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Design and Control of Boiler Systems for Enhanced Performance in Mini-MED Applications

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ABSTRACT

Using a step-by-step evaporation process, the multi-effect distillation (MED) system is an efficient thermal distillation technique that turns saltwater into fresh water. At each step of the process, the seawater is heated using steam produced by a boiler, and the pressure drops. Because local water sources include a lot of salt, this method is especially helpful in coastal areas where access to clean water is limited. In order to assist the distillation process, boilers serve as the mini MED system's primary heat source. Gas, which has been shown to be more energy efficient than electric heating, powers the boiler used in this investigation. In order to satisfy the unique requirements of the mini MED system, the control system is also employed to adjust the flow rate and vapour pressure. This guarantees the process's smooth and reliable operation. Choosing the right boiler and creating the best control system are essential for a micro MED system. Small-scale desalination operations can be completed effectively with a well-planned setup, satisfying the need for clean water in places with scarce freshwater supplies.

1. INTRODUCTION

Access to clean and safe water is a critical global challenge, especially in coastal regions where freshwater resources are limited due to high salinity in local water sources. Desalination technologies have emerged as an effective solution to address this issue, enabling the conversion of seawater into potable water. Among the various desalination methods, multi-effect distillation (MED) systems stand out for their efficiency and cost-effectiveness in producing fresh water [1, 2].

The concepts of boiling or evaporation and condensation form the basis of the thermal desalination process. Evaporation occurs when water is heated. As the vapour condenses to create new water, salt will be left behind [3]. According to multiple sources, there are a number of thermal desalination techniques, such as vapour-compression evaporation, multi-stage flash distillation, and MED [4-6]. The earliest desalination technique [7] is MED, which also has a high thermodynamic efficiency [8]. The procedure is developed at low temperatures (about 70℃), which reduces the power needed and can minimise chamber corrosion and the possibility of scale formation around the chamber surface [5, 9]. The MED technique is used in the seawater distillation system seen in Figure 1.

The MED system operates by utilizing a step-by-step evaporation process, where seawater is heated and evaporated in multiple stages under progressively lower pressure conditions. This approach efficiently recycles latent heat, making it one of the most thermally efficient desalination technologies [10, 11]. As the pressure drops in each stage, the boiling temperature of water decreases, which reduces the energy required for the process and enhances overall efficiency [12, 13].

One of the primary components driving the MED process is the boiler, which serves as the main heat source. Boilers provide the steam necessary for evaporating seawater and sustaining the distillation process. Gas-powered boilers have gained significant attention for their energy efficiency and cost-effectiveness, particularly in small-scale applications [14, 15]. These boilers offer consistent heat generation and have a lower environmental footprint compared to other heating methods, making them ideal for micro MED systems [16, 17].

In addition to efficient heat generation, the operation of mini MED systems requires precise control over key process parameters, such as flow rate and vapor pressure. A well-designed control system ensures stability and reliability by dynamically adjusting these parameters to optimize energy consumption and maintain consistent output quality [18, 19]. Advanced control systems can also help prevent operational disruptions, which is crucial for ensuring the long-term sustainability of small-scale desalination units [20, 21].

