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RASPBERRY PI 5-BASED MULTICHANNEL MEASUREMENT SYSTEM FOR GAS-FLOW RESISTANCE AND TEMPERATURE MONITORING IN A NATURAL ZEOLITE PACKED BED

***Grzegorz Walowski*[1], *Dorota Anders*[1], *Barbara Dybek*[1],**
***Vadym Ptashnyk*[2], *Serhiy Syrotyuk*[2]*, *Patryk Radek*[3]**
[1] *Institute of Technology and Life Sciences – National Research Institute,*
3 Hrabska Avenue, Falenty, 05-090 Raszyn, POLAND
[2]*Faculty of Mechanics, Energy and Information Technologies, Stepan Gzhytskyi*
National University of Veterinary Medicine and Biotechnologies of Lviv,
1 Volodymyra Velykoho Street, Dubliany, 79083, UKRAINE
[3]*Department of Optoelectronics, Faculty of Electrical Engineering,*
Silesian University of Technology,
2 Krzywoustego Str., 44-100 Gliwice, POLAND

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ABSTRACT

Background. Experimental characterization of granular beds for sorption thermal energy storage requires simultaneous measurement of gas-flow resistance and temperature using flexible multichannel data acquisition. This study developed a Raspberry Pi 5-supervised measurement system for a natural clinoptilolite packed bed.

Materials and Methods. Experiments were performed in a thermally insulated 0.5 m³ reactor containing a 0.4 m clinoptilolite bed with a particle-size fraction of 0.5–1.0 mm. Oxygen was used as the working gas. Pressure signals were processed by a miniSTM32-based subsystem, while ten Pt1000 sensors, ADG732 multiplexers, and an AD7124-4 converter were used for temperature monitoring. Three repeated series were performed at eight gas-flow settings. Pressure-flow data were analyzed using mean values, sample standard deviation, and linear regression; temperature-pressure relationships were evaluated by linear regression and Pearson correlation. A stationary two-dimensional MATLAB model was used to assess the thermal response.

Results. Functional operation of the platform was verified, including a 41-point comparison of three pressure channels showing close inter-channel agreement. Pressure drop ranged from 7.93 to 99.79 kPa, while the mean value increased from 25.49 to 93.41 kPa. Linear regression showed a significant positive pressure-flow relationship (R^2 = 0.840, p = 0.0014). Temperature remained within 16.83–16.92 °C, with no significant dependence on pressure drop. MATLAB-calculated mean temperatures differed from experimental means by no more than 0.08%, and the calculated temperature increase due to viscous dissipation was below 0.005 °C.

Conclusions. The developed system enables integrated measurement of gas-flow resistance and temperature in a natural clinoptilolite packed bed. Experimental and numerical results indicate that substantial changes in flow resistance were not accompanied by a detectable systematic temperature response under the investigated conditions. The architecture provides a basis for further studies of zeolite beds under controlled sorption conditions relevant to thermal energy storage.

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Keywords: embedded measurement system, Raspberry Pi 5, data acquisition, gas-flow resistance, natural zeolite, packed bed, thermal energy storage.

INTRODUCTION

The increasing integration of intermittent renewable energy sources and the need for more efficient use of industrial waste heat have intensified the demand for thermal energy storage technologies capable of decoupling heat generation from consumption. Among sensible, latent, and thermochemical storage concepts, sorption-based thermal energy storage is particularly attractive for long-term applications because energy can be stored through reversible adsorption–desorption processes with relatively high storage density and limited heat loss during the storage period. Zeolites are among the most extensively investigated sorption materials owing to their microporous structure, high affinity for polar adsorbates such as water vapor, thermal stability, and cyclic adsorption capability [1–5].

Both synthetic and naturally occurring zeolites have been investigated for thermochemical heat storage. Synthetic zeolite 13X generally exhibits high water uptake and favorable sorption performance, whereas natural zeolites are of interest because of their availability and potentially lower material cost. Recent studies have shown that the practical performance of zeolite-based storage systems depends not only on intrinsic sorption properties but also on heat and mass transfer conditions within the granular bed [1–3]. Consequently, the characterization of natural zeolite beds under controlled gas-flow conditions remains relevant when such materials are considered for thermal energy storage reactors.

In packed-bed reactors, gas-flow conditions directly influence pressure loss, mass transfer, and the spatial and temporal evolution of the temperature field. Experimental and numerical studies of zeolite reactors have demonstrated the importance of airflow rate, humidity, reactor geometry, and axial position for the resulting thermal response [6, 7]. Pressure drop is also an essential reactor-design parameter because it determines flow resistance and affects the energy required to transport the working fluid through the bed. Its magnitude depends on particle size and shape, bed porosity and dimensions, fluid properties, and superficial velocity; therefore, reliable simultaneous measurements of gas flow and pressure at representative locations are necessary for adequate packed-bed characterization [8].

Temperature measurements provide complementary information on heat-transfer processes occurring inside a packed bed. Modern experimental studies increasingly employ spatially distributed temperature sensing rather than relying exclusively on inlet and outlet temperatures. Such measurements allow thermal fronts, temperature gradients, and reaction zones to be identified and related to operating conditions [9,10]. In zeolite sorption reactors in particular, high-resolution intra-reactor temperature profiling has recently been used to characterize reaction-zone propagation and its relationship with thermal output [10]. These results indicate that a multichannel measurement system capable of acquiring temperature data at several positions within the bed can provide substantially more information than a single-point temperature measurement.

