.

Key words*: boiler safety, solid fuel boiler, closed hydronic system, steam explosion, BLEVE*

Introduction

The boiler design in question has a fixed grate. The primary air is supplied under the grate by natural draft created by the chimney. The secondary air is missing. The primary air quantity is regulated by a draft regulator which is actuated by the boiler supply water temperature. The fuel loading of the boiler is manual. Upon ignition all of the fuel charge (batch) is involved in the combustion process, consequently, there is no possibility of precise regulation and division of the combustion process into separate subprocesses – heating, drying, devolatilisation and burning. The same boiler is usually used for both coal and wood firing.

The boiler can be installed in the closed or open system. In the open system, an open tank at the highest point of the installation is used to store the expanded fluid. In the closed system (pressurized/sealed), a closed expansion vessel is used to store the expanded fluid.

* Corresponding author, e-mail: rajs.vladimir@gmail.com

Closed hydronic systems emerged in the 1960. They were an improvement on open ones. The fuel switch also contributed to this transition. For example, in West Germany in the 1950's coal stoves were the main device used for heating, and in the 1960 there was a fuel switch from coal to heating oil with the development of oil fired boilers. These boilers could fully automatically deliver heating and hot water. In the 1970 gas started to gain ground, and oil use decline started after the oil crises of 1973 and 1979.

The theory is clear on the subject of solid fuel boiler installation in closed systems. There is a clear warning in [1]: *It is forbidden to use closed expansion vessels if the boiler is fired by solid fuel, because in case of failure of a boiler component (for example safety valve) there is no possibility of momentarily stopping the heating, unlike in the case of liquid or gaseous fuel*.

On the other hand, the practice is clear too: the draft regulator is an element that regulates the temperature and thus eliminates the need for the safety heat exchanger. The safety heat exchanger requires a water supply access point, which is not always available in boiler rooms. The filling of the system is done using hoses.

The theory's *argument* is that the draft regulator is indeed a proven element, with over 50 years in service. Its operation is effective when it regulates slow changes in temperature and daily weather patterns, but it cannot handle abrupt changes in the heating system. These changes occur when the flow is stopped by electricity shortage, pump failure, air lock, or physical blockage in the flow system. The heat must then be removed from the system, which the draft regulator cannot perform. The result is overheating. Overheating stops when all the heat is dissipated.

The survey on the current practice, overview of the English, German and EU standards covering this topic, good practice examples, and testing methods proving when solid fuel boilers can be installed in closed systems are given in [2].

In closed systems boiling is unacceptable. The British standard [3] recommends that an anti-flash margin equivalent to 11 °C in temperature be allowed.

Closed-loop hydronic systems should be designed to ensure that the absolute pressure of the water at all the points in the system remains safely above the water's vapor pressure at all times. This prevents problems such as cavitation in circulators and valves or *steam flash* in the piping. The latter is a situation in which the water pressure drops below the vapor pressure, allowing the water to instantly change to vapor (*e. g.*, steam). This can cause loud banging noises in the piping and wide pressure fluctuations in the system [4].

In hydronic systems flashing is the prevalent cause of water hammer. It occurs whenever the actual pressure at any point in the system drops below the vapor pressure and steam bubbles form. This can happen throughout the system when there is a sudden drop in the pressure or when the circulating pumps, which provide a certain amount of overpressure, suddenly stop in an inadequately pressurized system. Additionally, water hammer can be localized at high points of the system, in the vena contracta of throttling devices, or in the eye of the circulating pump impellers, where the lowest system pressure is combined with acceleration of the entering water [5].

The normal operation of the heating system is up to 90 °C, fig. 1. By controlling the temperature, the pressure is also controlled in the closed system. If the system does not have proper temperature control, the elements that protect it from overpressure are put on the test. The problem is that these elements are not designed for temperatures above 110 °C and boiling. If the temperature is below 100 °C, there is no explosion in case of vessel failure.