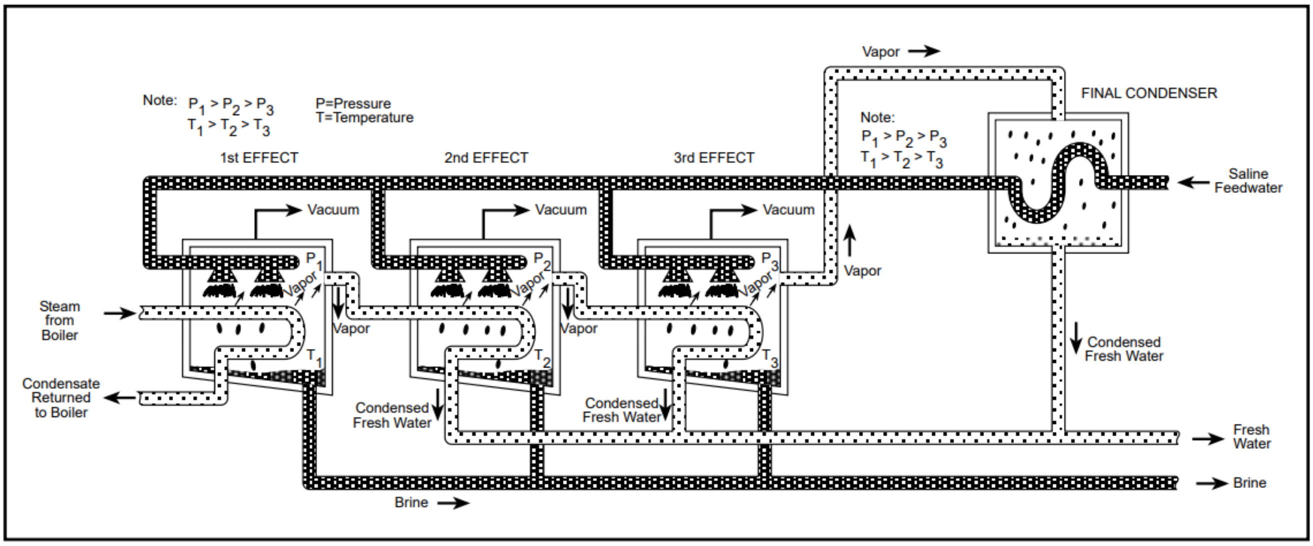

Figure 1. MED system

The need for compact and energy-efficient desalination systems is particularly pressing in remote and arid regions, where centralized water infrastructure is often unavailable. mini MED systems address this demand by providing scalable and sustainable solutions for freshwater production in such areas [22, 23]. These systems are particularly suited for small communities, industrial operations, and emergency water supply in disaster-prone regions [24, 25].

Despite their potential, designing a mini MED system involves addressing several technical and operational challenges. Selecting the right boiler and optimizing the control system are two of the most critical aspects that significantly influence system performance. Proper integration of these components can improve the energy efficiency and operational reliability of the system, ensuring its viability in water-scarce regions [26, 27].

The MED process has been the subject of extensive research, with numerous studies highlighting its advantages over other desalination technologies. Compared to Reverse Osmosis (RO), which requires substantial energy for high-pressure pumps, MED systems are less energy-intensive and can utilize low-grade waste heat, further improving their energy efficiency [1, 11]. Additionally, the lower operational pressures in MED reduce the risk of scaling and fouling, resulting in lower maintenance costs [13, 16].

Moreover, gas-powered boilers offer an environmentally friendly heating solution for MED systems, reducing greenhouse gas emissions compared to traditional fossil fuel-based boilers. This makes gas boilers a preferred choice for regions aiming to implement sustainable desalination projects with minimal environmental impact [18, 21].

An effective control system not only enhances the operational efficiency of MED systems but also extends their lifespan. By monitoring and regulating critical process variables, the control system prevents issues such as overpressure, uneven heating, and fluctuations in water quality. This level of automation reduces human intervention, making the system more user-friendly and reliable [19, 22].

In terms of scalability, mini MED systems can be tailored to meet the specific needs of diverse users. For instance, small-scale desalination plants can be deployed in isolated coastal communities, while larger systems can support industrial applications that require substantial amounts of clean water [22, 25]. This flexibility makes MED technology a versatile solution for tackling water scarcity on multiple fronts.

Additionally, the economic benefits of MED systems cannot be overlooked. The lower energy consumption and reduced maintenance requirements translate into lower operational costs, making them financially viable for both public and private sector investments [12, 26]. These cost advantages, combined with their robust performance, have positioned MED systems as a preferred choice for sustainable desalination projects worldwide [18, 23].

This study aims to explore the critical factors influencing the performance of mini MED systems, with a particular focus on boiler selection and control system optimization. By addressing these factors, the research seeks to enhance the efficiency and reliability of small-scale desalination units, contributing to global efforts to alleviate water scarcity in vulnerable regions [27, 28].

The subsequent sections of this paper will provide a comprehensive overview of the MED process, discussing its operational principles and advantages. The role of gas-powered boilers in driving the distillation process and their environmental benefits will also be explored in detail. Furthermore, the study will examine the importance of advanced control systems in optimizing mini MED operations and ensuring consistent freshwater output.

In conclusion, the findings of this research are expected to have significant implications for the design and deployment of sustainable desalination systems. By optimizing key components such as the boiler and control system, mini MED units can play a pivotal role in addressing the growing global demand for clean water while minimizing energy consumption and environmental impact.

2. METHODOLOGY

For the stages in the research process as shown in the Figure 2.

The stages of research based on the figure, are as follows:

- Determine the system's requirements while taking into account a number of factors, such as low energy usage and steam flow and pressure control system settings.

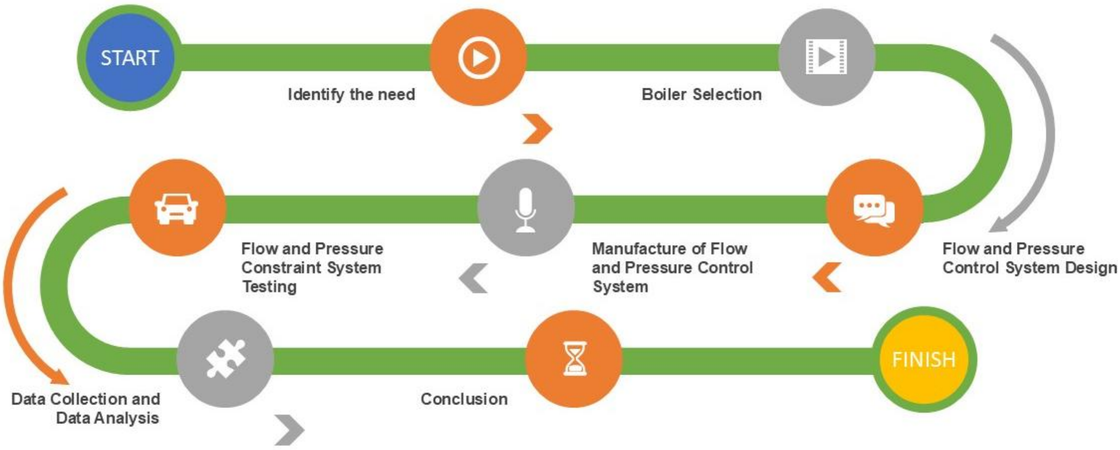

Figure 2. Research method

- A boiler with a minimum pressure of one bar should be chosen. This is ready for the first chamber to require high pressure.
- Create a microcontroller-based flow and pressure control system. The kind of microcontroller that can be trusted for the miniature MED system is chosen at this stage of design.
- The design of the control system is created in accordance with the requirements of the MED system after the type of control system to be used has been decided.
- To make sure the vapour pressure reaches at least 5 bar and can enter the first chamber of the micro multi effect distillation, the flow and pressure control system is tested. It must be possible to modify the installed control system to meet the requirements of the tiny multi effect distillation system.
- The team gathered the results at this point and examined the control system's preparedness for installation into the small MED system.

As seen in Figure 2, the mini MED system's boiler generates heat via a flame created by burning gas. With a 40-liter capacity and a 1 bar working pressure, the boiler in use. The schematic for the constraint system we use is as shown in Figure 2.

Figure 3. Boiler system

Table 1. Specification of component

Parameters	Spesifikasi	Description
Pressure Transmitter	0-10 bar; 0-10V; 250C	Detecting pressure in the boiler
Temperatur Transmitter	PT100; 0-300C; 0-10V	Detect the temperature of the boiler and chamber
Thermocouple	2 wire; Type K	
Pressure Transmitter	-1-1bar; 4-20mA;	Detecting vacuum pressure in the vacuum chamber
Selenoide Valve	3V; ¼ in	Disconnecting the LPG gas flow
Modul Ignitter	3VDC	Gas stove lighter
Adaptor power supply	24VDC; 2A 50W	Power supply electrical system control system
Digital Pressure Controller	0-10 bar; 4-20mA	Control system for gas flow
Loop Calibrator	4-20mA	Process calibrator
Pressure Resucing Valve	0-8bar; ½ in	Lowering the pressure in the boiler

Figure 3 shows the design of the boiler selected for use in the mini MED system, the boiler has a capacity of 40 litres. The Modbus system facilitates communication between the components of the constraint system in the scheme. The specs of the components utilised are displayed in Table 1.

Here's the wiring diagram for the boiler constraint system for the mini MED system.