The implementation of such experiments requires a data acquisition system capable of integrating heterogeneous measurement channels, including resistive temperature sensors and pressure transducers, with signal conditioning, analog-to-digital conversion, data logging, and subsequent processing. Single-board computers such as the Raspberry Pi can serve as a supervisory acquisition and processing platform, while dedicated analog front-end circuits and microcontroller-based modules perform sensor-specific signal conditioning and low-level measurement tasks [11–15]. Such a distributed architecture provides flexibility for multichannel experiments and facilitates the integration of different sensor interfaces within a common measurement environment.

Despite considerable progress in both zeolite-based thermal storage characterization and embedded data acquisition technologies, these two research directions are commonly addressed separately. Experimental studies of granular sorption beds require simultaneous information on gas-flow resistance and temperature behavior,

whereas the acquisition of spatially distributed data demands a flexible multichannel measurement architecture. Integrating these functions within a dedicated embedded platform can facilitate experimental characterization of zeolite beds and provide a basis for further monitoring and control of thermal storage systems.

Therefore, the aim of this study was to develop and experimentally evaluate a multichannel embedded measurement system, supervised by a Raspberry Pi 5, for the characterization of a natural zeolite packed bed intended for thermal energy storage applications. The system integrates pressure and temperature measurement channels, dedicated signal-processing electronics, and embedded data acquisition. The experimental study focused on gas-flow resistance and temperature behavior in a 0.5 m³ reactor filled with a 0.5–1.0 mm zeolite fraction. A MATLAB-based numerical model was additionally used for preliminary simulation and visualization of the temperature distribution.

MATERIALS AND METHODS

Experimental setup and test material

The experimental investigations were carried out using a thermally insulated cylindrical reactor with a nominal internal volume of 0.5 m³ (**Fig. 1**). The reactor was manufactured from AISI 304 stainless steel and had an internal diameter of 0.71 m, a maximum internal height of 1.25 m, and a wall thickness of 0.8 mm. The total mass of the reactor was approximately 20 kg. The reactor was installed on a mobile platform and thermally insulated to reduce heat exchange with the surroundings during the experiments.

The gas supply was introduced through a single 8 mm diameter inlet located at the bottom of the reactor, whereas the outlet of the same diameter was located in the upper cover. The pressure was monitored at the reactor inlet and outlet and at five levels along the bed height. At each internal measurement level, pressure readings were obtained from four circumferentially distributed pressure ports and averaged to characterize the local pressure conditions within the bed. The gas flow rate was measured using an Aalborg SMR1 glass-tube rotameter installed at the reactor outlet. For the 0–150 mm scale configuration, the manufacturer specifies an accuracy of ±2% of full scale and a repeatability of ±0.25%. Oxygen was supplied from a compressed-gas cylinder through a pressure regulator and used as the working gas during the permeability experiments.



Fig. 1. Experimental test stand with the thermally insulated 0.5 m³ cylindrical reactor used for gas-flow and temperature measurements in the zeolite packed bed

Natural clinoptilolite of volcanic origin from a Slovak deposit, with a particle-size fraction of 0.5–1.0 mm, was used as the granular bed material. During the reported experiments, the zeolite bed height was 0.4 m. The loose bulk density of the zeolite was 0.82 g cm^{-3}, while the geometrically determined interparticle bed porosity was $\varepsilon = 0.41$. Measurements of volumetric gas flow rate V', pressure drop ΔP, and temperature T were performed under single-phase gas-flow conditions. The data obtained were subsequently used to characterize the relationship between gas-flow rate and flow resistance and to analyze the thermal response of the zeolite bed.

Measurement system and data acquisition

A multichannel measurement and data acquisition system was developed with the Raspberry Pi 5 acting as the supervisory acquisition and processing platform. The system was organized into two main measurement branches: a pressure-measurement subsystem and a multichannel temperature-measurement subsystem. Sensor-specific signal processing was performed at the lower hardware level, whereas the Raspberry Pi 5 provided integration of the measurement channels, communication with peripheral modules, data acquisition, and subsequent data handling. A dedicated measurement board was designed, assembled, and commissioned for this purpose. The functional architecture of the developed measurement and data acquisition system is shown in **Fig. 2**. During functional testing, the power supply, communication interfaces, and operational stability of the hardware were verified. The measurement application provided the communication interfaces required by the implemented subsystems, including SPI for communication with the AD7124-4 converter and an asynchronous serial interface using the Modbus RTU protocol for communication with the miniSTM32-based pressure