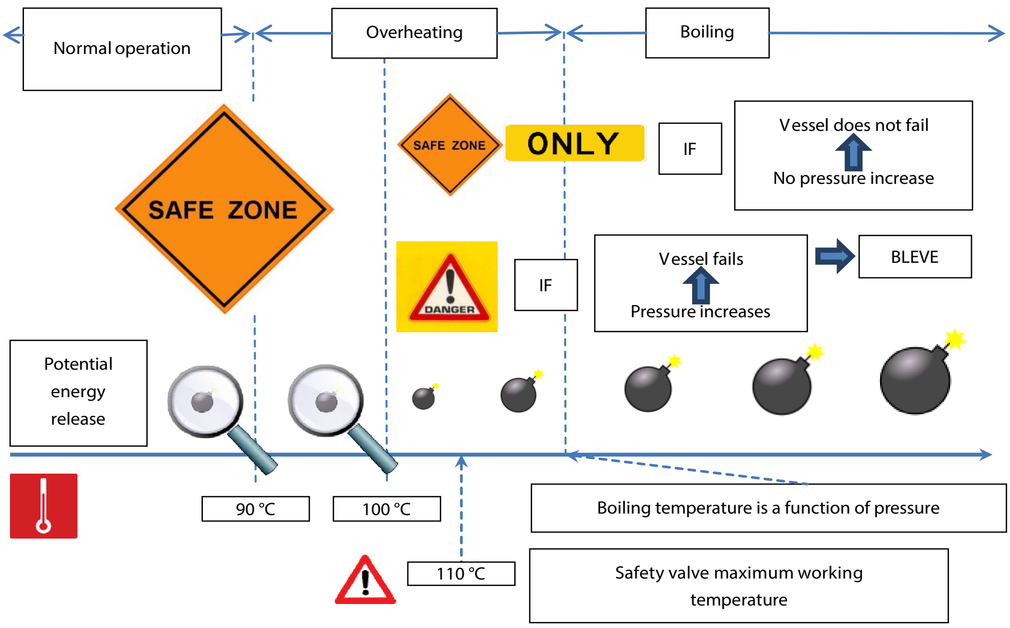

Figure 1. Infographic on safety in heating systems

Our answer to the problem was to design and build an experimental facility that would shed light on the phenomena in the closed system above 110 °C and during boiling, in a closed vessel protected by the safety valve. Our analysis does not include the expansion vessel, since the focus of our study was the time when its capacity is used up and the safety valve takes over the control. Our experiment physically models the case when there is no circulation in the heating system. This is the worst case scenario. With circulation, one part of the heat would be removed by the heat receivers.

The motivation for writing this paper was a potential danger for many households in Serbia. The risk of water exploding is somehow foreign to common reasoning. The steam explosion problem was brought to our attention during a court case in which we were asked to provide expertise on the topic. Although the standards are clear, they are not accompanied by explanations. Furthermore, this subject has not been sufficiently studied in the literature.

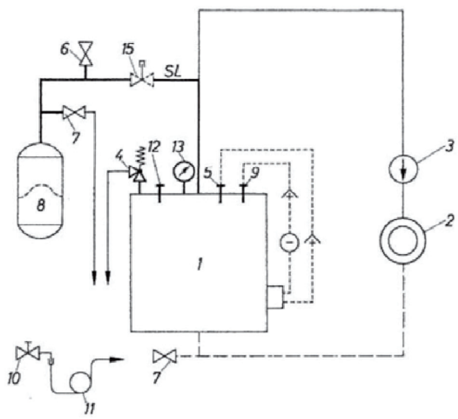

Figure 2. Elements of heating system;
1 – heat producing device, 2 – heat consumer, 3 – circulation pump, 4 – safety valve, ***5 – safety temperature limiter****, 6 – air bleeding valve, 7 – purge valve, 8 – expansion vessel,* ***9 – temperature regulator****, 10 – connection to the water main (supply) system, 11 – connection pipe, 12 – thermometer, 13 – manometer*

