Research and Analysis of a Smart System for Intelligent Control of PCM Water Storage Tank for Stock Farm Needs

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Abstract: - Energy efficiency is a very important component in modern systems. Modern research examines innovative methods and techniques for increasing the efficiency of heat generation systems. A popular approach is to apply combined methods of using energy from different heat sources. This article describes a basic algorithm for developing an intelligent control for a system of hot-water storage tanks with PCM adapted for a stock farm's needs. The main components of the system are described along with the PCM advantages. The prerequisites for the system's operation are analyzed and adapted for its management. The developed algorithm and a control system are tested in a simulated environment and are presented conclusions of the system's energy efficiency improvement.

Key-Words: - Hot water storage, Intelligent control, Control system, Energy Efficiency, Phase Changing Materials, Solar installations, Stock farms.

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1 Introduction

One of the most popular topics nowadays is the usage of renewable sources and The Green Transition in Europe, [1]. With the advancement of green energy technologies comes the need for storage and releasing the gained energy. As part of the loop of big energy users and an important economic source, farming has the potential to reduce energy consumption. More than 23% of the energy costs in a farm is used for heating water, [2]. Some of the most common hot water needs include cleaning of milk lines, tank washing, calf drinking water, etc. This is why optimizing this division by improving the energy efficiency of a water heating system is essential. The processes that require the usage of hot water usually take place during the daylight hours, because of animals' routines. This factor can significantly affect the logistics and management principle of water heating systems.

One solution is to use solar water heating panels, but they can provide only some of the heat for the water, which is unlikely to produce stable temperatures for all farm needs, [3]. They can be implemented together with indirect hot water storage cylinders that work by using an external source (like solar panels) to heat the stored water.

The system contains a heat exchanger, which is where water from the boiler passes through and in turn, heats the water inside of the indirect hot water cylinder. Once the water has passed through, it returns to the boiler. This process is repetitive. The water circulates between the top of the tank where it is hot, and the bottom where it is cooler, but heated up by the exchanger, [4]. The hot water tanks can store energy, thus they improve energy efficiency, and reduce the cost of heating, [5].

Solar panels are popular in stock farms. They have large open spaces and wide roof space where the panels can be installed or the construction of the solar panels can be used for providing the animals with shade, [6]. Unfortunately, they are a seasonal solution, most effective during the warm seasons. Solar heating system's thermal performance can be improved with tanks with PCMs (Phase Changing Materials). Using this type of material can prolong the heat release and the steady water supply can be provided for a longer period. The melting point for the PCMs is between 40 and 80 °C, it is relevant for industrial, commercial, and residential buildings.

The system's construction can be adapted to the conditions where it will operate. Some of the prerequisites that should be taken into consideration for example are purpose, flow rate, desired temperature, weather conditions etc., [7]. The integration of these hot water systems is a topic of investigation and analysis, [8]. For increasing the energy efficiency on site, they can be improved by intelligent control depending on the particular farm conditions and animal needs.

An example of the high usage of warm water is with milking robots. For each milked cow, considerable amounts of hot water are used to clean the teat cups and disinfect the udder. The inclusion of energy-efficient systems in the cleaning and disinfection systems of the milking robots will contribute to reducing the power consumption for heating water, [9].

This article describes the design and development of an intelligent system for controlling a hot water tank with PCM suitable for stock farms. The first chapter describes the system components and scope of operation. The second chapter describes the system's initial algorithm for operation based on the specific needs of a farm. A conclusion is presented with results of the system’s performance and energy efficiency.

2 System’s Design

The presented hot water storage system with PCM is designed with the following main components:

2.1 Hot Water Storage Tank with Phase-Change Material

The tank is made of steel, with aluminum cylindrical tubular containers filled with phase-changing material (paraffin) placed in its volume. When the inside temperature increases, the paraffin goes through a phase transition from solid to liquid states, thereby accumulating thermal energy, which when passing from liquid to solid state (i.e. lowering the temperature) is released and, accordingly, accumulated by the water in the tank. The operating temperature range of this material is between 45 and 68 °C, which allows hot water to be stored for a longer period.

2.2 Solar Panels

Solar panels are flat with a selective coating and include the following elements: absorber, coating, thermal insulation, and connecting pipes. They are located on the roof, and the installation follows the slope of the roof and the orientation of the building.

2.3 Circulation Pump

The circulation pump is electronically controlled, with variable regulation of flow rate and pressure. Its function is to ensure the circulation of the working fluid.