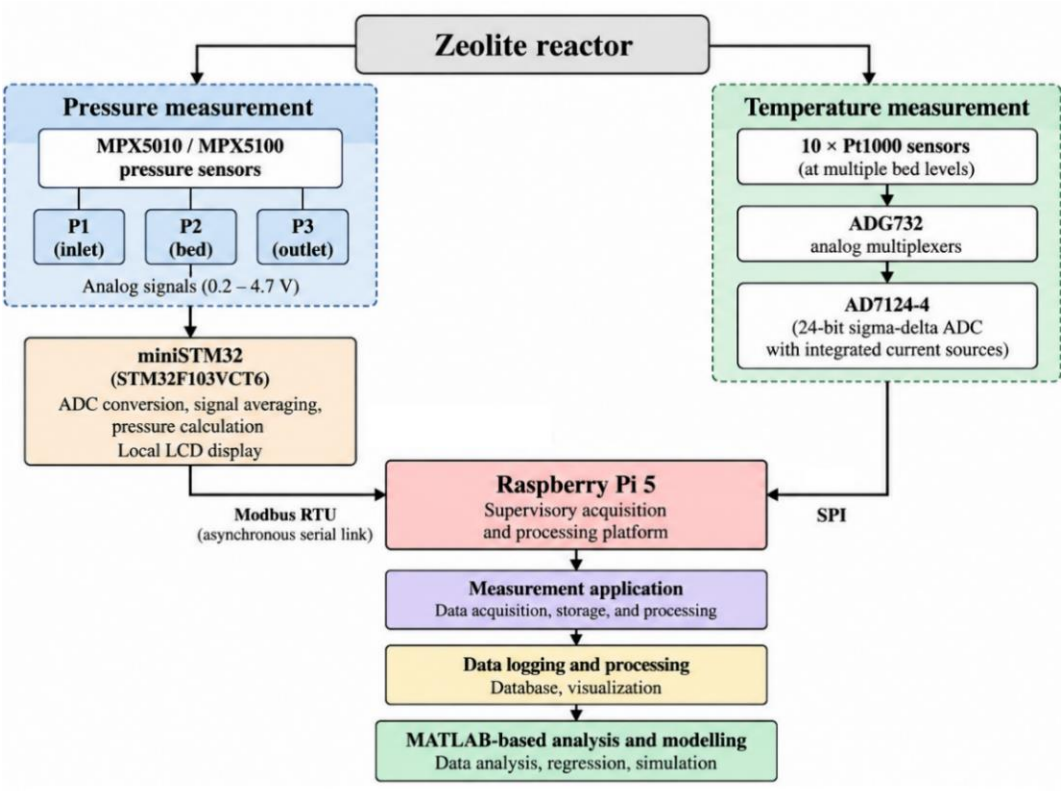


Fig. 2. Functional architecture of the embedded measurement and data acquisition system for pressure and multichannel temperature monitoring of the zeolite packed bed

subsystem. The three pressure-measurement channels were designated P1, P2, and P3, corresponding to the reactor inlet, the zeolite bed, and the reactor outlet, respectively.

The main components, their functions, and their integration within the measurement system are summarized in **Table 1**.

Semiconductor differential pressure sensors of the MPX5010 or MPX5100 series were used depending on the required measurement range (10 or 100 kPa). The sensors incorporate temperature-compensated piezoresistive sensing elements and integrated signal amplification. According to the manufacturer's specifications, the nominal transfer characteristics of the sensors can be expressed as:

$$V_{OUT} = V_S(kP + 0.004), \tag{1}$$

where V_{OUT} is the sensor output voltage, V_S is the supply voltage, P is the differential pressure, and k is the pressure-sensitivity coefficient equal to 0.09 kPa^{-1} for the MPX5010 and 0.009 kPa^{-1} for the MPX5100. The output-voltage tolerance specified for the sensor characteristic is ± 5% of the full-scale output span V_{FSS}, which is typically 4.50 V at V_S = 5.00 V.

Table 1. **Main components and functional organization of the measurement system**

Component / subsystem	Function	Configuration / interface	System integration
Pt1000 sensors	Temperature measurement	10 sensors: 1 at the inlet, 8 within the zeolite bed, and 1 at the outlet; three-wire connection	Connected to the temperature measurement chain through the ADG732 multiplexers and AD7124-4 converter
ADG732	Temperature-channel selection	Multichannel analog multiplexer	Provides sequential selection of Pt1000 channels for subsequent analog-to-digital conversion
AD7124-4	Pt1000 signal conditioning and analog-to-digital conversion	24-bit sigma-delta ADC; communication with Raspberry Pi 5 via SPI	Provides digital temperature data to the central acquisition platform
MPX5010 / MPX5100 pressure sensors	Differential pressure measurement	Measurement ranges of 10 and 100 kPa, respectively; three acquisition channels: P1, P2, and P3, analog output	Sensor signals supplied to the miniSTM32-based pressure-processing subsystem
miniSTM32 module	Processing of pressure-sensor signals	STM32F103VCT6-based subsystem; ADC conversion and signal averaging, Modbus RTU serial communication	Digitizes and processes pressure-sensor signals and transmits calculated pressure values to the supervisory acquisition system
Raspberry Pi 5	Centralized data acquisition and processing	Central computing platform; SPI and Modbus RTU serial communication	Integrates the temperature and pressure measurement subsystems and provides data logging and subsequent processing

For a supply voltage of 5.00 V, the nominal zero-pressure output voltage is 0.200 V. However, the experimentally determined zero-offset voltages of the sensors used in the measurement system were 0.182 V for the inlet channel, 0.176 V for the bed channel, and 0.182 V for the outlet channel. In addition, the sensor output signals were adjusted to the input-voltage range of the microcontroller ADC by a signal-level matching circuit. To account for the individual zero-offset deviations and the signal-conditioning stage, a corrected linear characteristic was determined separately for each pressure-measurement channel:

$$P = A \cdot U_{ADCIN} + B, \tag{2}$$

where P is the calculated pressure, U_{ADCIN} is the conditioned voltage applied to the ADC input, and A and B are channel-specific correction coefficients. The experimentally determined parameters of the three pressure-measurement channels are summarized in **Table 2**.

Pressure-sensor signals were processed using a miniSTM32 module based on the STM32F103VCT6 microcontroller. The three analog sensor signals were connected to the microcontroller ADC inputs, converted into digital form, averaged, and and subsequently converted to pressure values using the corrected channel characteristics given by Eq. (2). The calculated pressure values were displayed locally on the integrated LCD and transmitted to the supervisory data-acquisition system through an asynchronous serial link using the Modbus RTU protocol.