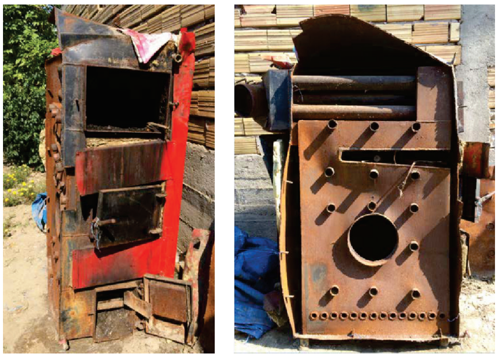

Figure 3. Aftermath of steam explosion

Problem steam explosion

There are two types of explosions that can occur in a boiler-flue gas side and water side explosions. This paper is focused on the latter type. In order to ensure the safety of systems, the standard requires that closed heating systems have a safety temperature limiter, fig. 2. It is usually in the form of a safety heat exchanger that is placed in the water space of the boiler and connected to the water mains. When the water temperature reaches 100 °C, cold water is admitted through the heat exchanger; it removes excess heat from the system and therefore, stops overheating.

Unfortunately, this recommendation is often ignored. Standards are obligatory only if they are included in the regulations. Residential boilers are not subject to any inspection or regulation. Thus, it is up to manufacturers and installers to do what they think is best, or to users to demand specific solutions. Given the low frequency of explosion occurrence and, in some cases, the unfamiliarity with the standards, manufacturers and installers choose the easier solution, *i. e.* the closed system without a safety heat exchanger. The fig. 3, shows a boiler that suffered a steam explosion. There are visible deformations of the top metal sheet, and the side sheet is completely blown away. The boiler is a three-pass solid fuel boiler. Reinforcements in the form of short cylinders can be seen on its side. We cannot disclose further information regarding the explosion, since it is the subject of an ongoing court case.

The energy that is released upon vessel fracture is calculated as the difference between the internal energy before and after the explosion. The acceptable estimate is the assumption that the process is isentropic [6].

The most important factor is the temperature of the water. The tables show the calculations for the released energy for different cases. Tables 1 and 2 represent a case in which the water temperature is above 100 °C and the pressure is varied. Table 1 shows the results in terms of kJ/kg of the released energy, and tab. 2 in terms of the vapor share in the expanded state 2. Table 3, however, depicts a case where the temperature of the water is below 100 °C, with a pressure range much wider than in the first case. As the released energy in the second case is much smaller, the results had to be multiplied by 1000.

Table 1. Energy released after vessel rupture when water is overheated (t > 100 °C)

$(u_1 - u_2)$ [kJkg^{-1}]		Temperature [°C]									
		105	110	115	120	125	130	135	140	145	150
Pressure [bar]	2	1.86	3.84	6.09	8.57	–	–	–	–	–	–
	4	1.85	3.84	6.08	8.56	11.29	14.26	17.46	20.89	–	–
	6	1.84	3.83	6.07	8.56	11.28	14.25	17.45	20.88	24.53	28.41
	8	1.84	3.82	6.06	8.55	11.27	14.24	17.43	20.86	24.51	28.39
	10	1.83	3.82	6.06	8.54	11.26	14.23	17.42	20.85	24.50	28.37

Table 2. Vapor share of the water mixture state after the expansion the atmospheric pressure

x_2 [%]		Temperature [°C]									
		105	110	115	120	125	130	135	140	145	150
Pressure [bar]	2	1	1.9	2.8	3.7	–	–	–	–	–	–
	4	1	1.9	2.8	3.7	4.6	5.5	6.4	7.2	–	–
	6	1	1.9	2.8	3.7	4.6	5.5	6.3	7.2	8.1	8.9
	8	1	1.9	2.8	3.7	4.6	5.5	6.3	7.2	8.1	8.9
	10	1	1.9	2.8	3.7	4.6	5.5	6.3	7.2	8.1	8.9
	11	1	1.9	2.8	3.7	4.6	5.5	6.3	7.2	8.1	8.9