2.4 Two-way Valve

Valves are designed to vary the flow rate. The valves with a logarithmic flow characteristic are most often used. They are equipped with electric actuators. Dual thermostatic valves operate with one or two sensors. They have wider possibilities of application. Along with the desired temperature, they also maintain a set temperature difference.

2.5 Controller

A digital controller is a device that reads the sensor's data and controls active devices by performing software instructions. In the proposed installation, this controller is the connection between the individual components of the system: solar collectors and storage tank with Phase-change material (PCM) (Figure 1).

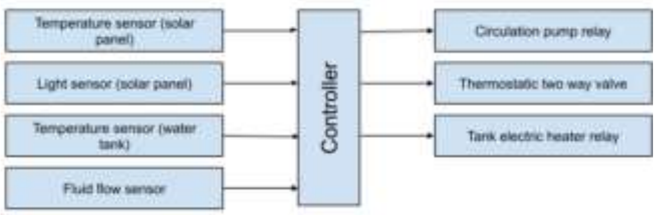

Fig. 1: Management of the individual circuits of the installation through the innovative programmable controller

2.6 Electronic Relay

Electromechanical component, that is controlled by the main controller. It switches on/off the electrical heater in the tank.

2.7 Temperature Sensors

Sensors work on the thermocouple principle. Thermocouples are temperature sensors with wide application in household and automation. They are devices composed of two different conductors, which are heated unevenly and generate a voltage proportional to the difference in temperature between the two ends of the conductors. This is the so-called thermoelectric effect.

2.8 Sunlight Sensors

It is a multi-channel digital light sensor, which can detect UV light, visible light, and infrared light.

2.9 Water Flow Sensor

This is a high-performance piezoceramic solution for reliable and precise flow measurement of liquid and gas flows using ultrasonic technology.

This type of installation is used for independent or partial operation depending on the geographical location and external atmospheric conditions. In the bright part of the day, the solar collectors transform the solar energy into thermal energy, which is stored in a hot water storage tank with a phase-change material and is utilized by the consumers when needed. The system is most productive in the period from May to September, due to the presence of a large number of sunny days, and it can satisfy 100% of the energy needs. For the rest of the year, to achieve the set operating parameters, the system works in hybrid mode, and an additional heat energy source (electric heater) is also included.

The control of the installation is carried out by the digital controller (DC), which is connected to all the components of the system utilizing various sensors. When a set temperature of the fluid in the solar panel is reached, the temperature sensor sends a signal to the controller, which turns on the circulation pump (CP). Fluid circulation continues until the temperature in the solar panel (SP) becomes lower than the temperature in the hot water storage tank (HWT). Then the controller sends a signal to the thermal valve (TV), which stops the circulation process. In case of an insufficient amount of solar energy, the controller turns on the electric heater (EH), which heats up the water in the tank to the set parameters. The process is illustrated in detail in Figure 2.

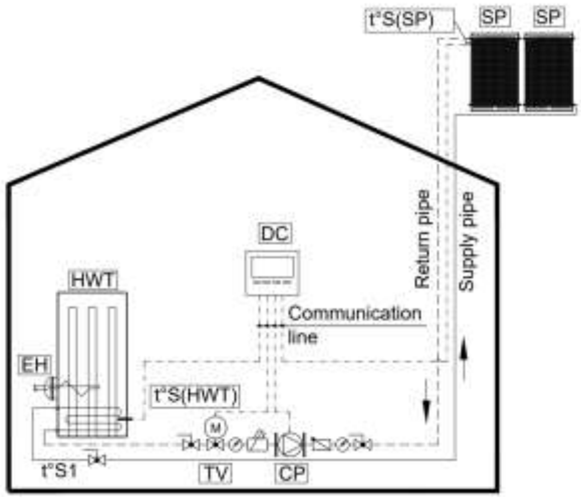

Fig. 2: Schematic diagram of the management of a solar installation with a storage tank with FPM

HWT - hot water tank, TV - thermostatic two-way magnetic valve, CP - circulation pump, SP - solar panels for hot water, EH - electric heater, t°S- thermal sensor.

3 Control System Operation

The studied system for hot water storage is complex and therefore it is necessary to develop a specialized algorithm to provide the necessary functionalities. In addition, we propose an IoT-based system for remote access to a heating system and possibilities for Smart solutions.

The proposed algorithm controls the desired temperature of the water in the heating system. That temperature depends on two circles of the heating system: the main circle (MC) and the solar circle (SC).

The mathematical description of the behavior of the individual elements of the entire system is presented in [10].