The temperature-measurement branch was based on ten Pt1000 platinum resistance temperature sensors. One sensor was installed at the reactor inlet and one at the outlet, while eight sensors were distributed vertically within the zeolite bed to obtain spatially resolved temperature information. The sensors operated in a three-wire configuration to reduce the influence of lead resistance. The Pt1000 measurement circuit used precision excitation current sources integrated into the AD7124-4 to convert sensor-resistance variations into voltage signals suitable for differential measurement and subsequent analog-to-digital conversion. Individual measurement channels were selected through ADG732 analog multiplexers, while signal conditioning and analog-to-digital conversion were performed using a 24-bit sigma-delta AD7124-4 converter interfaced with the Raspberry Pi 5 via SPI. The temperature acquisition circuitry was implemented as a dedicated shield for the Raspberry Pi platform, thereby providing a compact multichannel front end for monitoring the temperature distribution within the reactor.

At the system level, the Raspberry Pi 5 therefore acted as the common integration point for the pressure and temperature measurement branches. The pressure subsystem communicated with the supervisory platform through Modbus RTU, whereas the AD7124-4 temperature-conversion subsystem was interfaced through SPI. This separation between sensor-specific front-end electronics and the supervisory acquisition platform allows heterogeneous measurement channels to be incorporated into a single embedded system while retaining dedicated signal-processing paths for different sensor types.

Table 2. **Parameters of the corrected pressure-measurement channel characteristics**

Pressure channel	UOUT, V	UADCIN, V	A, Pa/V	B, Pa
P1 (inlet)	0.182	0.126	3209.877	−404.444
P2 (bed)	0.176	0.122	3205.829	−391.111
P3 (outlet)	0.182	0.127	3184.602	−404.444

Generalized cyber-resilience model synthesized from the literature

Gas-flow experiments were performed with the reactor filled with a 0.4 m layer of natural zeolite with a particle-size fraction of 0.5–1.0 mm. Oxygen was supplied to the bottom of the reactor through the pressure regulator, passed upward through the granular bed, and discharged through the outlet in the reactor cover. Three repeated measurement series were performed. Each series comprised eight gas-flow settings, for which the volumetric flow rate V', pressure drop ΔP, and temperature T were recorded. The same set of volumetric flow-rate values was used in all three series, enabling comparison of the repeatability of the measured pressure and temperature responses.

Prior to the packed-bed experiments, the agreement between the three pressure-measurement channels was evaluated by applying identical pressure conditions to the sensor inputs and comparing the calculated pressure values for channels P1, P2, and P3. The differences P1 – P2, P1 – P3, and P2 – P3 were determined for each test point. This procedure was used to assess inter-channel consistency after application of the individual correction characteristics.

The experimental data were analyzed in terms of two principal relationships: the dependence of pressure drop on volumetric gas-flow rate, $\Delta P = f(V')$, and the dependence of measured temperature on pressure drop, $T = f(\Delta P)$. For each of the eight gas-flow settings, the pressure-drop measurements from the three repeated measurement series were summarized using the arithmetic mean and sample standard deviation (SD, $n = 3$). The pressure-flow relationship was evaluated using linear regression applied to the mean pressure-drop values obtained at the eight gas-flow settings. The goodness of fit was assessed using the coefficient of determination R^2, and the statistical significance of the regression slope was evaluated using a two-sided test with a significance level of $p < 0.05$.

Because the measured temperature variations were small compared with the range of pressure changes, the $T = f(\Delta P)$ data were analyzed separately to determine whether a systematic relationship between the two variables could be identified. Linear regression and the Pearson correlation coefficient *r* were used to evaluate the direction and strength of the relationship. Statistical significance was assessed using a two-sided test with a significance level of $p < 0.05$. Statistical processing of the tabulated experimental data was performed using Python 3.13 with the NumPy and SciPy libraries.

In addition to the experimental data analysis, a stationary two-dimensional numerical model of energy and momentum balance in the porous zeolite bed was implemented in MATLAB. The model was used to evaluate whether the experimentally observed weak relationship between pressure drop and bed temperature was physically consistent with the expected thermal response of the system. The energy balance included heat generation associated with viscous dissipation of the gas flow and convective heat transfer through the reactor walls. The calculated mean bed temperatures were subsequently compared with the corresponding experimental mean temperatures obtained for the three measurement series.

RESULTS AND DISCUSSION

Measurement system implementation and functional evaluation

The proposed measurement architecture was implemented as a dedicated hardware and software platform for the experimental reactor. The custom measurement board was designed, assembled, and commissioned for operation with the Raspberry Pi 5. Initial verification included inspection of the assembled circuitry, replacement of faulty components where required, and functional testing of the power supply and communication interfaces. Particular attention was given to the SPI interface used by the AD7124-4 temperature-conversion subsystem, whose operation was successfully verified during commissioning. The miniSTM32-based pressure subsystem was also integrated

with the supervisory acquisition platform, including analog-to-digital conversion of the pressure-sensor signals, signal averaging, calculation of pressure values using the corrected channel characteristics, local visualization on the LCD, and data transmission through the Modbus RTU serial link.