Table 3. Energy released after vessel rupture when water is subcooled

$(u_1 - u_2)\cdot1000$ [kJkg^{-1}]		Temperature [°C]									
		90	91	92	93	94	95	96	97	98	99
Pressure [bar]	10	0	0	0	0	0	0	0	0	0	0
	30	2	2	2	2	2	2	2	2	2	2
	50	5	6	6	6	6	6	6	6	6	6
	70	11	11	11	11	11	11	11	11	11	11
	90	18	18	18	18	18	18	18	18	18	18

The data clearly show that the temperature must be controlled. Pressure increase in itself is a main factor that causes a vessel to rupture, but the temperature is the only factor that causes pressure increase. Therefore, control over the temperature is also control over the pressure.

The previous statements and conclusions are not quite straightforward, *i. e.* they are not intuitive. For this reason, experiments have been performed to demonstrate the phenomena. Watts USA, a heating and plumbing equipment manufacturer, performed some experiments [2] to show the danger of overheated water in the case of vessel failure. The experiments were done on gas and electric water heaters. During the experiments the pressure and temperature were recorded, and vessel failure was caused using a hydraulic hammer at the predefined time, when the water was overheated. The *Overheated* here means heated to a temperature above 100 °C. The consequence is shown in fig. 4(b).

(a)  (b) 

Figure 4. Steam explosion with overheated water [7]

Then a set of experiments were performed where the temperature was kept below 100 °C and the pressure was increased using a hand pump. The pressure was increased from 20.7-27.6 bars, and finally to 34.5 bars. The failure of the vessel was induced by hitting it with a spiked hammer, fig. 5(a). The consequence is shown in the second picture, fig. 5(b). There was no explosion, just a water jet.

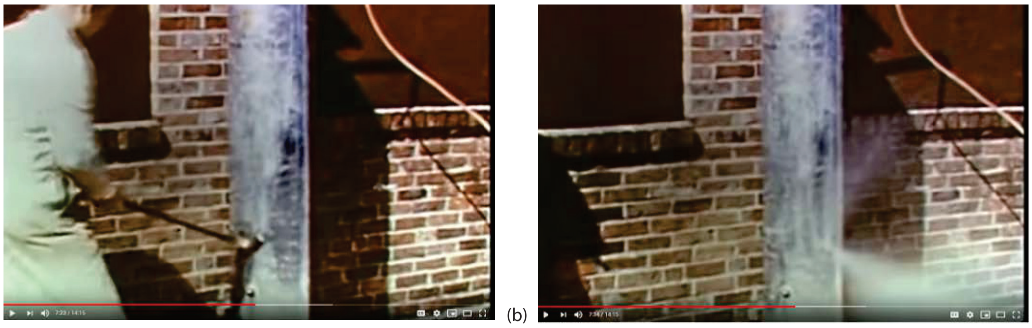
(a) (b)

Figure 5. Vessel rupture when temperature of the water is under 100 °C [7]

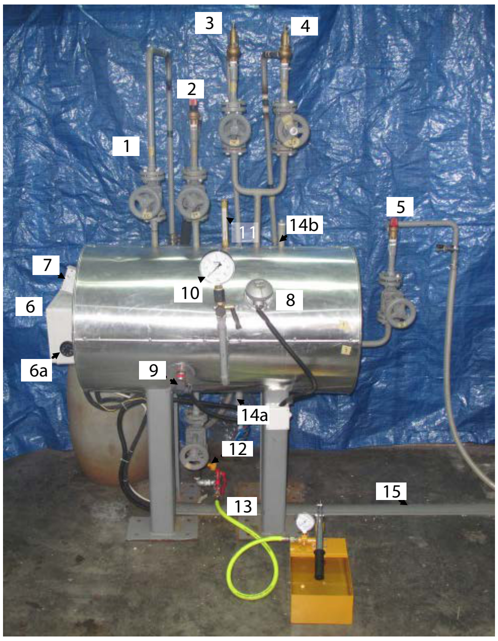

Figure 6. Experimental facility; *1 – venting line with globe valve, 2, 3, 4, 5 – lines with globe and safety valves, 6 – heater housing, 6a – thermostat regulator, 7 – KPI 36 pressure switch, 8 – PT100 sensor with transmitter, 9 – MBS 3000 pressure gauge with transmitter, 10 – bourdon type pressure gauge, 11– mercury thermometer, 12 – filling line, 13 – pressure increase line with hand pump, 14a – connection for future system extension, 14b – connection for future system extension, 15 – electricity and data acquisition signal line*

