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# IMPROVING THE RELIABILITY OF AN ELECTRIC CENTRAL HEATING BOILER

**Key words**

Electric boiler, reliability, damage analysis, design.

**Abstract**

The article presented an accomplished project of an improved construction of an electric boiler in terms of reliability. The improvement was achieved by identifying the causes of failures in the previous boiler construction and introducing solutions that proved to be effective during exploitation. The damage analysis indicated two main causes of failures, which were pollution of boiler water and surges in the electricity network. Changes from the previous construction included the elimination of the most unreliable unit, changing the regulation system, and effectively systemically securing a group of semiconductor switches.

## Introduction

Electric central heating boilers are devices designed for delivering heat energy to water heating installations of buildings. Water heating takes place in them as a result of interchanging heat between tubular heating elements (heaters) and flowing water in the conditions of forced convection. The movement of water is forced by a water pump built in the boiler or installed separately.

The aim of activities described in this article was to design a new construction of an electric boiler with improved efficiency in comparison to the solution produced so far. The principal of this project was one of the leading Polish manufacturers of electrothermal devices, and the research was performed in close cooperation with them. The new boiler was meant to be dedicated for the English market, where, due to the poorly developed service network of the manufacturer and service costs, reliability improvement was a key issue.

## 1. Boiler construction

The purpose of boiler's operation is to supply central heating installations with water (or another agent such as glycol-water mixture) at a certain set temperature. The construction and functional schema of the boiler before changes are presented in Figures 1 and 2.

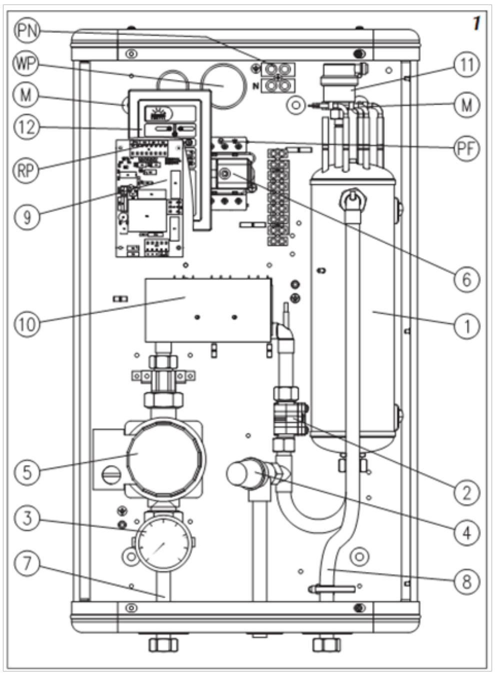


Fig. 1. Construction of the analysed boiler. 1 – exchanger, 2 – volumetric flow sensor, 3 – pressure gauge, 4 – safety valve, 5 – circulation pump, 6 – thermal safety switch, 7 – inlet ferrule, 8 – outlet ferrule, 9 – automatic regulation system, 10 – group of semiconductor switches, 11 – vent, 12 – control panel on the front cover, M – mounting points, PN – connector of neutral and protective conductor PF – connector of phase wires, WP – entry of power cables

In the analysed boiler type a, circulation pump P is installed. Measuring volumetric flow is performed by a VFS transducer. Additionally, water temperature is measured before (Tin) the exchanger and after (Tout) the exchanger. The exchanger is a leak-proof vessel, through which the agent flows, and in which a certain number of heaters is installed. The analysed boiler type is equipped with a six-heater exchanger. Signals about flow rate and water stream temperature are received by the automatic regulation system, which regulates the work of heaters, turning on a set number of them, depending in the setting and current working conditions. The switching of heaters is done with the use of semiconductor switching elements – triacs.

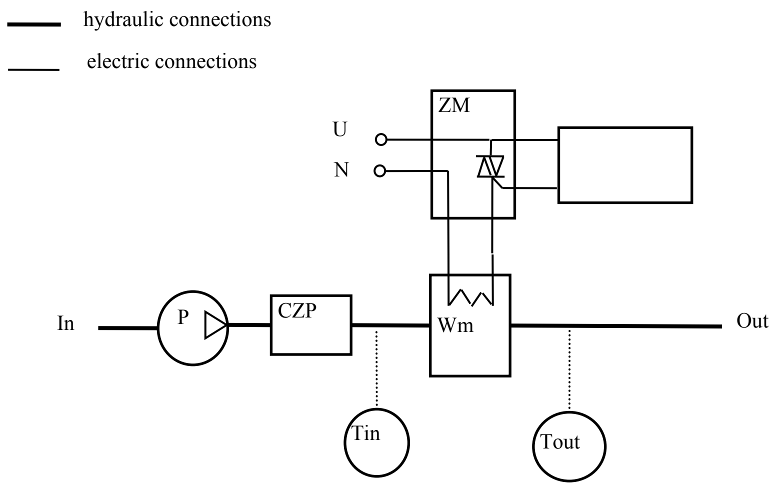


Fig. 2. Functional schema of the boiler. In – Cold water inlet (return from the heating system), Out – heated water outlet (supply of central heating), P – circulation pump, CZP – volumetric flow sensor, Tin – temperature sensor inlet, Tout – temperature sensor outlet, ZM – group of semiconductor switches, Wm – heat exchanger, URA – automatic regulation system, UN – electrical supply, terminals: phase and neutral

The regulation algorithm is based on calculating the required heating power necessary to reach the set outlet temperature in the presence of measurable disturbances (value of heat flux carried by the water stream). The calculated power is converted into the necessary number of switched on heaters and rounded up. In case of exceeding the outlet temperature above the setting, heaters are switched off.

It is significant that a failure of any of the elements listed in the functional schema causes an interruption of all system operations and a need of service intervention.

## 2. Statistics and failure analysis

In order to receive statistic data about the failures, an analysis of reports regarding warranty service returns of boiler parts from two subsequent years was performed. The percentage share of individual components in that period is presented in Table 1. The lowest reliability was shown by the volumetric flow sensor and semiconductor switches. The share of all other components was below 4%.

Table 1. Percentage share of components in warranty returns

| component name | percentage share in returns |
|---|---|
| volumetric flow sensor | 69% |
| semiconductor switches | 27% |
| others | 4% |

In the next stage, an analysis was performed of failures in the most unreliable component, which is the flow sensor. The sensor is produced in the plant of the boiler's manufacturer. It is an impeller-type flow meter. A stream of liquid flowing through the sensor was setting in motion a rotor whose rotational speed was proportional to the volumetric flow of the agent. A magnet was placed on the axle of the rotor, and its magnetic field changes during rotations were converted into electrical impulses by a Hall sensor. Examinations of 10% of flawed sensors coming from different parts of Poland within a period of 6 months pointed out the problem of boiler water pollutions. Deposition of contaminants on the axle caused increased friction of the rotor movement, resulting in slowing it down or stopping it. The sensors worked correctly after cleaning.

The group of semiconductor switches is an electronic system that supplies heaters in electric current through triacs. The schematic diagram of a single channel supplying one heater is shown in Figure 3. The analysis of failures involved 15% of flawed items from a 6-month period. The system elements that were damaged turned out to be triacs. To identify the cause of flaws, a certain number of damaged triacs and undamaged items from the same series were dismounted and examined in a laboratory specializing in examining semiconductor elements. In the course of examinations, any failures caused by the producer of triacs were excluded, and the damages were identified as typical in case of exceeding maximum allowed voltage on the anodes of this element, which was equal to 900 V.

The source of such high voltages in the energy network (called surges) are usually switching phenomena or atmospheric discharges (directly and indirectly, through induction). Before being sold on the European market, the boiler underwent the procedure of receiving a CE mark, which was connected with performing research regarding resistance to voltage surges. The varistor used in the system (RV1, Fig. 3) turned out to be sufficient protection in case of surge impulses defined in the requirements. Additional research was performed on the used group of sensors. The results showed that, in case of impulses with a shorter increase time, the varistor was not sufficient as protection. Figure 3a shows an example of a voltage impulse whose application on the triac anodes causes permanent damage because of exceeding the allowed voltage (900 V in case of the triad used). Applying such impulse on a system like the one shown in Figure 3 causes voltage decrease due to the protective varistor, which is shown in Figure 3b. However, the problems were surge impulses with voltage increase greater than approx. 900 V/µs (depending on triac samples). In this case, an irreversible damage of its structure took place (Fig. 3c).

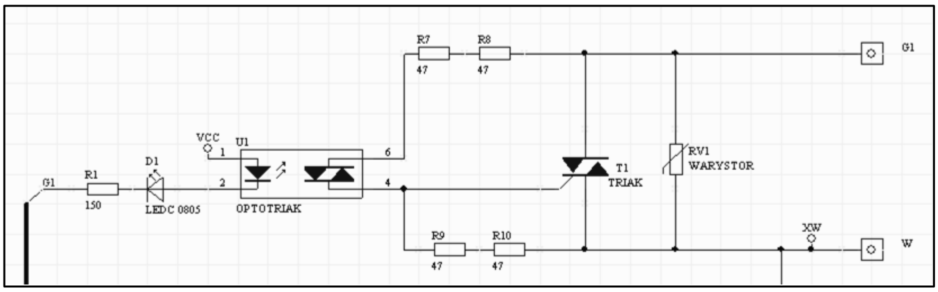


Fig. 3. Schematic diagram of a single heater switching system

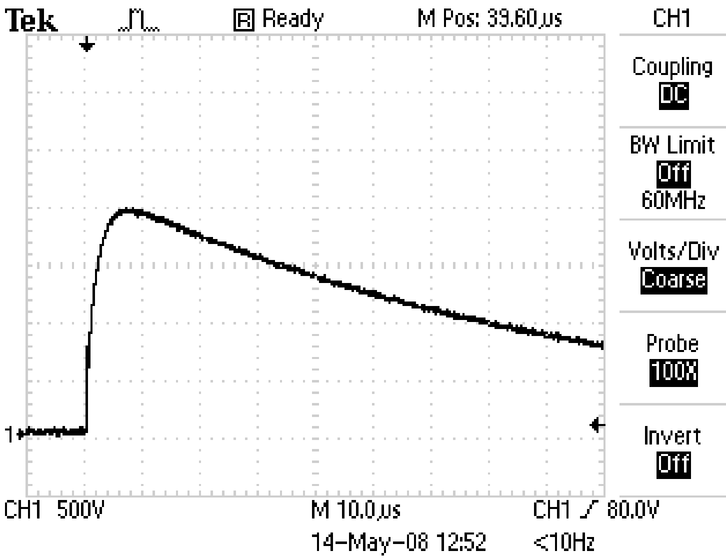


Fig. 3a. Time flow of an exemplary surge impulse with a voltage of 2 kV causing permanent damage to the triac due to exceeding allowed voltage

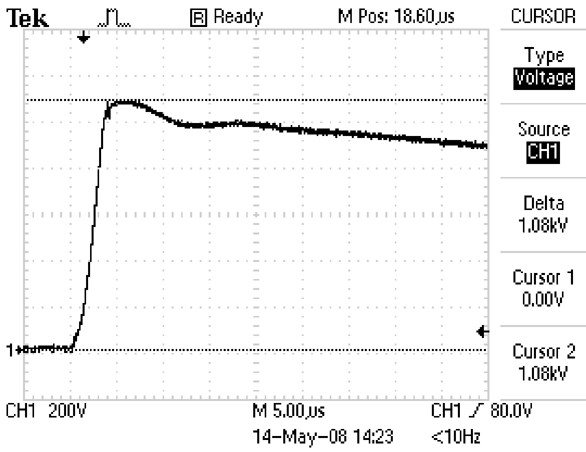


Fig. 3b. Voltage on triac anodes in case of using a varistor as protection in case of an impulse with voltage increase below 900V/µs

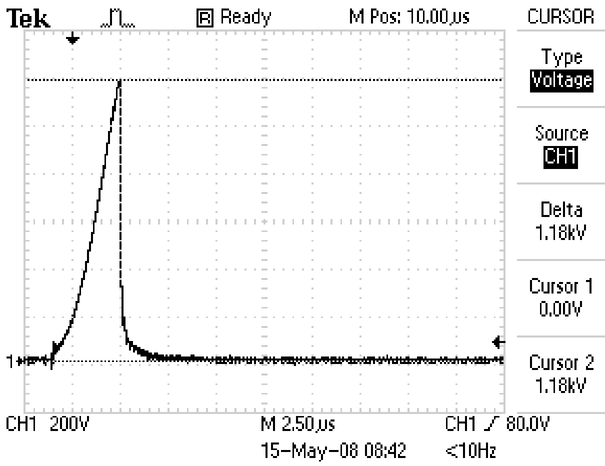


Fig. 3c. Voltage on triac anodes in a system with a protective varistor in case of an impulse with voltage increase above 900 V/µs. Visible voltage decrease caused by breaking the triac structure

## 3. Construction modifications

In order to reduce the risk of failure of the flow sensor, three possibilities were considered: sensor reconstruction towards increasing space between the rotor and the axis, using filters and changing the sensor to another one that does not contain moving parts and more resistant to pollution. Eventually, a radical solution was chosen – removing the flow sensor, and as a result, changing the regulation system. Introducing this sort of change was possible thanks to a new regulation algorithm and changing the construction of the exchanger.

In the chosen algorithm, the process of temperature regulation identified four states depending in the value of regulation error. When the error was negative (too low temperature) the steering device switched on, in 90 second intervals (value close to the time constant of the process), consecutive heaters until reaching the set temperature or maximum number of heaters. The algorithm moved to a second state when the regulation error was equal to zero. In that state, switching of heaters was maintained in the number received from the previous state. The algorithm moved to a third state when the regulation error was positive (but only up to 4°C). In this case, heaters were switched off one by one every 20 seconds. In case the regulation error was above 4°C, the algorithm moved to a fourth - emergency state, in which all heaters were turned off and the regulation process was restarted. The emergency state usually appeared in the case of a sudden flow stop (e.g. by turning off the circulation pump) or turning on an additional source of heat in the hydraulic system. As a result of using the new algorithm, significantly smaller over-regulations were achieved (Fig. 4).

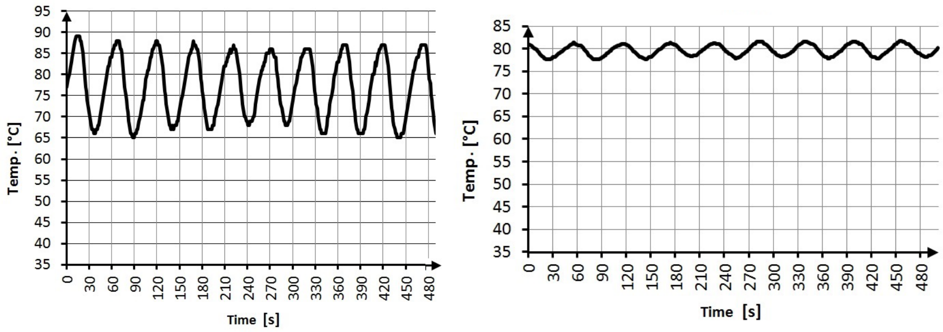


Fig. 4. Timing of outlet temperature before (at the top) and after modification. Flow 3.5 l/min, setting 80°C

Additional research performed proved that the new algorithm not only fulfilled the requirements towards automation systems of central heating boilers, but also increased the quality of regulation. The flicker factor and over-regulations decreased, and average outlet water temperature was equal to the setting. The regulation time increased three times, but in the case of electric boilers, that was not significant. Construction of the exchanger was modified (Fig. 5). The change consisted of placing the outlet ferrule vertically upwards, simplifying hydraulic connections inside the boiler. The water outlet was placed in the upper part.

A series of prototype tests was performed in a laboratory station in order to find the most advantageous place for the outlet temperature sensor and the "over-temperature" switch sensor. Finally, the outlet temperature sensor was placed in the outlet opening at the top of the exchanger, which enabled correct readings in conditions of flow forced by pump operations and during its breakdown during lack of flow. The capillary of the over-temperature switch was placed horizontally in the upper part of the exchanger. This guaranteed proper operation of the switch in case of failure of the regulation system or an attempt to run without water (the sensor was heated up by radiation from the heaters).

In order to increase the resistance of semiconductor switches to disturbing voltage impulses, the following options were considered: using a lower voltage varistor, using transient voltage suppressor instead of a varistor, and using an additional RC suppressor system. Unfortunately, using a lower voltage varistor was impossible due to wide tolerance of these elements and the range of allowed of voltage fluctuations in the energy network. Similarly, trials with transient voltage suppressors and a suppressor system did not bring the expected results. It was however observed that a trait of disturbing impulses in the energy network was their short duration time of around a dozen milliseconds. They are then usually low energy impulses, but have a destructive impact on the triac structure. However, a characteristic trait of triacs is their high resistance to electric impulses. The used triac type BTA24 is capable of conducting 250 A in a ten-millisecond surge impulse (during normal activity only 25 A). This indicates that a triac is most prone to damage when it is switched off and does not conduct electricity. In the state of conducting, all disturbing voltage impulses change into electric impulses.

For the above reasons, in the case of semiconductor switches, a decision was made to perform galvanic disconnection from the power mains when the boiler is not working (not heating). In our climate, most of the time, a boiler is connected to the power main in standby mode. That is when it is most exposed to damages by voltage impulses. Galvanic disconnection of triacs would guarantee an increase of their protection. The galvanic disconnection was achieved by a contactor controlled by the regulation system. Introducing an additional element with an unknown reliability ratio was a controversial decision. To minimize the risk of damaging the contactor, a special mode for switching it on and off was used. Literature analysis indicated that contactors are damaged mostly as a result of the burning of contacts, the main cause of which is arc phenomena. The contactor switching mode was based on switching it on and off voltage-free. In order to do that, the contactor was always switched on before the triac, and the triac was switched off before the contactor, always maintaining a certain delay time.

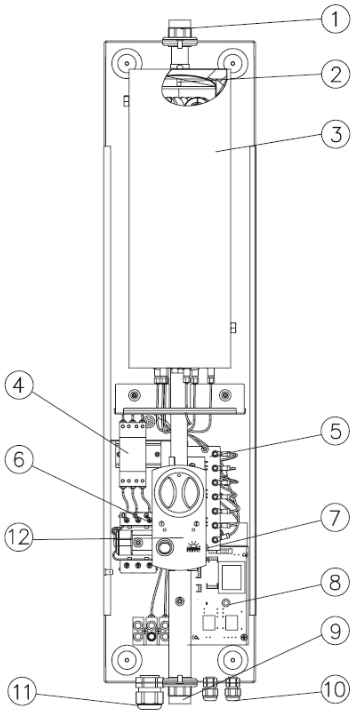


Fig. 5. Modified boiler construction. 1 – outlet ferrule, 2 – capillary of over-temperature switch, 3 – exchanger, 4 – contactor, 5 – group of semiconductor switches, 6 – over-temperature switch, 7 – control panel, 8 – automatic regulation system, 9 – inlet ferrule, 10 – glands for pump cable and room thermostat, 11 – gland for power cables

Due to specific requirements of the English market, in the designed boiler a decision was made to resign from placing the following components inside: circulation pump and fitting elements such as safety valve or pressure gauge, which were moved outside of the device.

## 4. Results

The new boiler passed the certification procedure and received the CE mark, and then it was implemented for production. Due to its simplified construction, it turned out to be an economically more beneficial solution, and yet no worse than its predecessor in terms of functionality. After three years of its production, a decrease in service interventions was noted by nearly ten times in relation to production volume in comparison to the previous boiler type, which confirms the increase of reliability of the new construction. For the above reasons, the manufacturer became interested in implementing the presented solutions in other types of their devices.

## Conclusions

In the described design process, the method used was based on improving the properties of the solution used so far through inference based on research results of failure causes. This method turned out to be effective.

A reliability increase was achieved in several ways: by simplifying the construction in the case of flow sensor, and by isolation from risk factors in case of semiconductor sensors. Both ways proved to be efficient, which was confirmed by a significant decrease of service interventions and returns.

Although an electric boiler is not a device with a high complexity level, as a mechatronic device, it required the performance of research works in several areas such as electronics, control theory, or thermokinetics.

The presented article mentioned cases of damages that do not depend directly on the working time of the device; they were not the result of component wear, but were mostly caused by random factors. The sources of those damages were the reasons for most failure cases.

Resistance to surges defined in the regulations does not guarantee resistance of the device during its exploitation.

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**Polepszenie niezawodności elektrycznego kotła centralnego ogrzewania**

**Słowa kluczowe**

Kocioł elektryczny, niezawodność, analiza uszkodzeń, projektowanie.

**Streszczenie**

W artykule przedstawiono zrealizowany projekt ulepszonej pod względem niezawodnościowym konstrukcji kotła elektrycznego. Ulepszenie osiągnięto w drodze identyfikacji przyczyn awarii dotychczasowej konstrukcji kotła i zastosowania rozwiązań, które okazały się skuteczne w czasie eksploatacji. Analiza uszkodzeń wskazała na dwie główne przyczyny uszkodzeń, jakimi były zanieczyszczenia w wodzie kotłowej i sieciowe przepięcia elektryczne. Z wcześniejszej konstrukcji wyeliminowano najbardziej zawodny podzespół, zmieniono sposób regulacji oraz układowo zabezpieczono skutecznie zespół łączników półprzewodnikowych.