The functional consistency of the three pressure-measurement channels was evaluated under identical pressure conditions. A total of 41 comparison points were recorded for channels P1, P2, and P3. As shown in **Fig. 3a**, the three channels followed the same imposed pressure profile over the complete set of 41 comparison points. Because the pressure values obtained from the individual channels were very close, the

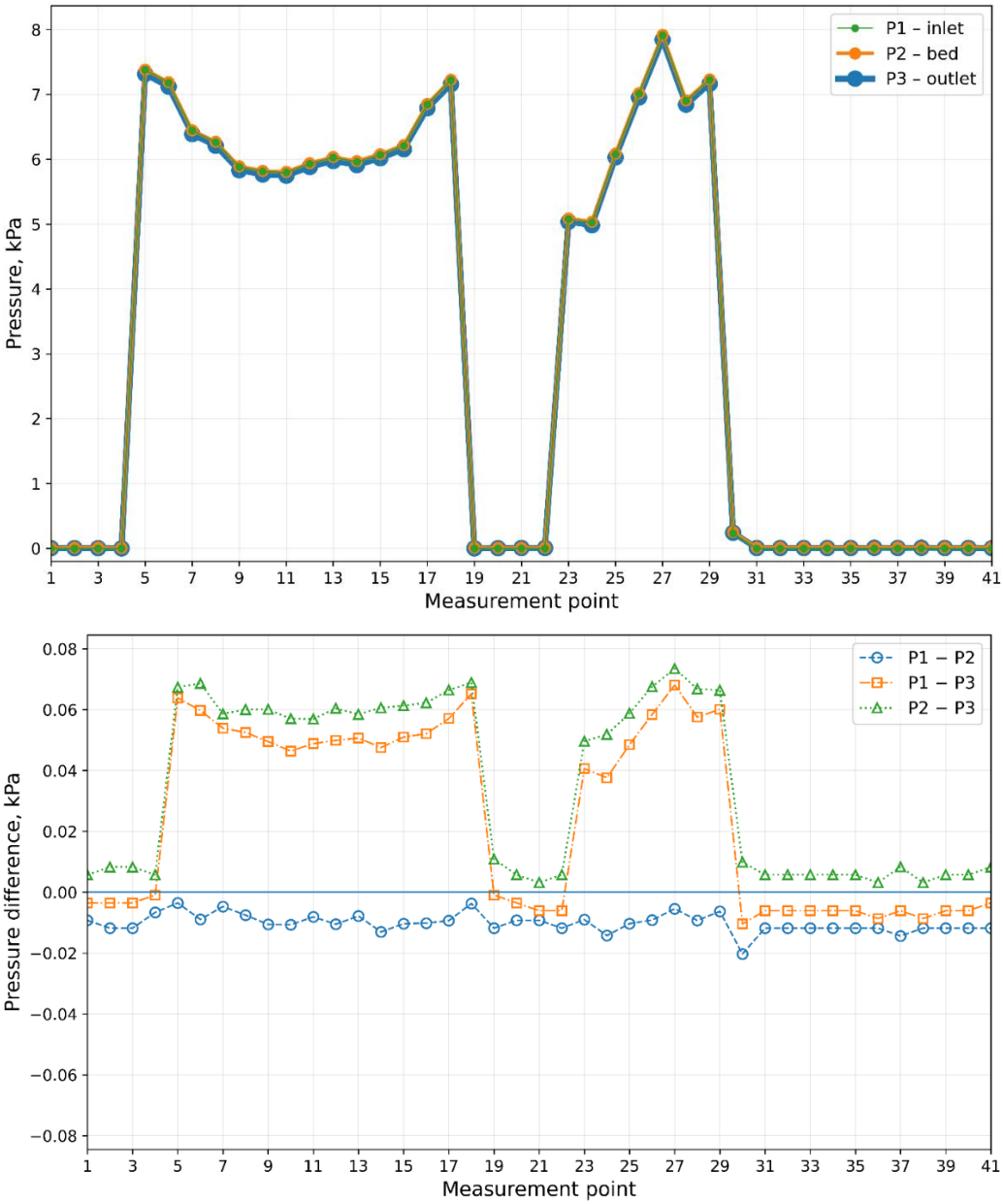


Fig. 3. Inter-channel comparison of pressure measurements under identical applied-pressure conditions: (a) pressure readings of channels P1, P2, and P3; (b) pairwise differences between the pressure-channel readings

curves largely overlapped. The pairwise differences shown in **Fig. 3b** provide a more detailed representation of the inter-channel deviations. The comparison revealed a small but systematic channel-dependent offset, particularly between P3 and the other two channels, supporting the use of individual correction characteristics. The comparison also revealed persistent channel-dependent offsets, particularly between P3 and channels P1 and P2, supporting the use of the individual correction characteristics. Since the verification procedure was based on comparison of the three channels under identical input conditions rather than against an independent reference pressure instrument, the results are interpreted as an assessment of inter-channel consistency rather than absolute measurement accuracy.

The AD7124-4-based temperature-acquisition subsystem was integrated with the Raspberry Pi 5 measurement application, and Pt1000 temperature measurements were tested as part of the commissioning procedure. Functional testing confirmed operation of the multichannel temperature-measurement path, including channel selection through the ADG732 multiplexers, signal conditioning and 24-bit analog-to-digital conversion using the AD7124-4, and data acquisition at the Raspberry Pi level.