Experimental set-up

The water vessel consists of a cylindrical part (⌀406.4 mm × 8.8 mm × 500 mm) and two heads (⌀406.4 mm × 8.8 mm, according to EN10253-1), with a total volume of 90 liters.

The design conditions are the pressure 16 bar and the temperature 200 °C. All the elements of the vessel were made of steel P235GH. The vessel is dimensioned according to the standard SRPS EN 13445.

On the vessel there are connections for: two 9 kW heaters (each heater consists of three 3 kW heating elements), the pressure switch, elements for temperature and pressure measurement, four safety valves, and venting, fig. 6.

The following safety measures were implemented: a line to the safety valve with the pressure set at 6 bar, which was always open – 3, a pressure switch – 7, a thermostat – 6a, the distance of the measuring desk from the vessel (6 m), a safety screen to prevent direct exposure to hot water, safety helmets, and finally manual control of the heaters at the control cabinet located above the measuring desk.

The temperature was recorded by a PT100 sensor – 8, and the pressure by MBS3000 – 9. Both of the signals were converted to a 4-20 mA signal that was lead through – 15, to the data acquisition set positioned at the far end of the laboratory. The pressure and temperature were sampled at 1second. The mass was sampled at 3 seconds in the first experiment.

The measuring uncertainty for temperature measurement by PT100 is 0.5% of full scale (150 °C), so it is +/– 0.75 °C. The measuring uncertainty for pressure measurement by MBS3000 is 0.5% of full scale (16 bar), so it is +/– 0.08 bar.

The experimental facility can work in different working regimes. Therefore, there are globe valves that can determine which safety valve is operational.

The experimental procedure is the venting line is opened, the vessel is filled with water, and then the venting line is closed. In order to purge the air from the lines that lead to the safety valves, the pressure in the system is increased using a hand pump. One by one, the safety valve lines are purged by opening the globe valve in each line.

When the system is purged from the air, the venting line is opened and three heaters are started (the total of 9 kW). When the temperature reaches 95 °C, the venting line is closed and the line to the safety valve that is to be tested is opened. In this case, the line to the safety valve is open, with the pressure set at 1.5 bar. Two heaters are turned off. The measurement of the mass can be performed until the point of boiling. This was done in Experiment I. The positions of the safety valves are interchangeable. Line 5, fig. 6, is considered for future experiments in terms of the effect of air in the system. The schematic representation is given in fig. 7.

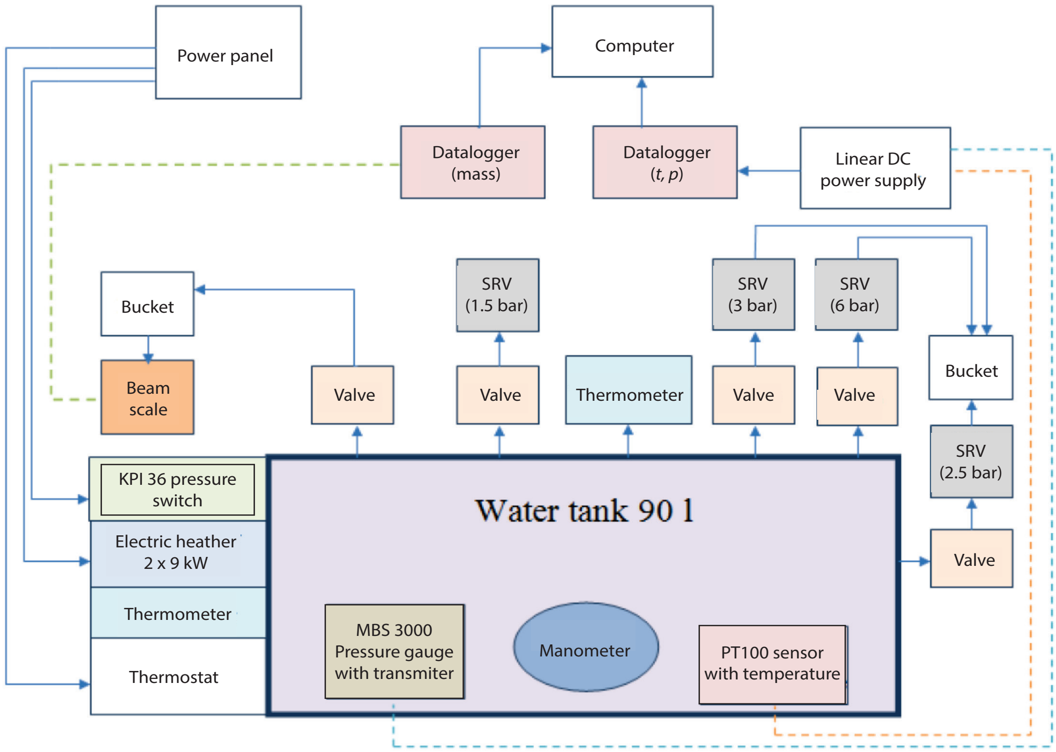

Figure 7. Schematic representation of experimental facility

Results

In Experiment I, the mass measurement was done. The results are shown in fig. 8. Since the scales were limited to 4.2 kg, the measuring bucket had to be emptied periodically,

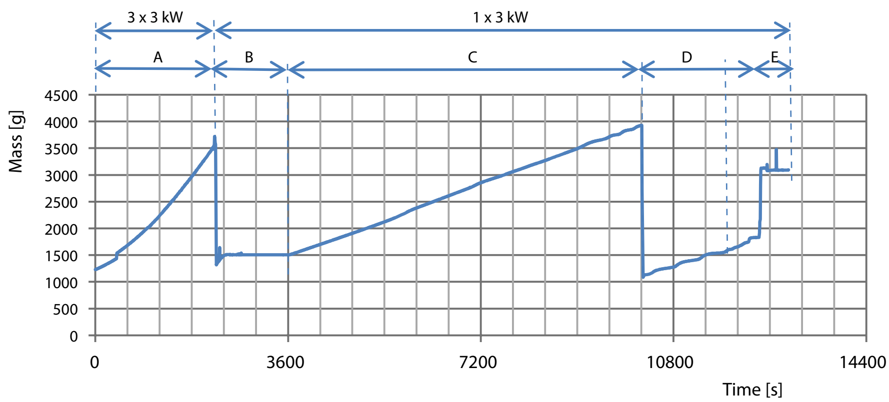

Figure 8. Mass measuring in Experiment I

at the end of periods A and C. Period B should be discarded as this was the bucket manipulation time. The angle of the slope in period A was greater because three heaters were turned on, compared to one heater in periods C and D. The mass change rate in A was 1.1 g/s. In period C the system was closed at the beginning and heated. This caused a rise in the pressure, resulting in the opening of the safety valve. The mass change rate in period C was 0.36 g/s.There was no distinction in mass change between these two phenomena. Additionally, local boiling could not be distinguished in period C. In period D there were some variations in the change of mass, which were the result of local boiling. In period E significant changes were observed, since boiling conditions were reached in a large part of the vessel. The maximum mass change rate was 45 g/s – a 125-fold increase compared to period C.

The goal of this research was to safely measure the pressure change in the boiling phase. This was done in Experiment II, and the results are presented in figs. 9 and 10. Figure 9 also shows the saturation temperature for the measured pressure, and fig. 10 the saturation pressure for the measured temperature.

