https://www.proconference.org/index.php/gec/article/view/gec41-00-027
DOI: 10.30890/2709-1783.2025-41-00-027

УДК 536.24:681.518:620.9

DESIGN OF AN INFORMATION ACQUISITION SYSTEM FOR THERMOPHYSICAL EXPERIMENTS ON LOW-POTENTIAL HEAT STORAGE SYSTEMS

РОЗРОБКА СИСТЕМИ ЗБОРУ ІНФОРМАЦІЇ В ТЕПЛОФІЗИЧНОМУ ЕКСПЕРИМЕНТІ НА ПРИКЛАДІ ДОСЛІДЖЕННЯ СИСТЕМИ АКУМУЛЮВАННЯ НИЗЬКОПОТЕНЦІЙНОЇ ТЕПЛОТИ

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Abstract. *The article presents the development of an automated data acquisition system for thermophysical experiments, demonstrated through the study of low-grade heat storage processes. The design of the experimental setup is described, which enables the analysis of heat exchange between storage materials — gravel (sensible heat) and paraffin (latent heat). The proposed system is based on a three-level architecture employing an Arduino Mega 2560 R3 microcontroller, an ESP32 communication module, and a Raspberry Pi 5 minicomputer, providing real-time data collection, processing, transmission, and visualization. The system operates autonomously using solar power. Measurement results obtained at 10-second intervals were analyzed to evaluate the efficiency of heat accumulation and the potential for heat utilization.*

Key words: *thermophysical experiment; heat storage; low-grade heat; data acquisition system; Arduino; Raspberry Pi; ESP32; energy efficiency; greenhouse*

Introduction

In modern energy systems, the efficient collection and analysis of experimental data play a crucial role in the study of thermophysical processes. The increasing use of renewable and low-grade heat sources requires reliable monitoring and control tools to optimize heat storage and utilization. Traditional measurement methods often lack automation and scalability, limiting the accuracy and continuity of experiments. This study presents the development of an automated data acquisition system designed for thermophysical experiments on low-grade heat storage. The system integrates modern microcontroller technologies — Arduino Mega 2560 R3, ESP32, and Raspberry Pi 5 — to provide continuous measurement, processing, and visualization of experimental parameters. The proposed solution improves data accuracy, reliability, and autonomy, enabling long-term monitoring of heat exchange processes in experimental setups.

Development of the Data Acquisition System

During a thermophysical experiment, it is necessary to ensure the efficient collection of data related to the investigated parameters, such as temperature, humidity, air velocity, and others. At present, this process can be effectively organized through the use of modern devices and methods.

In this study, a measurement system was developed for an experimental setup designed to investigate heat exchange between storage materials represented by a dense layer of gravel and paraffin. These materials are intended for the accumulation of low-grade heat from greenhouse air during daytime hours (charging phase) and for transferring this heat to the inner space of the greenhouse during nighttime (discharging phase). The schematic diagram of the experimental setup is presented in Figure 1.

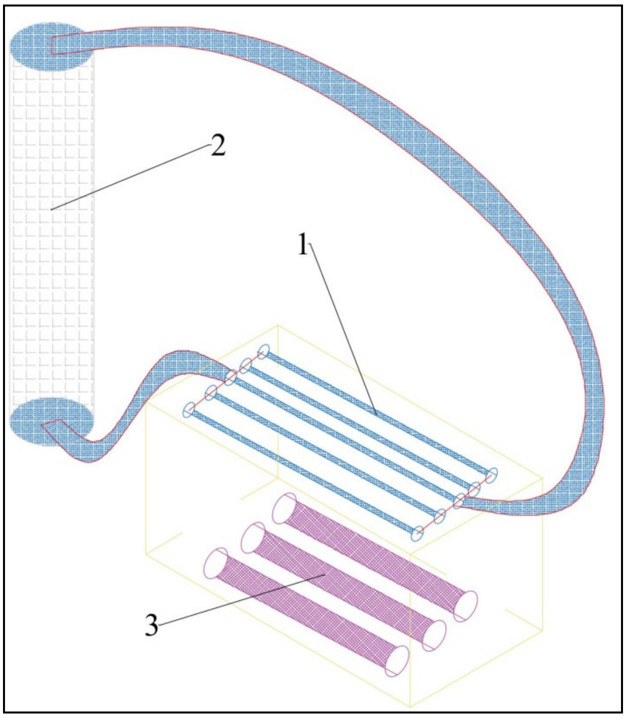


Fig. 1. Schematic diagram of the experimental setup for studying the heat storage process in sensible (gravel) and latent (paraffin) forms.