The functional tests therefore confirmed operation of both measurement branches and their integration within the common supervisory platform. The pressure subsystem provided corrected and averaged pressure values through the miniSTM32/Modbus RTU acquisition path, while the temperature subsystem provided spatially distributed Pt1000 measurements through the AD7124-4/SPI path. Following commissioning and inter-channel verification, the integrated system was used to acquire pressure and temperature data during the zeolite packed-bed experiments, while the corresponding volumetric gas-flow rate was measured independently using the outlet rotameter.

Gas-flow resistance and thermal response of the zeolite bed

The experimental results obtained for the natural zeolite fraction of 0.5–1.0 mm and a bed height of 0.4 m are presented in **Fig. 4**. Three repeated measurement series were performed using the same eight volumetric oxygen-flow settings. Over the investigated range of $V' = 3.83 \cdot 10^{-9}$ to $3.07 \cdot 10^{-8}$ m³·s⁻¹, the measured pressure drop ranged from 7.93 to 99.79 kPa. Although the overall pressure drop increased with increasing gas-flow rate, the individual measurement series exhibited different degrees of nonlinearity and scatter (**Fig. 4a**). The mean pressure drop calculated from the three series increased from 25.49 kPa at the lowest flow setting to 93.41 kPa at the highest setting. Linear regression of the mean values showed a significant positive relationship between volumetric flow rate and pressure drop $R^2 = 0.840$, $p = 0.0014$. The variability between the individual measurement series was particularly pronounced at the lower flow rates, indicating that the repeatability of the experimental pressure-drop response should be considered when interpreting the gas-flow characteristics of the bed.

The observed overall increase in pressure drop with gas-flow rate is consistent with the expected gas-flow resistance behavior of a granular packed bed. However, the available data characterize the overall flow resistance rather than directly determining the intrinsic permeability of the zeolite bed. A quantitative interpretation using Darcy- or Ergun-type relations would additionally require parameters such as superficial gas velocity, bed porosity, gas properties, and an appropriate flow-regime criterion [8]. Therefore, the present results are interpreted primarily as an experimental characterization of the relationship between gas-flow rate and pressure loss in the investigated zeolite bed.

In contrast to the pressure response, the temperature remained within a very narrow range throughout the experiments (**Fig. 4b**). Across all 24 measurement points, the recorded temperature varied from 16.83 to 16.92 °C, corresponding to a total variation of only 0.09 °C and an overall mean value of approximately 16.88 °C. Identical or nearly identical temperature values were observed at substantially different pressure drops. This

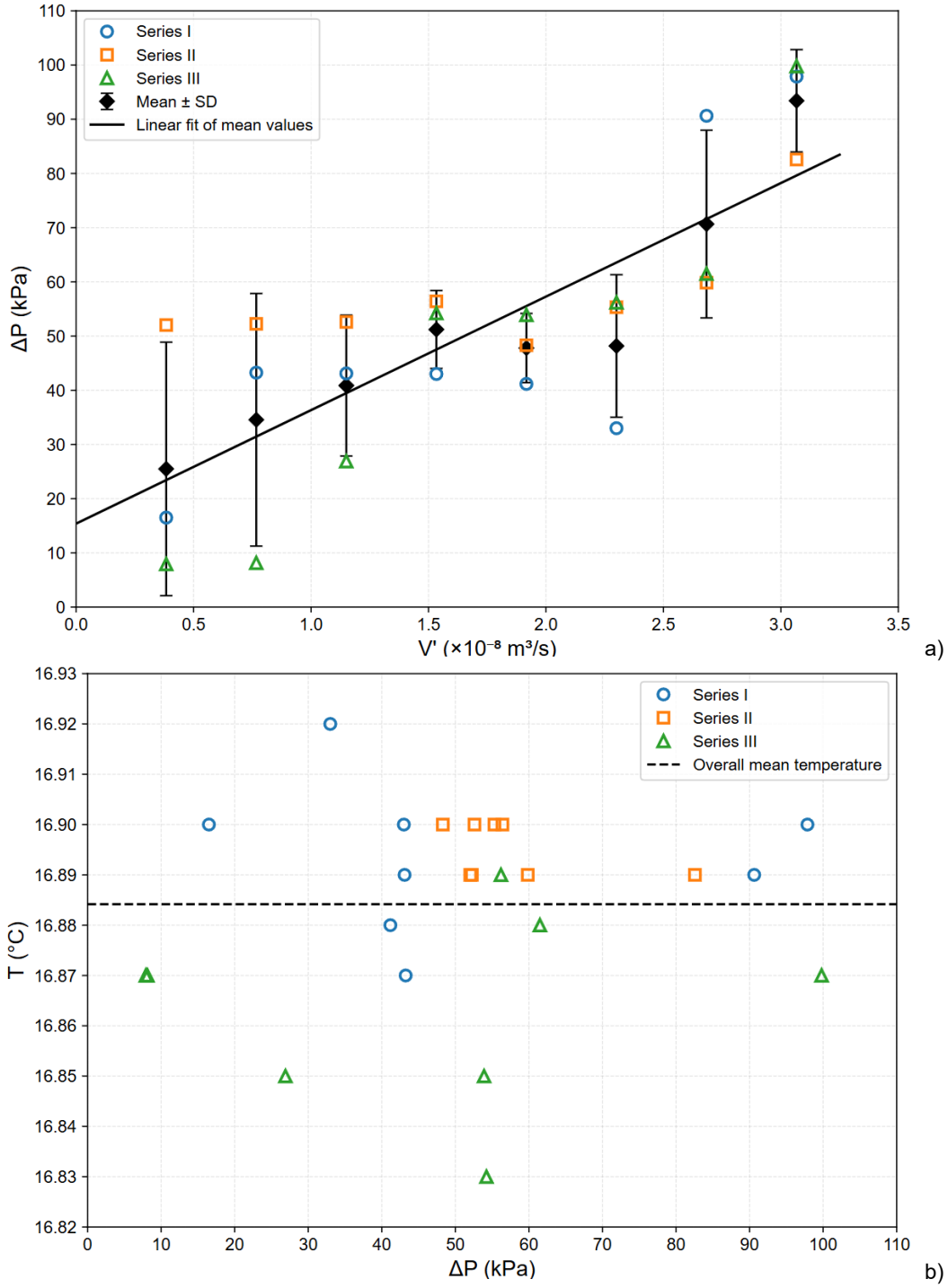


Fig. 4. Experimental characteristics of the natural zeolite packed bed (particle-size fraction 0.5–1.0 mm, bed height 0.4 m): (a) pressure drop versus volumetric oxygen-flow rate, with mean ± SD and linear regression; (b) temperature versus pressure drop, with the overall mean temperature

indicates that changes in the hydraulic resistance of the packed bed were not accompanied by a measurable change in its thermal state under the investigated conditions. Linear regression performed separately for measurement series I, II, and III

resulted in R^2 values of 0.007, 0.180, and 0.004, respectively. In all cases, the relationship was statistically non-significant $p > 0.29$. Analysis of all experimental points together also showed only a negligible correlation between pressure drop and temperature $r = 0.107$, $R^2 = 0.012$, $p = 0.618$. The measured temperature values therefore do not support a monotonic dependence of T on ΔP.

The MATLAB model provided results consistent with the experimentally observed thermal stability of the bed. A comparison of the experimental and MATLAB-calculated mean temperatures for the three measurement series is presented in **Table 3**. The calculated mean temperatures were 16.885, 16.889, and 16.878 °C for measurement series I, II, and III, respectively, compared with the corresponding experimental mean values of 16.891, 16.894, and 16.866 °C. The resulting relative differences did not exceed 0.08%. The model further indicated that the temperature increase associated with viscous dissipation under the investigated flow conditions was below 0.005 °C. This calculated contribution is substantially smaller than the experimentally observed temperature range and supports the conclusion that changes in pressure drop were not accompanied by a detectable systematic thermal response under the investigated conditions.

The observed behavior is also consistent with the broader literature on heat and mass transfer in porous beds. Numerical studies of zeolite-based thermochemical reactors have shown that the thermal response depends strongly on operating conditions, including inlet-gas flow rate and sorbate content [16]. At the particle–pore scale, heat transfer in packed beds is additionally affected by bed porosity, pore structure, and local flow conditions [17]. Although the operating conditions considered in these studies differ from those of the present experiments, their results support the interpretation that the thermal response of a packed bed cannot be inferred from pressure drop alone.

The physical interpretation of this result is that the pressure drop and temperature describe different aspects of the packed-bed behavior. The pressure drop reflects the resistance encountered by the gas flowing through the granular material and therefore varies strongly with the gas-flow conditions. In the present experiments, however, this hydraulic response did not produce a detectable thermal response of the bed, which is also consistent with the numerical results described above. Consequently, repeated temperature values at different pressure drops should not be regarded as anomalous; rather, they indicate that the bed remained approximately thermally stable while its gas-flow resistance changed substantially. Since the observed temperature differences are only of the order of hundredths of a degree Celsius, their interpretation should also take into account the resolution, rounding, and measurement uncertainty of the complete Pt1000 acquisition chain. Until the uncertainty of the complete Pt1000 acquisition chain is quantified, such small differences should not be interpreted as evidence of a separate thermal effect.

CONCLUSIONS

A multichannel embedded measurement system supervised by a Raspberry Pi 5 was developed and functionally evaluated for experimental characterization of a natural zeolite packed bed. The system integrates a miniSTM32-based pressure-measurement

Table 3. **Comparison of experimental and MATLAB-calculated mean temperatures**

Measurement series	ΔP range, kPa	Texp, °C	TMATLAB, °C	Relative difference, %
Series I	16.4–97.9	16.891	16.885	0.035
Series II	48.2–82.6	16.894	16.889	0.029
Series III	8.0–99.8	16.866	16.878	0.071
Overall	8.0–99.8	16.884	16.884	0.000

subsystem with a ten-channel Pt1000 temperature-measurement subsystem based on ADG732 analog multiplexers and an AD7124-4 analog-to-digital converter. Inter-channel verification of the three pressure channels under identical applied-pressure conditions showed close agreement over 41 comparison points, while the observed small channel-dependent deviations supported the use of individual correction characteristics.

Experiments performed with a 0.4 m bed of natural zeolite with a particle-size fraction of 0.5–1.0 mm showed an overall increase in pressure drop with increasing gas-flow rate, although noticeable variability was observed between the three repeated measurement series. The mean pressure drop increased from 25.49 to 93.41 kPa across the investigated gas-flow settings, and linear regression of the mean values confirmed a statistically significant positive relationship R^2 = 0.840, p = 0.0014. The obtained data characterize the overall gas-flow resistance of the investigated packed bed; determination of intrinsic permeability and quantitative interpretation using Darcy- or Ergun-type relations would require additional information on the bed structure and gas-flow conditions.

The measured temperature remained within 16.83–16.92 °C and showed no statistically significant dependence on pressure drop. Thus, substantial changes in gas-flow resistance were not accompanied by a detectable systematic temperature response under the investigated conditions. The developed platform can therefore serve as a basis for further experimental studies of zeolite packed beds, including tests under controlled adsorption–desorption conditions relevant to thermal energy storage. Further development should include metrological characterization of the measurement channels and more detailed analysis of packed-bed flow and thermal behavior.

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COMPLIANCE WITH ETHICAL STANDARDS

The authors declare that they have no competing interests.

AUTHOR CONTRIBUTIONS

Conceptualization, [G.W., D.A., B.D.]; methodology, [G.W., D.A., P.R.]; software, [V.P., S.S., P.R.]; validation, [G.W., D.A., B.D., P.R.]; formal analysis, [V.P., S.S.]; investigation, [G.W., D.A., B.D.]; data curation, [G.W., D.A., V.P.]; writing – original draft preparation, [G.W., D.A., B.D., V.P.]; writing – review and editing, [V.P., S.S., P.R.]; visualization, [V.P.]; supervision, [G.W., S.S.].

All authors have read and agreed to the published version of the manuscript.

REFERENCES

[1] Feng, C., E, J., Han, W., Deng, Y., Zhang, B., Zhao, X., & Han, D. (2021). Key technology and application analysis of zeolite adsorption for energy storage and heat-mass transfer process: A review. Renewable and Sustainable Energy Reviews, 144, 110954. https://doi.org/10.1016/j.rser.2021.110954

[2] de Gennaro, B., Cappi, A., de Gennaro, M., Bianco, N., Langella, A., Cappelletti, P., Marocco, A., Aprea, P., & Pansini, M. (2022). Use of zeolites in the capture and storage of thermal energy by water desorption–adsorption cycles. Materials, 15(16), 5574. https://doi.org/10.3390/ma15165574

[3] Kouchachvili, L., Bardy, D. A., Djebbar, R., & Hogg, L. E. W. (2023). Natural zeolites as host matrices for the development of low-cost and stable thermochemical energy storage materials. Journal of Porous Materials, 30, 163–173. https://doi.org/10.1007/s10934-022-01277-3

[4] Abedin, A. H., & Rosen, M. A. (2012). Closed and open thermochemical energy storage: Energy- and exergy-based comparisons. Energy, 41(1), 83–92. https://doi.org/10.1016/j.energy.2011.06.034
[5] Yu, N., Wang, R. Z., & Wang, L. W. (2013). Sorption thermal storage for solar energy. Progress in Energy and Combustion Science, 39(5), 489–514. https://doi.org/10.1016/j.pecs.2013.05.004
[6] Gao, S., Wang, S., Hu, P., Wang, J., Sun, Y., & Ma, Z. (2023). Performance of sorption thermal energy storage in zeolite bed reactors: Analytical solution and experiment. Journal of Energy Storage, 64, 107154. https://doi.org/10.1016/j.est.2023.107154
[7] Kim, H., Hong, S. K., Kang, J. G., Moon, S. W., Kim, G. H., Yoon, S., Wei, D. J., Moon, H., & Kim, B. S. (2024). Exploration adsorption characteristics of zeolite 13X depending on humidity and flow rate in sorption thermal energy storage applications. International Journal of Heat and Mass Transfer, 221, 125049. https://doi.org/10.1016/j.ijheatmasstransfer.2023.125049
[8] Hassan, E. B. E., & Hoffmann, J. (2024). Review on pressure drop through a randomly packed bed of crushed rocks. Discover Applied Sciences, 6, 126. https://doi.org/10.1007/s42452-024-05773-w
[9] Ahmed, Z., Constantin, A., & Bindra, H. (2022). The thermal response of a packed bed thermal energy storage system upon saturated steam injection using distributed temperature sensing. Energies, 15(10), 3704. https://doi.org/10.3390/en15103704
[10] Wang, T., Wang, Y., Zhang, Y., & Chen, Y. (2026). Reaction zone evolution governing thermal output in a zeolite 13X sorption reactor: An experimental study. Energies, 19(8), 1874. https://doi.org/10.3390/en19081874
[11] Knapp, A., & Bloom, A. J. (2022). Easy as piadcs: A low-cost, ultra-high-resolution data acquisition system using a Raspberry Pi. Applications in Plant Sciences, 10(3), e11485. https://doi.org/10.1002/aps3.11485
[12] Véliz, M. E., Real, G. E., & Otero, A. D. (2024). Flexible and configurable embedded electrical energy measurement system to acquire and process high-frequency features. HardwareX, 19, e00539. https://doi.org/10.1016/j.ohx.2024.e00539
[13] Evangelisti, L., De Cristo, E., Monteleone, S., Guattari, C., Gori, P., Pini, I., de Rubeis, T., & Ambrosini, D. (2025). A new customized measurement system for a non-contact, enhanced thermometric method. Energies, 18(6), 1537. https://doi.org/10.3390/en18061537
[14] Amorim, M. L. M., Ando Junior, O. H., Gazziro, M., & Carmo, J. P. P. (2026). Nexus: A modular open-source multichannel data logger – Architecture and proof of concept. Automation, 7(1), 25. https://doi.org/10.3390/automation7010025
[15] Payet, P., Fakra, D. A. H., Rakotosaona, R., Ratsimba, M. H., & Randrianarison, M. P. (2025). Design of a highly affordable and reliable data acquisition unit system dedicated to experimental research and education. Measurement, 251, 117187. https://doi.org/10.1016/j.measurement.2025.117187
[16] Abohamzeh, E., & