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Electrode boiler integrated with an energy management and storage system

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Abstract:

The implementation of successive EU regulations in the field of environmental protection confirms the necessity of a consistent and pro-ecological reform of heating systems. Heating companies are beginning difficult and costly modernization processes but usually choose known and proven solutions based on cogeneration, biomass combustion, or waste incineration. Solutions that can permanently reduce dependence on fossil fuels and increasing environmental costs are relatively underutilized. One such solution is electrode boilers working in conjunction with renewable energy sources. An electrode boiler is a heating device that uses electrical energy to generate heat. It is an alternative to traditional boilers powered by gas, oil, or other fossil fuels. By using electrode boilers, surplus green energy in the power grid can be converted into heat.
This paper presents the concept of an electrode boiler working in cooperation with a thermal energy storage system, which constitutes a solution that can be integrated with heating systems to optimize the supply and demand for thermal energy.

Keywords: electrode boiler, thermal energy storage, accumulator, power grids

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1. Introduction

The energy sector is facing global challenges related to climate change, increasing ecological awareness, and the need to adapt to new realities. The energy transition and decarbonization have become key priorities for many countries worldwide. Moving away from fossil fuels in favor of renewable energy sources (RES) is essential, but it requires advanced technologies. As a result, heating companies are seeking new methods of heat production based on solutions other than burning fossil fuels [1, 2]. One such technical solution is the use of electrode boilers powered by electricity derived from RES. However, effective utilization of these boilers requires an additional heat storage system [3-7]. Depending on their intended use, these storage systems can be either long-term or short-term. Their primary advantage is the ability to store generated heat during times when energy is cheap or in excess.

Electrode boilers use electrical energy to heat a medium, typically lightly salted water, via electrical current, which causes it to heat up through the Joule effect. Electrodes, which are the key components of these boilers, are immersed directly in the medium, making energy transfer exceptionally efficient. This solution is advantageous because it demonstrates high energy efficiency, with nearly all electrical energy being converted into heat with minimal losses.

The article presents a review of existing electrode boilers on the market. Based on this, an innovative conceptual solution for the boiler's mechanical parts, power and control systems, and thermal energy storage has been proposed, along with the determination of thermal storage capacity adapted to the size of the electrode boiler. A separate issue is the analysis of substances with heat storage properties that can be applied in thermal energy storage.

2. Review of Existing Solutions

Electrode boilers are modern heating devices that are gaining popularity due to their efficiency and eco-friendliness. Various types of electrode boilers are found worldwide and are used for generating steam and hot water. The following types of electrode boilers can be distinguished:

- Fully Submerged Electrode Boiler,
- Semi-immersed Electrode Boiler,
- Jet Electrode Boiler.

The largest electrode boiler manufacturers worldwide include Elpanneteknik, VAPEC, Acme Engineering, Cleaver-Brooks, Vapor Power International, Hangzhou Runpaq Energy Equipment Co., Ltd., Inopower, and PARAT Halvorsen [8-11].

The aforementioned boilers use electricity as an energy source, ensuring zero carbon footprint and zero on-site emissions where thermal energy is generated. They also feature almost 100% efficiency, meaning that all supplied energy is converted into steam or hot water.

An example of such a boiler is the CEJW boiler by ACME Engineering Products (Figure 1). It is a boiler with fully submerged electrodes. The geometric parameters A and B of a boiler with a power range of 2.5 MW to 7 MW are A=2.1 m and B=4.2 m, with a medium flow rate of 300 m^3/h. The CEJW boiler is also equipped with control systems that monitor operational parameters such as temperature, pressure, and water flow, optimizing the hot water or steam generation process. The boiler's power control is achieved via electrode covers that move upward, exposing the active surface of the electrode and thereby increasing the boiler's power. Additionally, the boiler has appropriate thermal insulation that minimizes heat losses and ensures high energy efficiency.

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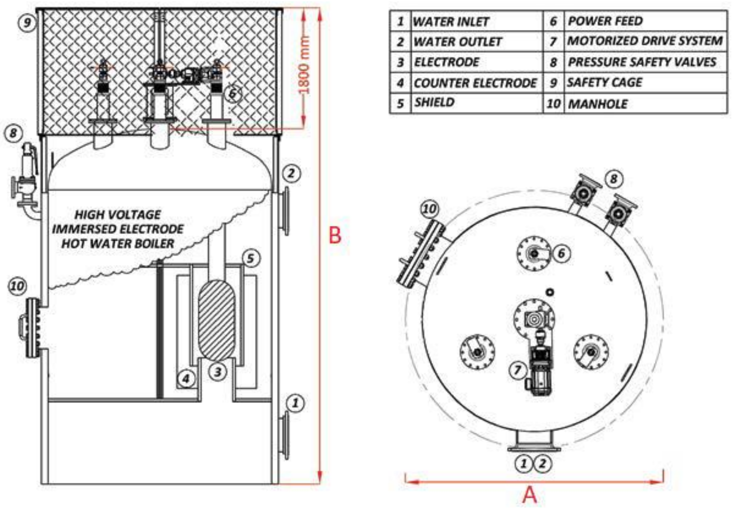

Fig. 1. Electrode boiler for hot water CEJW by ACME Engineering Products (USA) [8]

In semi-immersed electrode boilers, the boiler tank is not completely filled with water, and the power regulation can be achieved by adjusting the water level, increasing or decreasing the surface area of the submerged electrode working part (Figure 2). The boiler consists of an external and an internal tank, with the internal tank electrically insulated from the external casing. Electrodes are placed inside the internal tank, and the water and the internal tank form an isolated zero point in a star connection between the electrodes.

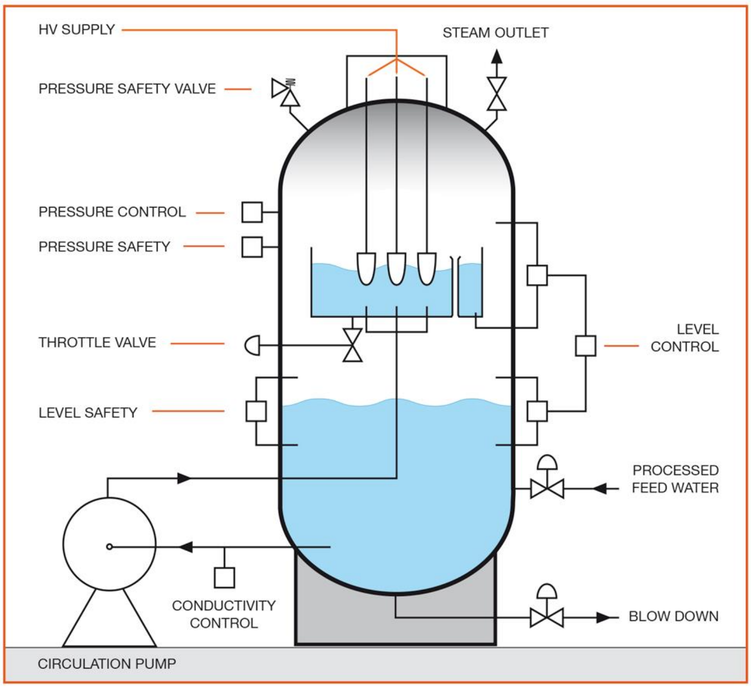

Fig. 2. Electrode boiler from Parat (Norway) [9]

A characteristic feature of the Jet Electrode Boiler type is the water flow between the electrodes. In these boilers, water is continuously pumped from the lower jet electrode. The water is then directed through multiple nozzles toward the target electrode, creating an electrical current path. The boiler's performance is controlled by raising or lowering a shield that controls the number of open nozzles. To shut off the boiler, it is sufficient to stop the recirculating pump.

It is important to note that electrode boilers with a capacity above 0.5 MW are not produced in Poland (Table 1). The most common electrode boilers available on the domestic market are intended for installation in individual closed heating systems, mainly used in hot water heating systems with a heat exchanger. An example of domestic production is the "GAZDA" electrode boiler offered by Galan Sp. z o.o. (Figure 3).

Fig. 3. Gazda type electrode boiler [10]

The introduction of electrode boilers with higher capacities than 0.5 MW to the Polish market represents a development potential with significant opportunities. Although this involves certain technological and economic challenges, it could contribute to increased energy efficiency in Poland, supporting efforts to reduce CO_2 emissions and the energy transition. This also presents an opportunity for Polish manufacturers to enter new export markets.

Table 1. Electrode Boilers

Company	Supply Voltage [kV]	Power [MW]
VAPER AG	6 - 36	1 - 90
Cleaner-Brooks	4, 16 - 25	1 - 102
PARAT	6 - 24	60
Precision Boilers	4 - 14	3 - 50

3. Assumptions Adopted for the New Solution Along with Technical Data

Electrode Boiler The preliminary design of the electrode boiler is based on the following assumptions:

- Container-type installation.
- Maximum liquid temperature in the electrode boiler: 150°C.
- Electrodes rigidly mounted to the tank.
- Heat exchange via plate heat exchangers.
- Power supply for the electrode boiler with MV voltage of 6 kV or higher, in accordance with applicable standards.
- Tank pressure: 16 bar.
- Tank dimensions:
  - Tank diameter: approx. 1 m.
  - Tank height: max 2 m (tank dimensions result from the need to fit it into a container).
- Control will be implemented based on the liquid level and, consequently, the electrode immersion depth in the liquid.

Thermal Energy Storage The preliminary design of the mobile heat storage system is based on the following assumptions:

- The storage system structure will fit inside a 40' shipping container.
- The structure will allow the use of a heat storage medium in the form of water or water and PCM (phase change material).
- Liquid temperature in the storage system: 90-130°C.
- The storage system's working fluid tanks will be connected in parallel and isolated from the rest of the system with valves, allowing thermal exchange of a single tank with the receiver.
- The structure will be adapted for integration with an electrode boiler or another heat source.

4. Concept Description of the New Solution

The proposed concept includes an electrode boiler with power ratings of 1, 3, and 5 MW (Fig. 4), intended for integration with heating systems, e.g., PEC (District Heating Company S.A.). The electrode boiler unit heats a water-based salt solution (brine) within a temperature range of 90–130°C and a pressure range of 5–16 bar. The solution is directed from the boiler to the heat exchanger. On this section, the temperature at the boiler outlet and before the heat exchanger, as well as the flow rate and conductivity of the solution, are monitored. The solution temperature is also monitored directly after the heat exchanger. After the heat exchanger, the solution is returned to the boiler. This section is equipped with a diaphragm tank for pressure compensation and a circulation pump (M3). If necessary, the salt concentration in the system can be increased by adding a 5-10% aqueous salt solution. The dosing is carried out by the brine tank unit with a dosing pump (M4). After the circulation pump, the solution is directed back to the electrode boiler tank, and the temperature and pressure of the returning solution are monitored directly before the tank. Boiler power control is managed by the solution level in the tank, and thus by the immersion of the electrodes. This is achieved using a buffer tank. If operation at a temperature of 130°C (increased power) is required, the solution from the buffer tank should be supplied to the boiler tank until the desired operating parameters or maximum level are reached. The transfer of the medium between the tanks is carried out by pumps (M1, M2). Pump (M5) replenishes the water level in the system. The compressor's task is to maintain the appropriate pressure at the maximum level in the boiler unit and to purge the accumulated hydrogen in the buffer tank unit and the electrode boiler unit.

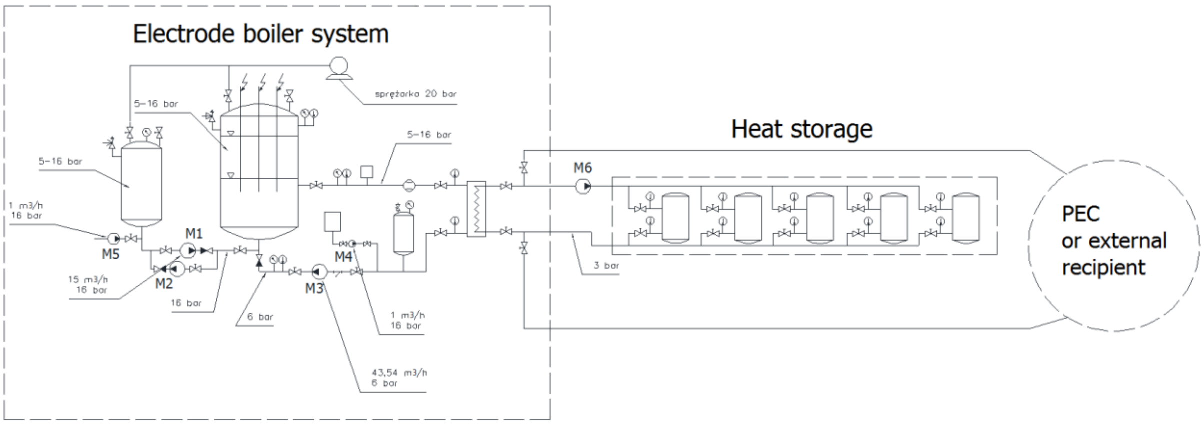

Fig. 4. Hydraulic diagram of the electrode boiler system

4.1. Construction of the Electrode Boiler System

The electrode boiler system, shown in Fig. 5, consists of the following components:

1. Electrode boiler unit.
2. Buffer tank unit.
3. Brine tank unit.
4. Plate heat exchanger.
5. Expansion tank.
6. Compressor.
7. Pumps.

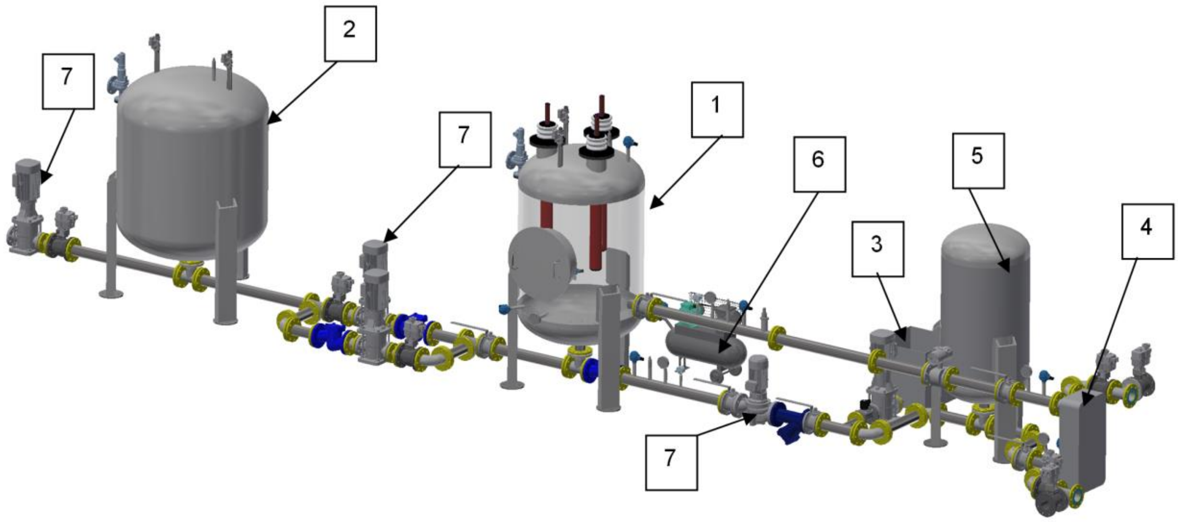

Fig. 5. Electrode Boiler System

4.2. Electrode Boiler Unit

The construction of the electrode boiler unit is illustrated in Fig. 6. The unit consists of a vertically positioned cylindrical tank (1) made of carbon steel. Inside the tank, at the upper section, electrodes (2) are installed along with temperature sensors (3) and pressure sensors (4). A safety valve (6) is mounted on the tank to prevent exceeding the allowable pressure, as well as fittings that allow the tank to be purged with compressed air (7). Ventilation of the tank is necessary due to the hydrogen generated and accumulated in the upper part of the unit.

The boiler unit is designed to operate within a temperature range of 90°C to 130°C and at pressures between 5 and 16 bar.

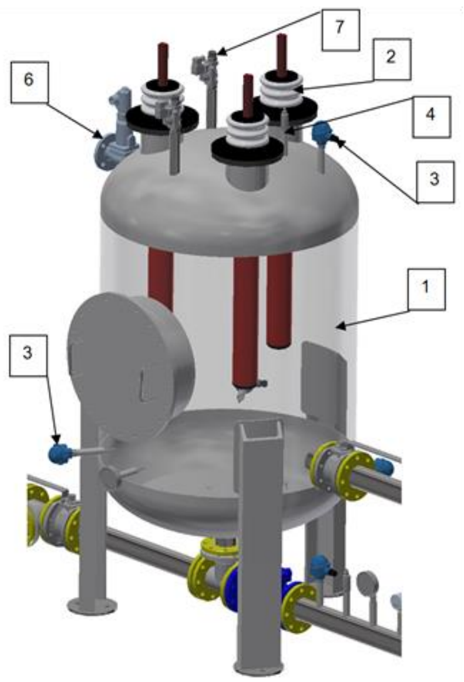

Fig. 6. Electrode Boiler Unit

4.3. Operating Principle

When voltage is applied to the electrodes, electrolysis of salt molecules occurs, with negatively charged ions rushing towards the "positive" electrode and positively charged particles moving towards the "negative" electrode. After the salt breaks down into ions, the salt itself becomes an electrical conductor, which, when current passes through the liquid, heats it up very quickly. The higher the concentration of salt, the more electrically conductive the solution becomes. With a certain ratio of water to salt, the liquid can become a typical electrical conductor, potentially causing a short circuit. On the other hand, if there are too few ions, heating will occur very slowly. Distilled water does not conduct electricity, so in this case, it will not heat up.

Therefore, the proper functioning of the entire water heating system directly depends on the well-prepared fluid, i.e., the heat transfer medium for the electrode boilers, which must have the appropriate salt concentration in the solution. This way, the effect of electric current on the liquid will be most efficient in terms of releasing thermal energy, ensuring the most economical and efficient operation of the entire heating system.

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4.4. Electrode Construction

Electrodes in electrode boilers are a crucial component that enables the transfer of electrical energy into the liquid between the electrodes. Depending on the boiler's design and power supply method, electrodes can vary in shape and quantity. The most commonly used electrode shapes include rods, rings, and tubes. They are typically made of materials resistant to corrosion and high temperatures, such as stainless steel or special metal alloys.

In the presented concept, the electrodes will be constructed from carbon steel in a rod shape (Fig. 7). They will be placed inside the boiler housing and each connected to a separate phase. To ensure effective utilization of inter-phase voltage, the electrodes will be installed at equal distances from one another.

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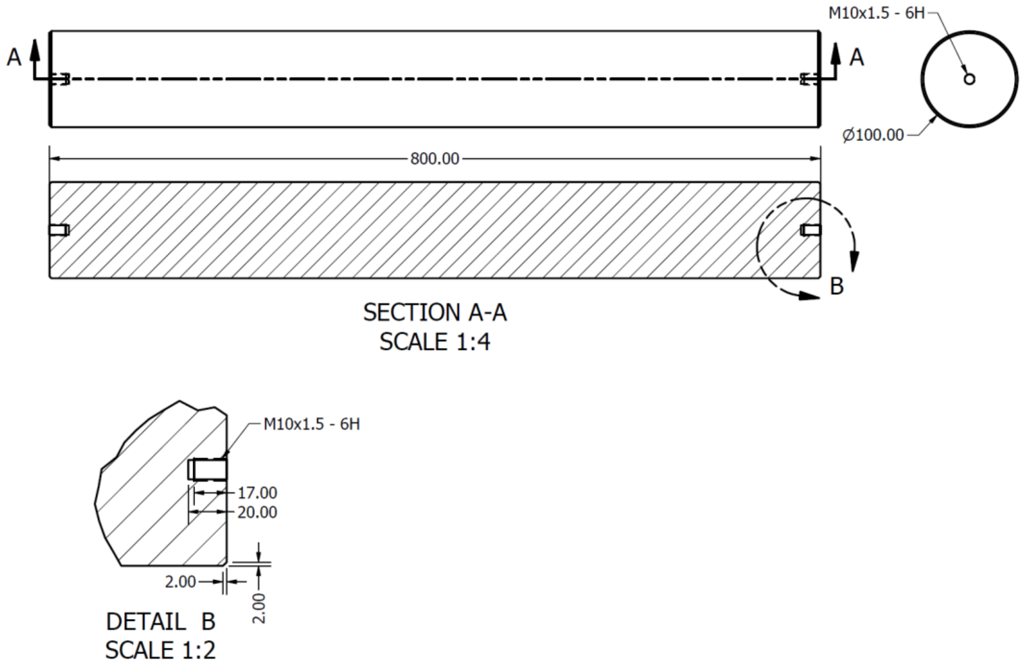

Fig. 7. Electrode design for the electrode boiler

4.5. Heat Transfer Medium

In electrode boilers, the primary heat transfer medium is typically water, which can be enriched with salts. This enhances the efficiency of the heating process. The main parameter for the heat exchange fluid in an electrode boiler is its electrical conductivity, which determines the efficiency and safety of the boiler's operation. Maintaining conductivity within the recommended range ensures optimal current flow, which translates into proper heating power and system stability. The higher the conductivity, the more current flows through the fluid, increasing the boiler's power. Conductivity is measured in Siemens per centimeter (S/cm), and a conductometer is used for this measurement.

The optimal conductivity for electrode boilers typically ranges from 300 to 500 µS/cm at 20°C. This value can vary depending on the fluid's temperature and the boiler's design, particularly the electrode working area.

Therefore, as a heat exchange fluid for an electrode boiler, either a specialized liquid with a low freezing point (for building antifreeze heating systems) or a water-based solution with a specific electrical conductivity level can be used. To prepare the heat exchange fluid, distilled, rain, or snow water can be used, to which baking soda is added (30 g per 100 liters of water).

For the heat transfer fluid in the electrode boiler concept, sodium chloride (table salt) will be used to enrich the water.

4.6. Containerized Heat Storage

One of the assumptions of the concept is the cooperation of the boiler with a thermal storage unit that will be mobile. It is assumed that mobility will be ensured by enclosing the components within the dimensions of a transport container. A 40-foot container is a standard type commonly used in both road and maritime transport.

The main element of the storage unit, according to the presented concept (Fig. 8), consists of five tanks (1), each with a capacity of 3,400 liters. They are mounted to the container structure using a frame (2), parts of which are welded to the container walls. The tanks are connected in parallel with

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DN80 piping (3), and each tank is isolated from the rest of the system using solenoid valves (4) on both the inlet and outlet. In case of solenoid valve failure, manual ball valves are also installed on the inlet and outlet. To ensure fluid circulation in the storage unit, a pump is installed at the beginning of the supply line. To compensate for the thermal expansion of the fluid due to temperature changes, the storage unit is equipped with a diaphragm expansion tank (5), connected to the tanks by DN40 pipes. The expansion tank and the pump are mounted on an installation platform welded to the container structure.

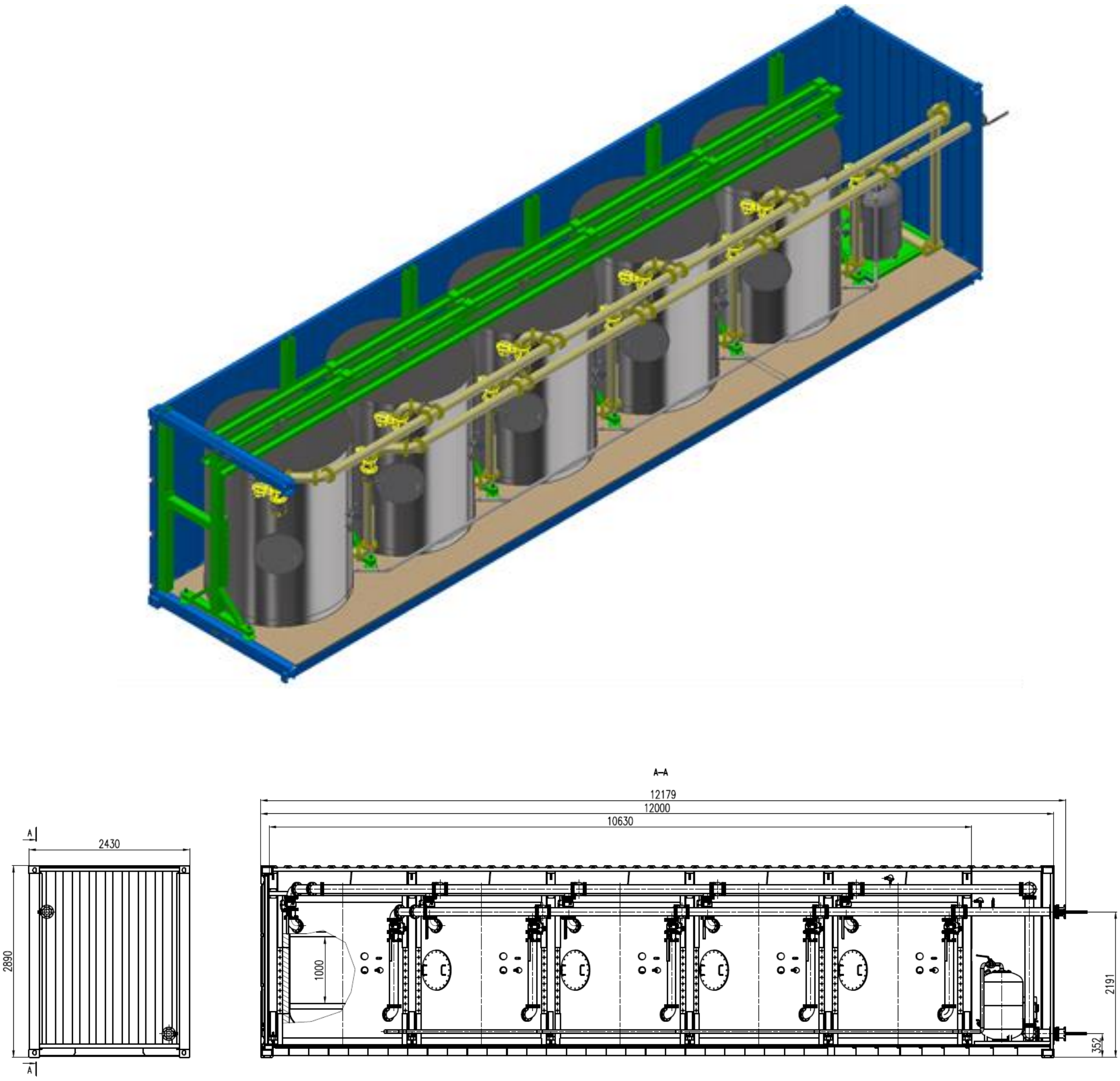

Fig. 8. Preliminary design model and dimensions of the mobile heat storage unit

The storage unit will enable cooperation with the electrode boiler, where, after connection to a heat exchanger, the heated water is stored in the tanks and released to an external consumer when needed.

The storage unit design allows the use of water as the heating medium or other materials with thermal storage properties, such as thermal oils or phase-change materials (PCM). A properly selected

PCM will increase the energy density in the storage unit by utilizing the latent heat of the phase transition.

If the storage unit needs to operate with a fluid other than the process fluid used in the district heating network (DHN), an additional heat exchanger must be integrated into the storage unit to isolate the system from the heating network. In this case, the thermal storage unit will operate according to the scheme shown in Fig. 9.

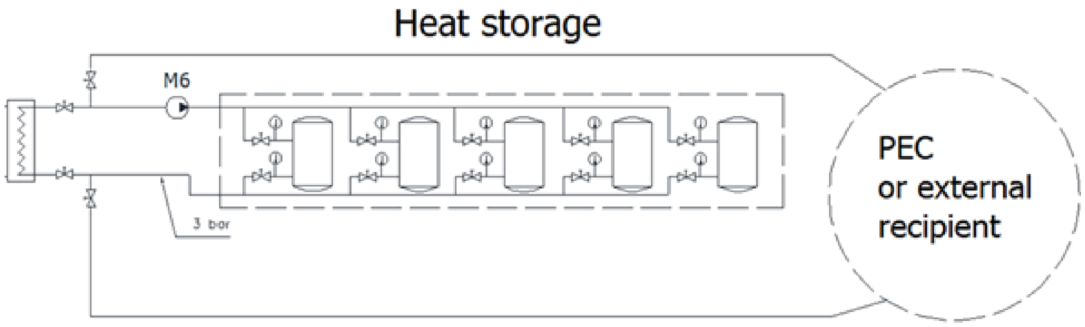

Fig. 9. Heat storage system scheme for operation with a medium other than water

4.8. Control System

The electrical power equipment can be divided into three components: the medium voltage (MV) cabinet, the low voltage (LV) cabinet, and the control system (see Figure 10).

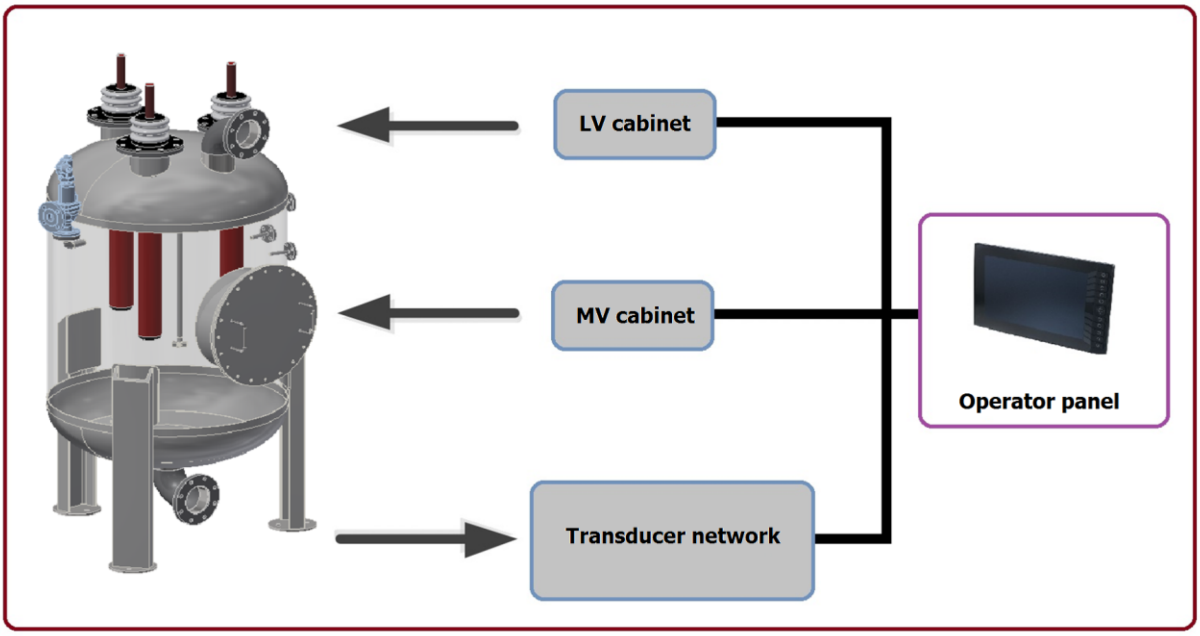

Fig. 10. Simplified block diagram of the electrode boiler control system

4.1.1. MV and LV Cabinets

The basic elements are the MV (medium voltage) and LV (low voltage) cabinets, which contain protection devices, transformers, current transformers, inverters, and contactors controlling the operation of valves and pumps.

From an electrical standpoint, the electrode boiler consists of a metal body, which is the current-conducting element, with inlet and outlet pipes, as well as electrodes installed in a sealed enclosure via an insulator. The boiler body, along with its inlet and outlet connections, is grounded to ensure safe and reliable operation when powered by the MV power grid.

The operating principle of the electrode boiler, electrically, involves supplying the electrodes with three-phase current, which is isolated from the MV power grid via a transformer and heats the water through the flow of electricity between the electrodes. The electrode power supply system will be equipped with the appropriate protections, such as circuit breakers and surge protection devices, to ensure the safe operation of the boiler. On the other hand, the thermal energy storage system, in electrical terms, mainly involves supplying power to the pump, controller, and electric valves.

The electrical equipment for the thermal energy storage system will be located in the control cabinet. It will contain the necessary electrical equipment along with ground fault protections and power fuses. Inside, there will also be a signal concentrator, power supplies, an inverter, and power contactors. The electrical equipment will be arranged in such a way that it allows for the easy addition of components that facilitate the operation of the energy storage system.

4.1.2. Control System

The third element is the control system for the electrode boiler and the thermal energy storage system. The control system diagram is shown in Figure 11.

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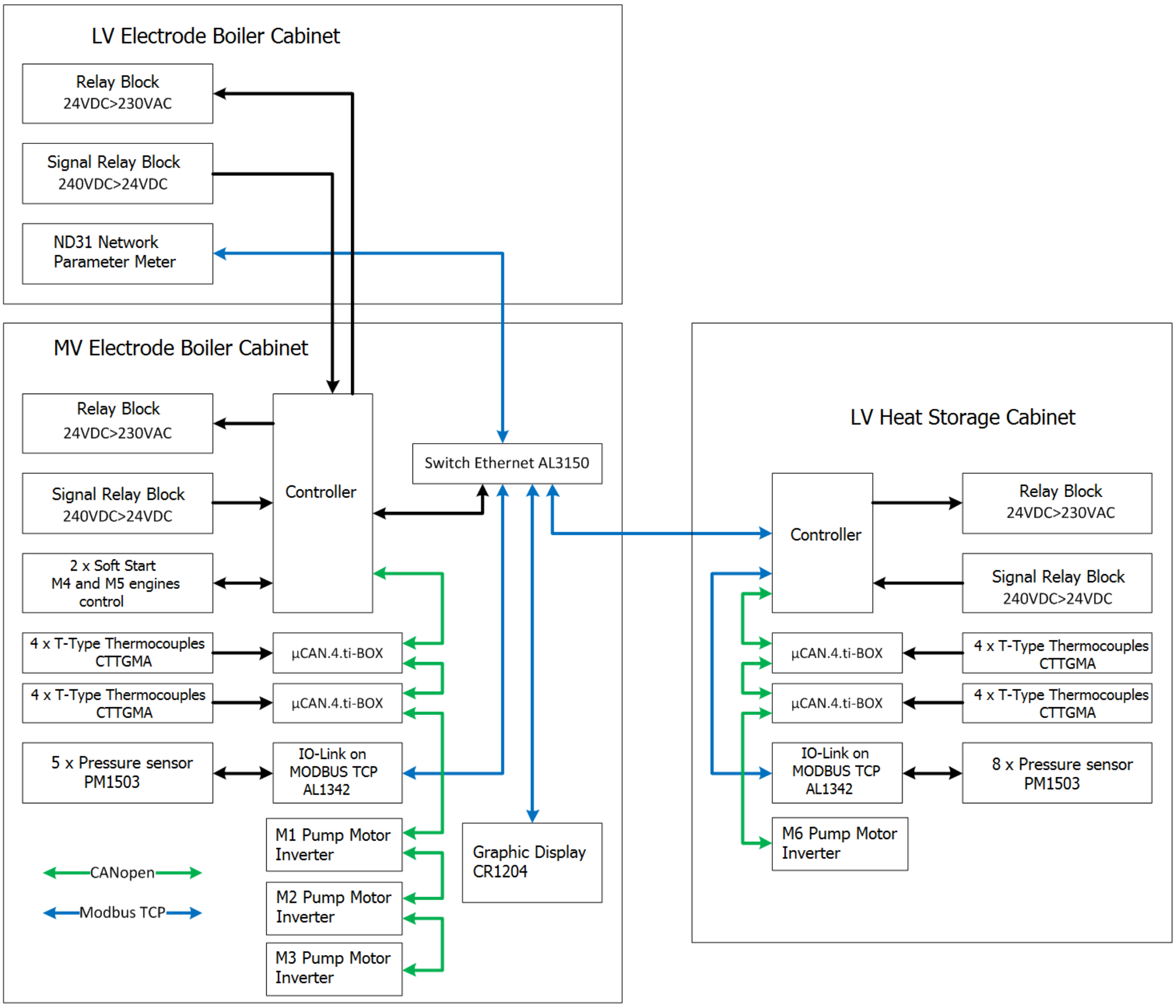

Fig. 11. Block diagram of the control system

The automation devices will be installed in three cabinets:

- the medium voltage (MV) cabinet of the electrode boiler,
- the low voltage (LV) cabinet of the electrode boiler,
- the low voltage (LV) cabinet of the thermal energy storage unit.

The control system is based on controllers and an operator panel from IFM Electronic GmbH. These devices collect data from transducers and sensors and control relays, contactors, and inverters. The LV cabinet of the electrode boiler houses the CR720S controller with the CR2530 extension module. The LV cabinet of the thermal storage unit contains the CR0709 controller. The selected controllers support the following digital communication protocols for data transmission:

- Ethernet with Modbus TCP protocol.
- CAN with CANopen protocol.

The Ethernet bus with the Modbus TCP protocol (shown in blue in Fig. 11) connects the main controller and the CR1204 monitor, enabling remote management of both the boiler and the thermal storage unit. It also connects to AL1342 modules, which act as IO-Link signal concentrators.

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The CAN bus with CANopen protocol (shown in green in Fig. 11) is used for connecting temperature transducers and for communication with inverters.

The following actuators and measuring devices are used in the system:

- Electric motors of pumps M1–M3 and M6, controlled via inverters using the CAN network (4 digital outputs [DO] and 4 digital inputs [DI] for handling contactors before inverters).
- Electric motors of pumps M4 and M5, controlled via soft-start modules (1 DO) with feedback on contactor status (1 DI).
- Two contactors, 1K1 and 1K2, used to control the electrode system (2 DO and 2 DI).
- Ball valve actuators, controlled by two binary signals (2 DO) and providing two binary feedback signals indicating extreme positions (2 DI).

Measurement system consisting of:

- Thermocouple temperature sensors – signals concentrated via µCAN.4.ti-BOX modules communicating with the controller via CAN.
- IO-Link pressure sensors – signals concentrated via AL1342 modules communicating via Modbus TCP.
- Level indicators – binary signals directly connected to the controllers.
- Power network analyzer – communicates with the controller via Modbus TCP.

The MV cabinet of the boiler contains the CR720S controller, which monitors the operation of the electrode boiler installation and calculates its instantaneous power based on voltage and current measurements. Additionally, this controller performs the following control functions:

1. Local and remote switching of system-operated devices (pump motors, valves), both in automatic and manual remote modes from the operator station.
2. Maintaining the set boiler power by controlling pumps M1 and M2.
3. Controlling the heating circuit in the heat exchanger system via pump M3.
4. Brine dosing via pump M4.
5. Refilling the installation with water using pump M5.
6. Reversing the heat flow direction (on operator request) – toward the thermal storage or the consumer.

The controller installed in the LV cabinet of the thermal storage unit collects signals from this part of the installation and controls the circulation pump within the storage system and the valves connected to individual tanks.

5. Summary

An innovative approach to electrode boilers holds significant potential in the context of achieving energy transition and decarbonization goals. Their application in combination with renewable energy sources, along with the implementation of modern control technologies, can contribute to increased energy efficiency, reduced CO_2 emissions, and optimized energy consumption. The key to success lies not only in the development of the electrode boiler technology itself but also in its integration with broader energy systems, which would enable a more complete utilization of renewable energy sources.

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Heating liquids using electrode boilers gained popularity in the first half of the 20th century due to its simplicity, reliability, and low failure rate. The design, shape, and arrangement of electrodes inside the boiler depend on its construction and power supply method. Electrodes most commonly take the form of rods, rings, or tubes. In the liquid, the charge carriers are ions, and their concentration determines the liquid's conductivity—its ability to conduct electric current.

The power output of an electrode boiler primarily depends on several factors. The first is the voltage applied to the electrodes. In commonly used electrode boilers, this is the low-voltage (LV) grid voltage for low-power boilers (up to 100 kW), such as 230 V AC (L–N) or 400 V AC (L–L) for three-phase systems, and medium-voltage (MV) grid voltage for high-power boilers (above 0.5 MW), such as 6000 V AC (L–L). The second factor is the current flowing through the liquid, which depends on the boiler's construction (size and arrangement of electrodes) and the conductivity of the liquid flowing between the electrodes. While the size and arrangement of electrodes are fixed—being directly determined by the boiler's design—other parameters vary to a greater or lesser extent.

A third factor that significantly influences the current flowing through the liquid is temperature. As the liquid's temperature increases, the kinetic energy of the molecules rises. This results in a higher ion mobility and, consequently, greater electrical conductivity of the liquid. In such systems, this phenomenon is particularly important, as warmer liquids generally conduct electricity better, potentially leading to significantly increased power output. In the case of electrode boilers, the conductivity difference between cold and hot liquid can indeed affect system performance. The statement that power output can vary by more than 100% is plausible, though it depends on specific system conditions, such as the type of liquid, its chemical composition, and the operating temperature.

As a result, it can be concluded that an electrode boiler achieves its rated power output only under specific conditions. When the water in the system is cold, its conductivity is lower, resulting in reduced boiler power—precisely when the demand for power is highest due to the need for rapid heating.

The implementation of this project will contribute to the creation of a more flexible and sustainable heating system that better meets users' energy needs and improves energy efficiency on a local level. This, in turn, will allow for more effective use of available energy resources and minimize energy losses.

The main goal of using an industrial electrode boiler integrated with a thermal energy storage system is to optimize self-consumption or reduce peak load in district heating systems operated by heating utility companies (PEC – Przedsiębiorstwo Energetyki Cieplnej S.A.).

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