The following parameters were monitored during the experiment: the temperature of the water circulating through a transparent channel on the roof of the greenhouse model (1), which is heated by solar radiation; the temperature of the gravel layer measured at three different heights along the heat exchange channel (2); the temperature of the paraffin contained in polyethylene tubes placed in the soil layer of the greenhouse (3); the ambient temperature; and the air humidity both inside and outside the greenhouse model.

Temperature measurements were consistently performed using DS18B20 thermocouples. The intensity of solar radiation was measured using a GY-302 BH1750FVI digital light sensor

To analyze the thermal regimes, a continuous experiment was conducted over an extended period (two days).

To ensure uninterrupted monitoring of air and soil temperature and humidity, solar radiation, and carbon dioxide concentration, an automated system for data acquisition, storage, and transmission was developed.

The system is based on Arduino Mega 2560 R3, ESP32, and a Raspberry Pi 5 minicomputer, which perform distinct but interrelated functions. Pump and fan control is automated and governed by the sensor readings.

The system consists of the following levels:

1. Sensor level – measurement of thermophysical parameters of the environment.
2. Controller level (Arduino Mega 2560 R3) – data processing and control.
3. Server level (Raspberry Pi 5) – data collection, storage, and visualization.
4. Power supply module – autonomous energy provision from solar panels and a rechargeable battery.

I. Arduino Mega 2560 R3 — Central Controller of the Sensor Network The Arduino board serves as the core of the entire measurement system. It receives data from all sensors, including eight DS18B20 thermocouples, an air humidity sensor DHT11, a soil humidity sensor (hygrometer), and an air quality sensor CCS811.

Arduino functions as the primary computational node responsible for ensuring the stable operation of the sensor network, even in cases of temporary loss of connection with the server.

II. ESP32 Module — Communication Gateway (Wi-Fi Module) The ESP32 module operates as an intermediary link between the Arduino and the Raspberry Pi 5 server. It receives structured data from Arduino via the UART interface and transmits it over Wi-Fi to the local network.

The main tasks of the ESP32 module include:

- Providing wireless data transmission using the HTTP or MQTT protocol;
- Reducing the computational load on the Arduino by delegating network-related functions;
- Allowing configuration of network parameters (SSID, password, IP address) without reflashing the main controller;
- Buffering data packets during unstable network connections.

Thus, the ESP32 acts as a network gateway, ensuring separation between data acquisition and network processes, which significantly enhances the overall stability and reliability of the system.

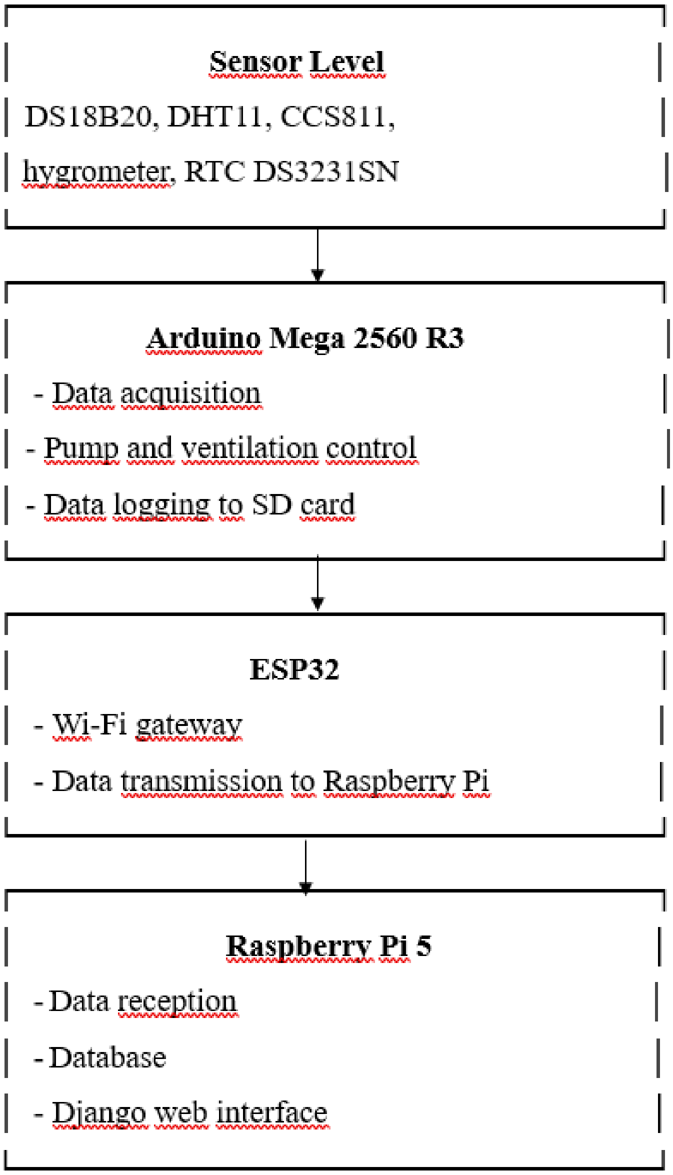
III. Raspberry Pi 5 Minicomputer — Data Collection, Storage, and Visualization Server

The Raspberry Pi 5 functions as the central server responsible for data acquisition, storage, and visualization. Its primary functions include:

- Receiving data over Wi-Fi from the ESP32 module;
- Writing information to a database (PostgreSQL or SQLite);
- Processing and analyzing the collected data;
- Displaying the information to the user via a Django-based web interface.

Thus, the Raspberry Pi serves as the central node of the data storage and visualization system, providing seamless interaction between the hardware components and the user through a web interface.

The overall logical interaction scheme of the system components can be represented as follows:



Rationale for Integrating Modules into a Unified System

The feasibility of integrating the modules into a single system is explained by the following factors:

• Distribution of computational tasks. The Arduino performs low-level control and management functions, while the Raspberry Pi handles resource-intensive operations such as data processing, storage, and visualization. This distribution prevents overloading of any single device.

• Increased reliability. In the event of Wi-Fi disconnection or server failure, the Arduino continues to autonomously record data onto an SD card. Once the connection is restored, the data are synchronized, ensuring no information loss.

• Flexibility and scalability. The architecture is easily extendable — new sensors or actuators can be added, or additional greenhouses equipped with separate Arduino and ESP32 modules can be connected to the same central server. Energy efficiency and autonomy. Powered by solar panels and a rechargeable battery, the system can operate completely autonomously without a 220 V mains connection, which is particularly important for remote installations.

- Modularity. Each subsystem performs a clearly defined function, simplifying maintenance, repair, and system upgrades.

A fragment of the resulting table is shown in Figure 2.

J(Y2)	K(Y2)	L(Y2)	M(Y2)	N(Y2)	O(Y2)	P(Y2)	Q(Y2)	R(Y2)	S(Y2)	T(Y2)	U(Y2)	V(X3)	
thermo1	thermo2	thermo3	thermo4	thermo5	thermo6	thermo7	thermo8	relay1	relay2	relay3	relay4	Time (s)	T
C	C	C	C	C	C	C	C					s	
19,7	20,54	30,01	22,7	22,2	21,7	21,2	22,65	1	0	1	0	0	
19,7	20,59	30,01	22,69	22,2	21,7	21,21	22,87	1	0	1	0	10	1
19,7	20,27	30,02	22,69	22,2	21,7	21,21	22,36	1	0	1	0	20	3
19,7	20,52	30,02	22,69	22,2	21,7	21,22	22,69	1	0	1	0	30	
19,7	20,5	30,03	22,68	22,2	21,71	21,22	22,63	1	0	1	0	40	6
19,7	20,61	30,03	22,68	22,2	21,71	21,22	22,87	1	0	1	0	50	8
19,7	20,51	30,04	22,68	22,2	21,71	21,23	22,8	1	0	1	0	60	
19,7	20,56	30,04	22,68	22,2	21,71	21,23	22,69	1	0	1	0	70	1
19,7	20,55	30,05	22,67	22,2	21,71	21,23	22,67	1	0	1	0	80	1
19,7	20,61	30,05	22,67	22,2	21,71	21,24	22,81	1	0	1	0	90	
19,71	20,48	30,06	22,67	22,2	21,71	21,24	22,63	1	0	1	0	100	1
19,71	20,65	30,06	22,66	22,2	21,71	21,25	22,84	1	0	1	0	110	1
19,71	20,46	30,07	22,66	22,2	21,72	21,25	22,63	1	0	1	0	120	
19,71	20,57	30,07	22,66	22,2	21,72	21,25	22,8	1	0	1	0	130	2
19,71	20,56	30,08	22,66	22,2	21,72	21,26	22,79	1	0	1	0	140	2
19,71	20,77	30,08	22,65	22,2	21,72	21,26	22,93	1	0	1	0	150	
19,71	20,45	30,09	22,65	22,2	21,72	21,27	22,58	1	0	1	0	160	2
19,71	20,58	30,09	22,65	22,2	21,72	21,27	22,87	1	0	1	0	170	2
19,71	20,5	30,1	22,65	22,2	21,72	21,27	22,63	1	0	1	0	180	
19,71	20,41	30,1	22,64	22,19	21,72	21,28	22,66	1	0	1	0	190	3
19,71	20,6	30,1	22,64	22,19	21,73	21,28	22,84	1	0	1	0	200	3
19,71	20,43	30,11	22,64	22,19	21,73	21,28	22,65	1	0	1	0	210	
19,71	20,53	30,11	22,64	22,19	21,73	21,29	22,74	1	0	1	0	220	3
19,71	20,62	30,12	22,63	22,19	21,73	21,29	22,84	1	0	1	0	230	3
19,71	20,59	30,12	22,63	22,19	21,73	21,3	22,8	1	0	1	0	240	
19,71	20,55	30,12	22,63	22,19	21,73	21,3	22,8	1	0	1	0	250	4
19,71	20,34	30,13	22,62	22,19	21,73	21,3	22,51	1	0	1	0	260	4
19,71	20,46	30,13	22,62	22,19	21,73	21,31	22,61	1	0	1	0	270	
19,72	20,48	30,13	22,62	22,19	21,74	21,31	22,8	1	0	1	0	280	4
19,72	20,41	30,14	22,62	22,19	21,74	21,31	22,69	1	0	1	0	290	4
19,72	20,31	30,14	22,61	22,19	21,74	21,32	22,49	1	0	1	0	300	
19,72	20,54	30,14	22,61	22,19	21,74	21,32	22,78	1	0	1	0	310	5
19,72	20,6	30,15	22,61	22,19	21,74	21,32	22,87	1	0	1	0	320	5
19,72	20,48	30,15	22,61	22,19	21,74	21,33	22,64	1	0	1	0	330	
19,72	20,62	30,15	22,6	22,19	21,74	21,33	22,81	1	0	1	0	340	5
19,72	20,37	30,16	22,6	22,19	21,74	21,33	22,48	1	0	1	0	350	5
19,72	20,41	30,16	22,6	22,19	21,74	21,34	22,65	1	0	1	0	360	
19,72	20,54	30,16	22,6	22,19	21,75	21,34	22,79	1	0	1	0	370	6
19,72	20,47	30,16	22,59	22,19	21,75	21,34	22,68	1	0	1	0	380	6
19,72	20,6	30,17	22,59	22,19	21,75	21,35	22,77	1	0	1	0	390	
19,72	20,58	30,17	22,59	22,19	21,75	21,35	22,72	1	0	1	0	400	6
19,72	20,48	30,17	22,59	22,19	21,75	21,35	22,65	1	0	1	0	410	6

Figure 2. Fragment from the data acquisition system showing the measured parameters.

Measurement results were recorded at 10-second intervals. The obtained data were used to analyze the thermal processes occurring within individual components of the setup — including the heat exchange channel, paraffin layer, and air inside the greenhouse model — as well as to evaluate the efficiency of heat accumulation and the potential for its utilization.

Conclusion

The developed automated data acquisition system has demonstrated reliable and efficient performance during the thermophysical experiment. The modular architecture based on Arduino, ESP32, and Raspberry Pi 5 enables stable operation, flexible configuration, and scalability of the setup. The integration of autonomous solar power supply provides energy independence and suitability for remote applications. The recorded experimental data confirm the effectiveness of the designed system for monitoring heat exchange processes and assessing the performance of low-grade heat storage materials. The proposed approach can be extended to other thermal energy systems and applied in sustainable greenhouse technologies.

Тези відправлено: 21.10.2025 г.