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Improving the Energy Efficiency of Electric Domestic Water Heaters through Alternative Heating and Thermal Energy Storage Solutions

Îmbunătățirea eficienței energetice a boilerelor electrice pentru apă caldă menajeră prin soluții alternative de încălzire și stocare a energiei termice

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Abstract - This paper investigates the potential for improving the energy efficiency of electric boilers through the implementation of two innovative solutions. The first involves replacing the conventional electric resistance, typically immersed in water, with a mesh of carbon fiber conductors installed tangentially on the boiler shell, beneath the thermal insulation. This system operates similarly to a heating blanket, uniformly covering the boiler surface and providing a significantly larger contact area compared to traditional heating elements. Subsequently, phase change materials (PCMs) are integrated inside the boiler, with the role of storing thermal energy during the heating process and gradually releasing it during hot water consumption periods, thereby enhancing thermal performance. The study includes a detailed monitoring of the thermal behavior by installing temperature sensors at key points to analyze thermal stratification and energy efficiency. Comparative tests were conducted for three configurations: a standard boiler, a boiler with a carbon fiber conductor, and a boiler equipped with both the carbon fiber conductor and phase change materials.

Index Terms - Carbon Fiber Conductor, Electric Boiler, Phase Change Materials

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INTRODUCTION

Electric boilers have experienced a significant increase in usage across Europe, being increasingly adopted for domestic hot water production in the residential sector. According to available data from the literature, the energy consumption associated with domestic hot water preparation accounts for approximately 14.8% of the total household energy consumption on average. In this context, the identification and implementation of efficient technological solutions to reduce the energy consumption of electric boilers becomes a priority, considering their growing adoption.[1,2]

This trend is further reinforced by the widespread deployment of renewable energy generation systems, particularly photovoltaic panels, which promote a shift towards electricity consumption at the expense of fossil fuels. Consequently, there is a growing interest in the use of electric appliances in the residential sector and in the modernization of household equipment, including boilers, towards more sustainable solutions that are better integrated into emerging energy paradigms.[3]

Carbon fiber conductors (CFCs) are increasingly employed in heating applications due to their high electrical efficiency and remarkable mechanical properties. A notable example is their use in concrete pavements for de-icing, where carbon fiber wires are directly embedded into the road structure to prevent ice accumulation during the winter season. Furthermore, the durability and mechanical strength of carbon fiber wires allow their operation under extreme conditions without significant degradation or performance loss [4]. This technology has also been extended to other heating applications, such as underfloor heating, radiant panels, and textiles (e.g., heated clothing, carpets, benches, covers, etc.), where their flexibility and uniform heat distribution make them an efficient and versatile alternative to conventional solutions [5,6].

In the case of electric boilers, the heating elements already exhibit high efficiency, and their thermal insulation has reached an advanced level of performance. Therefore, one of the most feasible directions for enhancing the energy efficiency of these devices is the optimization of thermal energy storage capacity.

In this context, an increasing number of studies focus on improving thermal energy storage capabilities. Phase Change Materials (PCMs) have attracted growing research interest due to their ability to store substantial amounts of thermal energy: *"The storage of PCM thermal energy is more beneficial than sensible energy storage because of its high density of storage energy per unit volume/mass."* [7]

Numerous studies have investigated the integration of Phase Change Materials (PCMs) into boilers, providing relevant solutions depending on the specific challenges addressed. For instance, in applications involving hot water tanks used for swimming pool heating, the use of PCMs enabled a reduction of the nominal tank volume by up to 25%, while energy consumption and CO emissions were decreased by 5% to 11.97% [8]. Another relevant example is the application of PCMs in solar- heated boilers, where the total amount of heat stored in a boiler equipped with phase change materials is 2.59 to 3.45 times higher compared to a conventional boiler [9].

EXPERIMENTAL PROJECT DESCRIPTION

To evaluate the influence of these technologies, an experimental setup was developed to enable comparative testing. For this purpose, two identical electric boilers, each with a volume of 80 liters, were used. One of the boilers was kept in its original configuration and served as the control, while the second was modified according to the details presented in the following sections.

A dedicated electric meter was used to monitor the electricity consumption. The volume of water introduced into the boilers, as well as the flow rate recorded during the simulation of hot water usage, were measured using a water meter. Temperatures at different points in the system were determined using temperature sensors connected to an Arduino board, with values recorded at 2- second intervals.

The sensors used to measure water temperature were installed in 15 mm diameter copper pipes, while those intended for monitoring the temperature within the Phase Change Material (PCM) were immersion sensors, placed directly within the PCM mass. Considering the impossibility of installing temperature sensors inside the control boiler, comparisons between it and the modified variants were carried out using a single temperature sensor, positioned in the sheath of the electric resistance immersed in water.

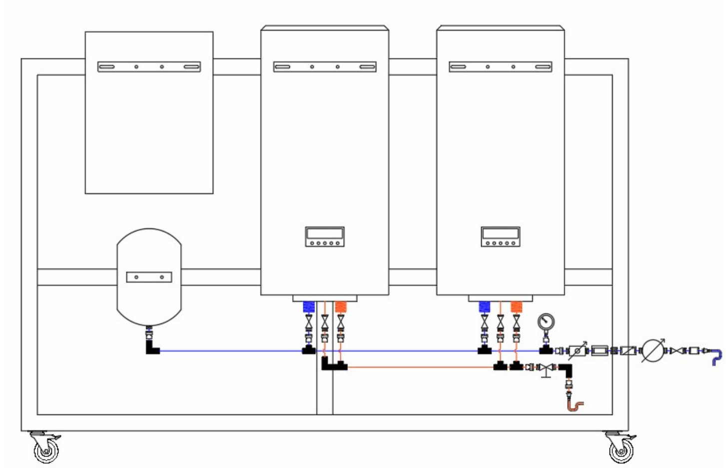

Figure 1 Experimental Setup Layout

Considering the need to install the carbon fiber conductor (CFC) on the boiler shell, the original polyurethane foam casing and insulation were removed. After mounting the CFC, the boiler was insulated with glass wool, protected externally by a metal sheet casing. To facilitate interior access for modifications or additional testing, the boiler was cut, and a DN400 flange was installed, allowing repeated opening. Additionally, four threaded fittings were welded onto the top cover to accommodate the connection of temperature sensor cables.

Figure 2 CFC Mounted on the Exterior

The Phase Change Material used was sodium thiosulfate pentahydrate (Na S O ·5H O). To introduce the material into the boiler, 54 copper tubes, each with a diameter of 28 × 1 mm and a length of 410 mm, were installed. These tubes were arranged in four concentric circles, containing 5, 11, 17, and 21 tubes, respectively. Temperature sensors were installed in one central tube and in one tube of the outermost circle. The PCM was poured in liquid form into each tube in an amount of approximately 330–340 g, resulting in a total of about 18 kg of PCM material.

Figure 3 PCM Tube Assembly

The temperature sensors are represented in Figure 4 as green squares. The tubes containing PCM are shown in red, two of which also include temperature sensors. The black tubes (left and middle) correspond to those housing the temperature sensors for water.

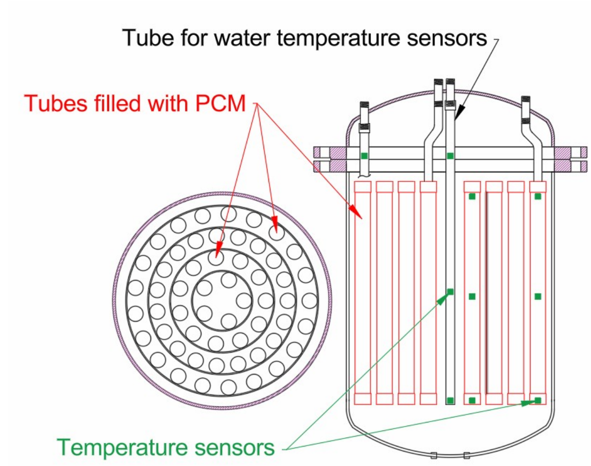

Figure 4 Boiler Diagram Equipped with PCM

The completed experimental stand is shown in Figure 5, while Figure 6 illustrates the electrical panel used for controlling the start and stop of the heating elements, as well as for measuring the electricity consumption.

Figure 5 Experimental Test Stand

Figure 6 Control and Measurement Electrical Panel

DATA PRESENTATION AND DISCUSSION

In the first stage, the temperature evolution during the water heating process was analyzed, from an initial temperature of approximately 22 °C up to 60 °C inside the boiler. The heated water volumes differ slightly among the three analyzed cases and will be specified individually for each scenario. Subsequently, all obtained results are normalized to a common unit of measurement to allow comparison of the efficiency of the three configurations.

The efficiency of a heating system is defined as the ratio of required energy to total energy consumption. The efficiency for the three variants is calculated using (1).

$$\eta = \frac{Qreq}{Qcons} * 100 \quad (1)$$

where η = Efficiency [%]; Qreq = Energy required to heat the water [kJ]; Qcons = Energy consumption [kJ]

The required energy represents the amount of energy needed to raise the water temperature from the initial value to the final value. It can be determined using (2).

$$Qreq = m * c * \Delta T \quad (2)$$

where m = Mass [kg]; c = Specific heat capacity [kJ/(kg·K)]; ΔT = Temperature difference between the final and initial values [°C, K]

In the case of the reference boiler, 81 kg of water were heated from an initial temperature of 23 °C to 60 °C. The total electricity consumption recorded was 3.62 kWh. Knowing the specific heat capacity of water, c = 4,18 kJ/kg·K, the energy required to heat the water (Qreq) is calculated using (2), and the boiler efficiency is determined based on (1).

In the case of the boiler modified with a carbon fiber conductor (CFC), 81 kg of water were heated from an initial temperature of 22 °C to 60 °C. The total electricity consumption was 3,68 kWh. As in the first case, the required energy (Qreq) and the system efficiency are determined.

In the case of the boiler modified with a carbon fiber conductor (CFC) and Phase Change Material (PCM), determining the required energy is more complex due to the phase change process of the PCM. The total required energy consists of three contributions: the energy needed to heat the water, the energy accumulated by the copper (considering approximately 16 kg within the system), and the energy associated with the PCM. For the latter, the required energy is divided into three stages: heating the material in the solid phase up to the melting point, the energy absorbed during melting, and the additional heating in the liquid phase.

In this system, there are 65 kg of water, 16 kg of copper, and 18 kg of Phase Change Material (PCM). The specific heat capacity of copper is known and has a value of c = 0,385 kJ/kg·K. For sodium thiosulfate pentahydrate, according to a study [10], the specific heat capacity in the solid phase is c_{solid} = 1,46 kJ/kg·K and in the liquid phase c_{liquid} = 2,38 kJ/kg·K. The analyzed temperatures remain unchanged compared to the other cases, from 22 °C to 60 °C. The total energy consumption of this system was 3.76 kWh. By applying (2), the required energy is determined for each component: water, copper, PCM in the solid phase, and PCM in the liquid phase.

According to laboratory analyses performed on the Phase Change Material (PCM), the data required to determine the energy during the melting stage are presented in Figure 7. These data indicate that the melting process begins at a temperature of 50.46 °C and ends at 52.19 °C. The same analysis also determined the latent heat, with a value of 181.75 kJ/kg. To calculate the required energy associated with the melting of the material, this value is multiplied by the total mass of PCM, namely 18 kg.

Differential Scanning Calorimetry (DSC) was used to determine the thermal properties of the PCM. A DSC 822 instrument (Mettler Toledo, Columbus, OH, USA) was employed for sample characterization. The dynamic method was applied, with an air flow rate of 25 ml/min and a scanning temperature range of 8–50 °C. The measurements were carried out at the Faculty of Pharmacy, "Iuliu Hațieganu" University of Medicine and Pharmacy, Cluj-Napoca.

Table 1

Summary of Required Energy Values for Heating in Case 3

Energy Required by type	Value
Qreq water	7167.36 [kJ]
Qreq copper	233,12 [kJ]
Qreq solid PCM	748,42 [kJ]
Qreq Liquid PCM	333,94 [kJ]
Qreq melting PCM	3271,5 [kJ]
Qreq total	3,27 [kWh]

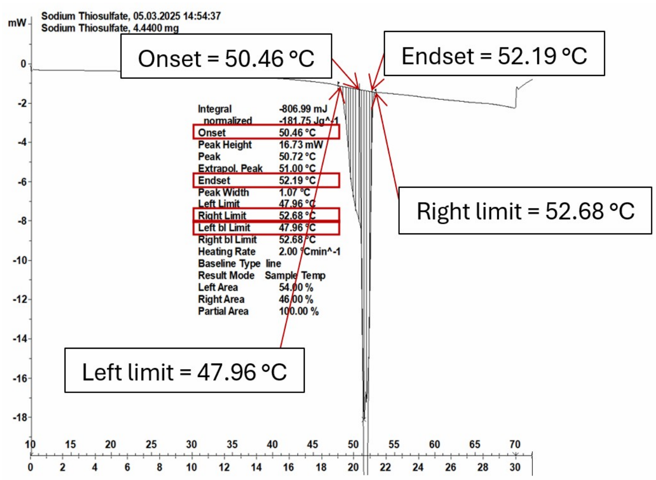

Figure 7 Melting of Sodium Thiosulfate Pentahydrate

Table 2

Summary of Heating Values

Parameter	Control Boiler	CFC Boiler	CFC/Cu/PCM Boiler
Mass [kg]	81	81	65 / 16 / 18
Temperature [°C]	23-60	22-60	23-60
Qreq [kWh]	3,48	3,57	3,62
Qcons [kwh]	3,62	3,68	3,76
Efficiency [%]	96,13	97,11	96,5

As the results indicate, the boiler modified with CFC shows an efficiency 0.98% higher than the control boiler, performing at a practically similar level. In the case of the boiler with both CFC and PCM, the efficiency is lower than that of the CFC-only boiler, due to the higher amount of stored energy. Nevertheless, its efficiency remains higher than that of the control boiler.

Figure 8 illustrates the temperature evolution over time for each of the three analyzed configurations. It can be observed that in all three cases, the heating process is linear and constant over time. The reference boiler heats up faster due to its higher electric resistance. Its heating element has a power of 1500 W, while the carbon conductor has a power of 1250 W.

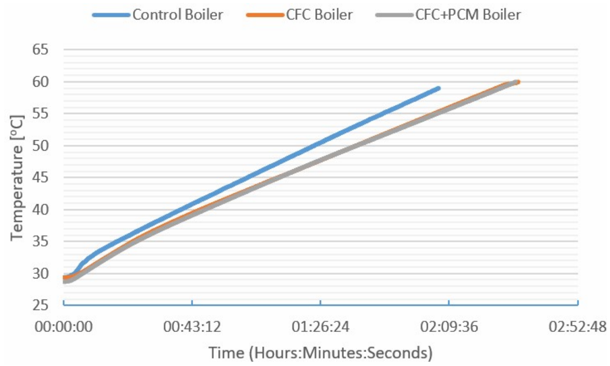

Figure 8 Temperature Variation Graph

To analyze the temperature behavior of the boilers under water consumption conditions, the inlet and outlet valves were opened, and the flow rate was adjusted to approximately 5.25 liters per minute. Simultaneously with the initiation of the water flow, the electric heating elements were activated in each case to ensure water heating during operation. The water flow was stopped when the outlet temperature reached approximately 35°C.

As observed in Figure 9, the reference boiler delivers hot water for the shortest period among the three configurations. The boiler with CFC is able to provide hot water for a longer duration within the high-temperature range, but the temperature drops more abruptly than in the reference boiler. This behavior is due to the position of the heating element. The carbon conductor boiler is able to deliver a greater amount of hot water.

Examining the temperature curve of the boiler with CFC and PCM, it is evident that an even larger quantity of hot water is supplied. This is due to the additional energy stored in the PCM, which is transferred to the water as it cools. In other words, the entire area between the grey CFC+PCM curve and the blue reference boiler curve represents the extra energy delivered to the water.

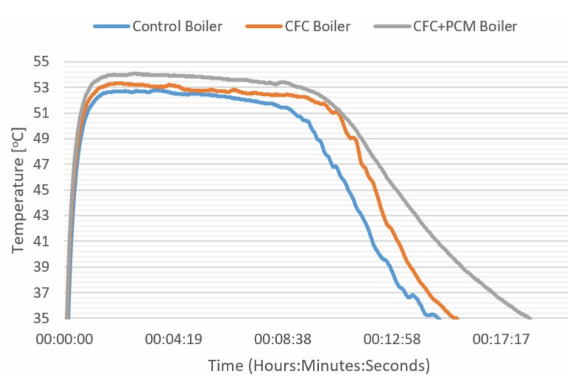

Figure 9 Temperature Variation under Water Consumption

Another, more intuitive interpretation is to consider a shower requiring a minimum temperature of 45 °C. With the reference boiler, a shower could last approximately 11 minutes. Using the CFC boiler, the shower could last 12 minutes, and with the CFC+PCM boiler, 13 minutes, effectively providing an additional 2 minutes of hot water.

CONCLUSIONS

The carbon fiber conductor provides a small increase in energy efficiency. However, even if its performance were considered equivalent to that of a conventional electric resistance immersed in water, the carbon fiber conductor offers numerous advantages. CFC is significantly more flexible, has a much larger contact surface ensuring more uniform heat transfer, is mechanically more durable, its electrical properties are less affected by temperature, eliminates corrosion issues, can be easily adapted into various shapes to accommodate different constructions, and has a lower carbon footprint associated with its production. Therefore, the carbon fiber conductor not only provides a modest energy efficiency gain but also offers a wide range of constructive benefits.

Phase Change Materials (PCMs) contribute to increasing energy efficiency. We observed that they help deliver a greater amount of hot water due to their ability to store more energy than water. However, I believe even greater benefits could be obtained from these materials compared to those presented in this study.

Before simulating water consumption, the boiler was left idle for 10 minutes at a temperature of 60 °C. From several separate tests on the PCM, we observed that it takes a longer time for the entire PCM mass to melt, especially in the center of the tube. It is likely that in the conducted simulation, the PCM melted in the outer part, but the heat did not reach the interior sufficiently to melt all the material. This would suggest that this configuration could potentially deliver even more hot water than the previous measurements, although with a higher energy consumption for heating.

It would be interesting to study how these configurations behave not only during heating from 22 °C to 60 °C followed by a simulated water draw-off, but also when maintaining the boiler at 60 °C for an extended period, as it is typically used, in order to assess the efficiency of maintaining water temperature, and then simulate water consumption.

Furthermore, it would be interesting to study the behavior of the carbon fiber conductor if it were placed inside the boiler, immersed in water. Another option could be to combine the exterior-mounted configuration with an additional conductor immersed in water.

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