3.1 Control of the Main Cycle System

The main circle includes the HWT with built-in ET and PCM. The main circle can operate independently of the solar circle. The control algorithm for that is proposed in Figure 3. The algorithm is implemented in the controller. To achieve optimal energy efficiency, the water temperature in the HWT has to be in the operating range of the PCM, described above. This approach is expected to provide optimal energy efficiency because we will use the generated energy of the PCM during the entire cycle. Every time the water is used for farm needs, we will have internal heating from the PCM.

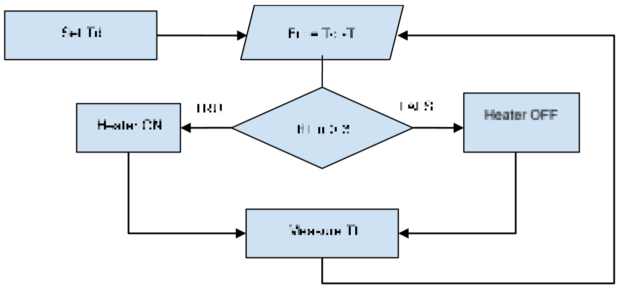

Fig. 3: Block diagram of the algorithm for control of the main circle

According to the described assumptions, we have to control the minimal water temperature in the HWT. That temperature must not be lower than 45°C. Regarding the upper limit, the water should not exceed 68°C. Therefore, the logic for controlling the MC is to turn on the water heater when the temperature is lower than 45°C and to turn it off when the temperature is more than 68°C. Considering the thermal parameters of the PCM, we have to include the generated thermal energy during the process of draining hot water and entering cold water in the tank. Therefore, we consider the following equation:

$$T_t = T_{ht}V_{ht} - T_cV_c + T_{pcm} \quad (1)$$

Where:
T_t - tank water current temperature,
T_{ht} - hot water temperature,
V_{ht} - hot water volume,
T_c - cold water temperature,
V_c - cold water volume,
T_{psm} - released temperature from the PCM

We measure the hot water temperature even in case no draining is detected. In that case, we expect that the heat loss will be too low and the generated heating of the PCM will provide enough energy. In case of a lower temperature than the lower threshold, the electric heater has to turn on. In that case, the Vc and Tc are 0, so we use the same equation for Tt.

Algorithm explanation: The desired water temperature range is set in the beginning, then it is compared to the current temperature of the water in the HWT, and the operating range of the PCM is also included. While the hot water is in the range of the PCM, we expect that it will generate heat while draining. To determine when to turn on the heater we calculate the error using the following equation:

$$Err = T_d - T_c \quad (2)$$

Where:
T_d - desired temperature threshold.

When the error drops below the lower threshold, then the heater is turned on. The proposed control system provides a prediction of the future water cooling and can turn on the heater in advance when an event of tank draining appears. This technique is expected to provide even better energy efficiency. The control system is illustrated in Figure 4. The controller used is of a PID type and it activates the heater relay. We use negative feedback by temperature.

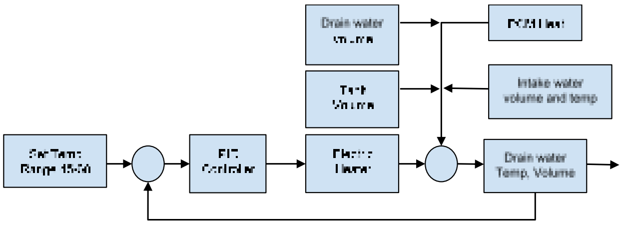

Fig. 4: Control diagram of the main circle

To verify that the proposed control system is able to achieve the desired behaviour of the heating system, we have completed some experiments in the Matlab Simulink environment. In Figure 5, the result from the simulation is shown. We show the temperature difference between the set temperature (yellow) and the real temperature (blue) while draining the water tank. We change the temp set point in the range (45-65), to test the system behavior, according to the draining volume of the water.

Based on the results, we may conclude that the system is stable and provides the desired performance. The generated heat from the PCM lowers the energy consumption. The heater is switched on, only when the temp is lower than 47 degrees. This proves that the suggested methodology is making the system more efficient.

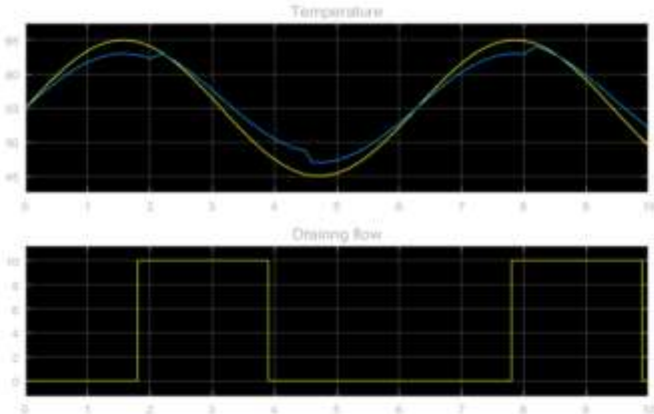

Fig. 5: Comparing temperature changes in the range of 45-65 degrees

3.2 Control of the Entire Cycle System

When we consider using both circles the system becomes more complex, because of the problems described in the previous chapter. The inclusion of the solar system circuit has the purpose of improving energy efficiency and providing higher water heating capacity. Therefore, the following aspects of Table 1 should be addressed.

Table 1. Important points for consideration

Element	Consideration	Solution
Solar cycle	Requires sunlight	Measurement of the light intensity
Thermostatic two-way magnetic valve	Requires hot water	Calculate SC power
Circulation pump	May provides efficiency	Control the water flow

The hot water flow from the SC has to increase the hot water in the tank. We control the SC flow by switching on/off the CP. That process concerns the temperature difference between the tank and SC water. To achieve maximum efficiency, we turn on the CP in three different cases:

- when the T_t is lower than the lower threshold and the CP water temperature is higher than the T_t;
- when the T_t is in the range of the T_d and the CP water temperature is higher than the T_t;
- when an event of draining is activated and the CP water temperature is higher than the T_t;

These cases will guarantee that the Tt will always be at maximum level in the condition of draining or lowering the current temperature in the water tank. The control system with the included solar system circuit is provided in Figure 6. We have added one more controller for switching on/off the CP and an additional block for adding the SC-released heating in the tank.

To decide which heating source to be used we add one more block at the beginning of the control system. That block switches on/off the two PID controllers according to the input values. We have the following conditions:
- if the error is in the range of 2-10% and the SC power is higher than 25%, switch on the PID2 only;
- if the error is in the range of 6-25% and the SC power is higher than 50%, switch on the PID2 only;
- if the error is in the range of 25-50% and the SC power is higher than 75%, switch on the PID2 only;
- if the error is higher than 50% and the SC power is higher than 90%, switch on the PID2 only;
- in all cases when the SC power is not higher than the required threshold, the system activates both the PID1 and PID2 systems;
- in all cases, if the SC power is lower than 10%, switch on the PID1 only.

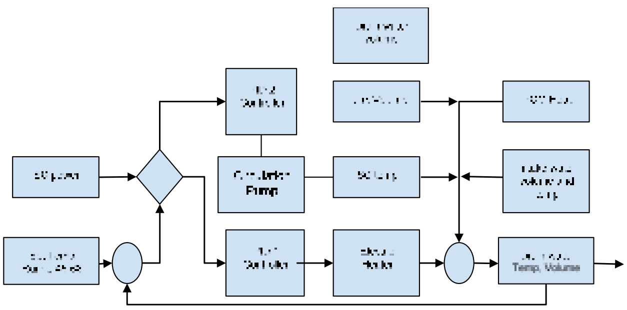

Fig. 6: Control diagram of the MC and SC

3.3 IoT Transition System

To be part of an IoT network, the system must be connected to the Internet and allow monitoring of data and setting of control parameters. To perform it qualitatively, we suggest the use of the following technologies: Connecting the controller to an Internet network, through a network adapter - Ethernet, WiFi, LoraWAN; Building a communication system based on MQTT communication protocols; Connection of a MongoDB-type database system for storing the information from the sensors, from the management and operation of the executive mechanisms; Development of a data analysis system. This way the system can be integrated with an application for intelligent control from any mobile device.

4 Conclusion

This study presents a system for intelligent control of a hot water tank with PCM with an algorithm for its operation.

The main purpose of this research is to increase energy efficiency in stock farms in terms of hot water usage and improve the quality of life of the animals. The use of PCM hot water tank has many advantages in reducing the energy used such as relative autonomy of the installation; lower operating costs compared to a conventional system; small carbon footprint; the possibility of integration in small and medium farms; ability to automate processes; a longer period of thermal energy storage due to the integrated PCM.

Although the hot water storage tank with Phase Change Material (PCM) presents several disadvantages, the developed working model significantly reduces energy usage. The system's limited temperature range, typically between 45°C and 68°C, may not suit all applications or climates, as efficiency can be compromised if ambient temperatures fall outside this range. The system's efficiency depends directly on the geographical conditions, being the highest in regions with intense sunlight and potentially requiring supplementary heating in less sunny areas. The need for a central power supply to operate essential components such as the circulation pump, digital controller, and electric heater further limits its applicability in remote or off-grid locations. Despite these challenges, the model demonstrates notable energy savings due to efficient energy storage and optimized heat utilization.