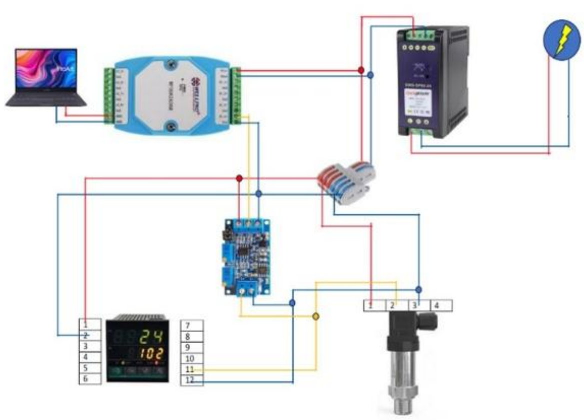

Figure 4. Schematic diagram for DAQ

Figure 4 shows a pressure sensor measurement system with several key components, including:

- Pressure sensor
  This sensor has 4 terminals (1, 2, 3, and 4). These pressure sensors typically produce a signal of current (4-20 mA) that must be transformed into a voltage.
- Current to voltage converter
  This module converts the current signal (4-20 mA) from the sensor into a voltage signal (e.g. 0-5V or 0-10V). The output of the converter is connected to a measuring instrument or monitoring system.
- Power supply
  Used to power the sensors and other devices in the system. Usually a voltage of 24V DC.
- Communication module to computer
  This module appears to be a communication converter (e.g. RS485 to USB) to connect the system to a computer or laptop. Used for monitoring or logging data digitally.
- Display Indicator
  shows measurement results in numerical form, including the sensor's pressure reading.

Wiring explanation

- Red → Positive line (+), used to conduct power from the power supply to sensors and other modules.
- Blue → Negative line (-), used as a reference to ground or voltage.
- Yellow → Signal lines, carrying data from sensors to converters and displays.

Workflow

The pressure sensor measures the fluid pressure and generates a current signal (4-20 mA). The current signal is converted to voltage by a converter module. The output voltage is sent to a display panel and to a communication system (e.g. laptop). The data can be monitored via a computer for further analysis.

3. RESULT DISCUSSION

Choosing the appropriate boiler for an industry is a critical choice that impacts both environmental impact and operational efficiency [29]. A boiler's environmental friendliness is influenced by both design elements, such as the type of boiler technology and auxiliary equipment, and operating practices, such as the quantity of extra air and flue gas temperature. Furthermore, the kind of fuel utilised has a significant impact on the emissions of greenhouse gases and pollutants, particularly CO_2.

In choosing between gas and electric boilers, there are several factors to consider, such as energy efficiency, operational costs, and environmental impact [30]. Gas boilers are generally more economical in the long run due to the relatively cheaper price of gas compared to electricity, especially for industrial needs or large-scale use [31]. In addition, gas boilers often have a higher heating capacity, making them more efficient for applications with large heat requirements [32]. However, electric boilers offer advantages in terms of easier installation, simpler maintenance, as well as more environmentally friendly operations because they do not produce direct emissions [33]. By considering the advantages and disadvantages of each type of boiler, the selection between the two should be tailored to the specific needs and availability of energy sources at the site of use.

The significance of multi-criteria analysis in industrial boiler selection, which considers both technical and economic factors, is emphasised in another study this method ensures a balance between optimal performance and economical expenses by evaluating multiple options and choosing the one that best meets the industry's unique requirements [34].

Thermal efficiency and fuel type must be taken into account when choosing boilers with minimal energy demand. High thermal efficiency boilers can reduce operational expenses and energy usage. By absorbing heat from the flue gas, an economiser can be used as an air pre-heater to increase the boiler's thermal efficiency while lowering fuel consumption and emissions [35].

Furthermore, efficiency and environmental impact are significantly impacted by the type of fuel chosen. For instance, natural gas is more efficient and emits fewer emissions than alternative fuels like coal or fuel oil. Therefore, the use of environmentally friendly fuels and efficient design should be taken into account when selecting a boiler that meets low energy requirements [36].

In light of these factors, the research team chose a boiler that uses gas as a heat source. Taking into account the comparatively low energy consumption.

Figure 5. Steam generator

Figure 5 shows the boiler/steam generator that has been completed. This boiler is what we used for the selection of the pressure control system. It is frequently more difficult to control heat produced by gas combustion than heat produced by electrical energy. Because gas combustion produces heat instantly and quickly, a more sophisticated control system is needed to ensure temperature stability. In contrast, electric heaters may be easily regulated with electric current settings and, because of their delayed reaction, allow for more accurate temperature regulation [37].

Furthermore, gas heaters need sufficient ventilation to prevent the buildup of hazardous gases, which makes temperature control and management more difficult. However, since electric heaters don't need specialised ventilation, their temperature control systems are easier to use and more effective. As a result, electric heaters are frequently chosen over gas heaters in applications that need for exact temperature control. Figure 3 illustrates the creation of the control and DAQ systems' schematic diagrams [38].

According to the design, we test the boiler in phases, beginning with a pressure of 1 bar.g. and working our way up to 5 bar.g. To make sure the DAQ system and the control system we created were prepared for use in the micro MED system, we first conducted our testing. These are a few of the records we created while evaluating the mini MED system.

Figure 6. Steam generator commissioning

Figure 6 shows the process of carrying out the commissioning stage for boilers that have been completed and ensuring that no leaks occur. Calibration of the data collection hardware is the first step in the calibration stage of a data gathering system. This gear consists of transducers, sensors, and instruments for signal processing. In order to make sure that the measurements generated match established values, the sensors are now verified using a common reference. Along with confirming the sensor's sensitivity and linearity, this procedure also looks for any systematic mistakes that might arise throughout a range of measurement ranges. To lower inaccuracies and guarantee that the data gathered accurately depicts the situation, adjustments are done [39].

Calibration of the software that controls the data collecting system comes after the hardware has been calibrated. The goal of software calibration is to guarantee that the data processing algorithms can accurately and usefully transform the raw signals obtained from the sensors. At this point, the system is tested to make sure that the frequency and timing of measurements are in sync with the conditions of observation and that the received data can be processed correctly. The method is modified to lessen any noise and distortion in the data [40].

Verification and validation of measurement results are the last steps in the calibration of a data gathering system. To guarantee the precision and consistency of the collected data, the system is tested in a variety of scenarios following hardware and software calibration. Usually, to accomplish this, the gathered data is compared to a more precise reference standard. In order to make sure that the calibration is maintained and the system can continue to produce accurate results over time, this validation also involves examining the system's long-term stability. Accurate measurements in a range of applications, from industrial process control to scientific research, are made possible by properly calibrated data acquisition systems. In this step, the team checks the data acquisition results with standardised measuring devices, in this case the boiler's pressure gauge. The calibration results for the planned data acquisition system are as follows:

Figure 7 shows the results of the calibration that has been done. The calibration equation is derived from the calibration findings. It is possible to enter this equation into the data gathering application.

The boiler's pressure control system's results, which are displayed in the figure, demonstrate that the system is capable of maintaining a steady pressure. The system is configured to sustain pressure at 1 bar or 1.01972 kg/cm^2 during the test. The graph indicates that the pressure increased to 1.32 kg/cm^2, but was able to return to 1.17 kg/cm^2 and was able to maintain constantly at a pressure of 1.17 kg/cm^2. From the tests carried out, the control system used can maintain constant according to the pressure that has been determined at the beginning.

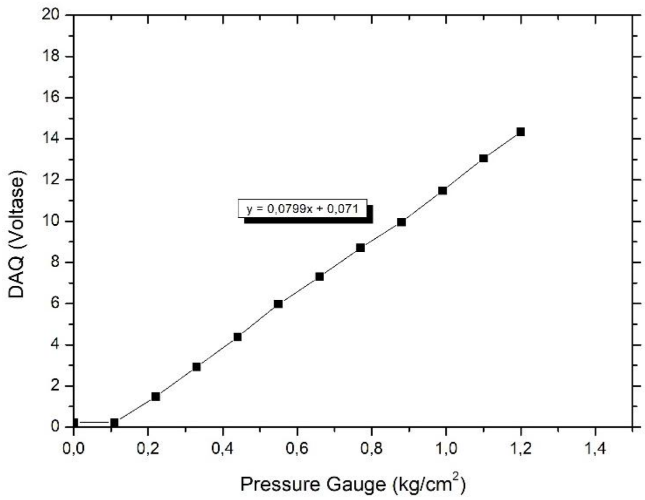

Figure 7. Calibration results of acquisition data vs pressure gage

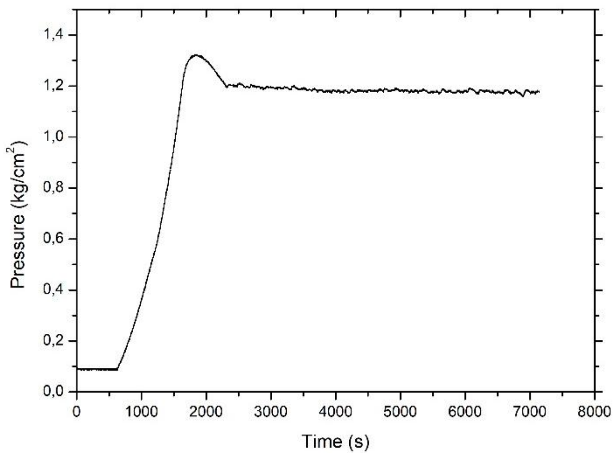

Figure 8. Graph of the pressure control system

Figure 8 shows the measurement results of the boiler performance through the DAQ system using the control system. The Multiple Effect Distillation (MED) micro system's operational stability is directly impacted by an efficient boiler pressure control system. The distillation system can function at its best if the pressure is continuously kept at 1.17 kg/cm² following early fluctuations. Uncontrolled pressure changes have the potential to raise energy consumption, decrease evaporation efficiency, and create imbalances in the seawater heating process [41]. Each distillation effect's heating operates at peak efficiency when the pressure is steady, generating enough water vapour for the purifying procedure without wasting energy.

The quantity and quality of fresh water generated in MED systems are significantly impacted by the boiler pressure stability. An excessively high or low boiler pressure might interfere with the creation of steam, which lowers the efficiency of evaporation at every distillation step [42]. The evaporation process is improved and a volume of fresh water that equals the system's design capacity is produced using a control system that maintains the pressure at 1.17 kg/cm². By doing this, freshwater production is guaranteed to be steady and meet operational requirements.

For mini MED systems to prevent overheating and possible component damage, the boiler's vapour pressure stability is crucial. Damage to the heat exchanger or evaporator pipes may result from overheating if the pressure increases over the allowable limit, as it occurred during the first spike to 1.32 kg/cm² [43]. This risk can be decreased by using a control system that can lower and keep the pressure at 1.17 kg/cm², increasing equipment life and cutting maintenance expenses.

The effectiveness of energy utilisation in MED systems is also impacted by proper boiler pressure control. Energy consumption can rise as a result of inefficient fuel combustion in the boiler caused by uncontrolled pressure changes [44]. Stable pressure allows for optimal fuel combustion, which lowers total fuel needs and boosts system thermal efficiency. Because of the increased fuel usage, this helps to lower operating expenses and the environmental impact.

Boiler pressure stability is essential from a safety standpoint since it helps avoid system breakdowns that may result in unexpected shutdowns or even operational risks. Uncontrolled pressure can cause structural damage or steam leaks that are dangerous for both the environment and operators [45]. The MED micro system can function more safely and dependably with a control system that can keep pressure at the appropriate level, lowering the likelihood of unforeseen operational problems.

4. CONCLUSION

Boiler systems must be carefully chosen and calibrated in order to enable MED systems' operational efficiency. To guarantee the measurement accuracy of the data gathered, the calibration process starts with testing hardware, such as sensors and transducers. Software calibration is next performed to guarantee correct data conversion. The graph demonstrating the system's capacity to maintain the pressure at the target level then demonstrates that the control system, which is intended to manage the pressure and vapour flow, must be able to stabilise the operating conditions.

Boilers are a crucial source of thermal energy for the distillation process in the context of MED, and choosing efficient boiler types—such as gas-powered ones—can lower energy usage and the emissions that result. MED systems can be run more effectively and sustainably by taking fuel kinds and thermal efficiency parameters into account. Furthermore, the stability and effectiveness of the small-scale seawater desalination process depend on the boiler's usage of appropriate control systems, such as flow regulation and steam pressure. MED provides a more effective desalination option than conventional distillation techniques, which might lower carbon emissions and promote sustainability as technology develops and the need for renewable energy rises.

Finally, by guaranteeing operational stability, enhancing freshwater production efficiency, preventing equipment damage, optimising energy usage, and raising overall system safety, an efficient boiler pressure control system benefits the MED micro system.

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