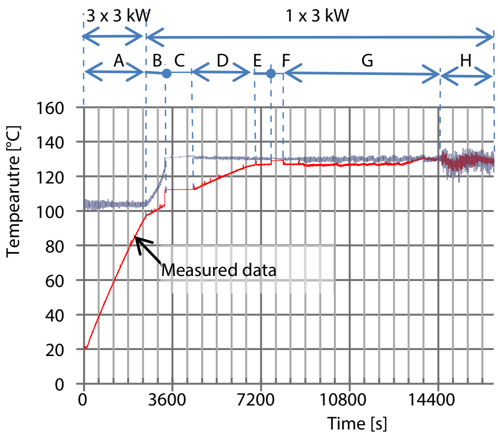

Figure 9. Measured *vs.* saturated temperature

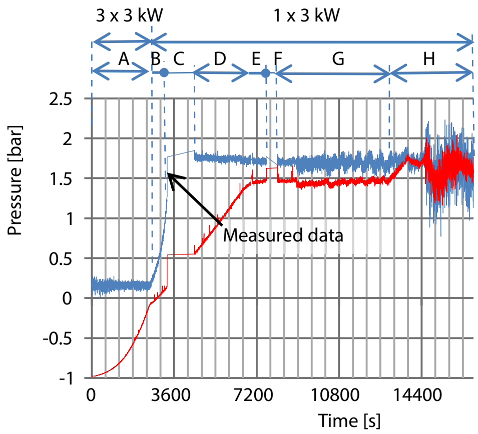

Figure 10. Measured *vs.* saturated pressure

In period A of the experiment the venting line was opened, three 3 kW heaters were on, and the heating was done until the temperature of 95 °C was reached. In period B the venting line was closed, and one 3 kW heater was on. In period C there was a data logging error. The begin point in period C was actually the end point in that period. There was a clear temperature rise trend that could be seen from periods B and D. In period C the safety valve was opened and stayed open. In period E local boiling was approached at the measurement point. Period F was also a data logging error. In period G the boiling volume increased further. Finally, in period H boiling was most intense.

The recorded pressure peaks were at 2.2 bar and the lows were at 0.8 bar. The pressure lower than the saturation pressure additionally intensified boiling.

The points of measurement for the pressure and temperature were different. The pressure was measured near the vessel wall, fig. 6, point 9, and the temperature in the axis of the vessel, 10 cm from the heaters, fig. 6, point 8.

The pressure and temperature changes during period B did not correspond to changes expected when water is heated in a rigid vessel. According to the calculation, the time needed to reach 2.7 bar under the given conditions (constant, volume, heating) was about 10 seconds, tab. 4. The measured time was 900 seconds, fig. 10. The calculated temperature change was 0.1°, compared with the measured temperature change, which was above 10°. The question is, under what conditions would the isochoric change calculation be applicable? In cases where it is, a significant rise in the pressure would be achieved with a small amount of energy. The calculated time needed to reach 10 bar was 14.4 seconds. Temperatures above 100 °C would cause a steam explosion.

Table 4. Isochoric change calculation

p [bar]	1	2	4	8	10
v [m^{3}kg^{-1}]	0.00104	0.00104	0.00104	0.00104	0.00104
t [°C]	95	95.07	95.2	95.46	95.6
u [kJkg^{-1}]	397.9	398.2	398.7	399.7	400.2
s [kJkg^{-1}K^{-1}]	1.2502	1.2509	1.2522	1.255	1.2563
m [kg]	86.57				
Q [kW]	3				
$\tau = m\Delta u/Q$, [s]		8.7	14.4	28.9	14.4

Conclusions

- A niche problem has been identified. The heating practice does not conform to the standard. The standard is not included in the regulations, and residential heating systems are not supervised. Manufacturers and installers decide how to install them, and explosions happen.
- The core of the problem lies in BLEVE, *i. e.* the steam explosion. A BLEVE occurs only if water temperature exceeds 100 °C and the vessel fails due to increased pressure.
- The safety valve protects the system against pressure increase, but it does not stop overheating.
- Overheating leads to boiling. Safety valves in common use are designed neither for temperatures over 110 °C nor boiling.
- In order for the system to be safe, it must have a safety heat exchanger – the very element that is absent from the practice. The pressure is controlled indirectly, through temperature control.
- A physical model of the worst case scenario was therefore, designed – a scenario in which there is no flow in the system.

- Because of explosion risks, we adopted a cautious approach. Therefore, the first experiments were done with the safety valve set at 1.5 bar and the overheating rate of 3 kW. Our experimental facility had a 3-18 kW power range. The usual boiler heating power in homes is 50 kW. The testing of safety valves with 2.5 and 3 bar set pressure is also planned, where the 3 bar setting is common.
- The aim of our research was to test how a normally operating valve behaves in non-operating conditions.
- Results show that safety valve did not prevent neither overheating nor boiling. However, that was not its job. Its job is maintenance of pressure. By its opening, safety valve should maintain pressure but it could not release all of the extra heat that was in the system. Result was gradual overheating of the system that led to boiling.
- In the experiments, the boiling zone, unacceptable in closed systems, was entered. The recorded pressure peaks were at 2.2 bar and the lows were at 0.8 bar. Based on these results, it was concluded that the safety valve operation (intensive opening and closing) intensified boiling. Therefore, closed systems cannot be considered safe, even with a brand new safety valve and at low overheating rates.
- In Experiment I, a 125-fold increase in mass-flow was recorded, due to boiling phenomena.
- We believe that the significant difference observed between the calculated and measured time during isochoric heating is the result of air dissolved in water. This will serve as a guideline for future research.
- Experiments are also planned with different heating rates and safety valves that have different set pressures, are produced by different manufacturers and belong to different types.
- However, we cannot exclude safety valve failure; to make the system absolutely safe, the temperature must be kept below 100 °C. In that case a leak would occur, instead of a steam explosion. In view of these considerations, the aforementioned heating practice is unacceptable.
- In our opinion, it is not acceptable practice to allow the closed heating system to enter boiling if it is protected with a safety valve designed for temperatures up to 110 °C. From the engineering point of view, it is easier to prevent temperature rise than to cope with pressure oscillations caused by boiling. That is exactly what the standard demands through the introduction of the safety heat exchanger. By limiting the temperature to below 100 °C, the risk of BLEVE is eliminated.

Acknowledgment

This paper is part of a project supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia, III 43008, *Development of methods, sensors and systems for monitoring the water, air and soil quality*.

We extend our special gratitude to KNOTT Autoflex YUG Ltd. Bečej for financial support and Novi Sad Heating Plant (Novosadska toplana) for their support and provision of pressure and temperature measuring equipment.

References

[1] Zrnić, S., Ćulum, Ž., *Heating and Air Conditioning with Application of Solar Energy* (in Serbian language), Naučna knjiga, Belgrade, Serbia, 1991
[2] Stepanov, B., *et al*., Safety Issues in Solid Fuel Heating Practice in Serbia, *Proceeding*s, (Ed., Todorovic, B.), International Congress on Climatisation, Heating and Cooling, Belgrade, Serbia [S. l.], Vol. 49, 1, pp. 125-134

[3] ***, British Standard: BS 7074: Application, Selection and Installation of Expansion Vessels and Ancillary Equipment for Sealed Water Systems, Part 2, BSI, 1989
[4] Siegenthaler, J., *Modern Hydronic Heating: For Residential and Light Commercial Buildings,* Delmar Cengage Learning, Clifton Park, New York, USA, 2012
[5] Hansen, E., *Hydronic System Design and Operation: A Guide to Heating and Cooling*, McGraw-Hill, New York, USA, 1985
[6] ***, Center for Chemical Process Safety New York, Guidelines for Vapor Cloud Explosion, Pressure Vessel Burst, BLEVE, and Flash Fire Hazards, John Wiley and Sons, Hoboken, USA, 2010
[7] ***, Watts Regulator Video: Explosion-Danger Lurks, https://www.youtube.com/watch?v=5lJq5UkdVZU

Paper submitted: June 23, 2017
Paper revised: June 24, 2019
Paper accepted: July 12, 2019