The development and improvement of control systems present several promising areas for future research, of particular importance for improving performance, reliability, and adaptability in various applications. One of the important directions includes the development and improvement of a control algorithm. Future research should focus on creating algorithms that can better manage nonlinearity and uncertainty in dynamic systems. Comparative studies of these algorithms in different applications could provide information on their relative strengths and weaknesses.

An important consideration is the analysis of Multi-Control (MC) and Single-Control (SC) systems. MC systems that include multiple controllers working in tandem offer advantages in terms of redundancy and fault tolerance, but can be complex to design and manage. Conversely, SC systems are simpler but may lack the robustness of MC systems. Future studies should explore the capabilities of MC and SC systems by investigating how MC systems can be optimized for efficiency and how SC systems can be improved for greater reliability.

Another key area is the integration of Internet of Things (IoT) technologies. Research should explore how IoT-enabled sensors and actuators can improve real-time data collection and control accuracy.

Scalability and flexibility of control systems are important to adapt to different operating scales and conditions. Research should focus on modular and reconfigurable control architectures that can provide systems that are more resilient to change and capable of evolving over time without significant redesign. Furthermore, future studies should prioritize the development of control systems that optimize energy use and minimize environmental impact. This includes exploring energy-efficient strategies for the control and use of renewable energy sources.

The application of effective management systems in the field of animal husbandry leads to a significant reduction in energy costs and increases the possibilities for precise monitoring of technological processes.

Such a system can be applied not only in farms, but also in different home, agriculture, and industrial sectors. This way we can get one step closer to the transition to a greener and safer future.

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Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the authors used the AI-assisted technologies “Grammarly” and “Google Translate” in the writing process in order to improve the readability and language of the manuscript

References:

[1] The European Green Deal – Delivering the EU’s 2030 Climate Targets, European Commission, October 2023, [Online]. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en#documents (Accessed Date: August 18, 2024).

[2] Debbie James, *Guide to water heating options for your dairy parlour*, Farmers Weekly, 06 June 2019, [Online]. https://www.fwi.co.uk/livestock/dairy/guide-to-water-heating-options-for-your-dairy-parlour (Accessed Date: January 15, 2024).

[3] A. Jamar, Z.A.A. Majid, W.H. Azmi, M. Norhafana, A.A. Razak,, A review of water heating system for solar energy applications, *International Communications in Heat and Mass Transfer*, Vol. 76, 2016, pp.178-187, https://doi.org/10.1016/j.icheatmasstransfer.2016.05.028.

[4] Patrick Garner, *Types of Hot Water Storage Cylinders/Tanks for Boilers*, [Online]. https://heatable.co.uk/ (Accessed Date: February 15, 2024).

[5] Cibse Journal, *Smart hot water tanks at the heart of the energy transition*, March 2021, [Online]. https://www.cibsejournal.com/technical/smart-hot-water-tanks-at-the-heart-of-the-energy-transition/ (Accessed Date: January 15, 2024).

[6] Alex Sandro Campos Maia, Eric de Andrade Culhari, Vinícius de França Carvalho Fonsêca, Hugo Fernando Maia Milan, Kifle G Gebremedhin, *Photovoltaic panels as shading resources for livestock*, *Journal of Cleaner Production*, Vol. 258, 2020, 120551, https://doi.org/10.1016/j.jclepro.2020.120551.

[7] A. Lasmar, *Modeling a Hot Water Storage Tank for Thermal Energy Storage Using Encapsulated Phase Change Materials*

(PCMs), Memorial University of Newfoundland, 2018.

[8] Saulius Pakalka, Jolanta Donėlienė, Matas Rudzikas, Kęstutis Valančius, Giedrė Streckienė, Development and experimental investigation of full-scale phase change material thermal energy storage prototype for domestic hot water applications, *Journal of Energy Storage*, Vol. 80, 2024, 110283, https://doi.org/10.1016/j.est.2023.110283.

[9] Rodenburg, Jack, Robotic milking: Technology, farm design, and effects on work flow, *Journal of Dairy Science*, 100, no. 9 2017, pp.7729-7738. https://doi.org/10.3168/jds.2016-11715.

[10] M. Haralampieva, R. Petrov and V. Yosifova, "Modern Hot Water Storage Technologies for Livestock Farms", 2023, *International Conference on Big Data, Knowledge and Control Systems Engineering (BdKCSE)*, Sofia, Bulgaria, 2023, pp. 1-5, doi: 10.1109/BdKCSE59280.2023.10339698.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed to the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare.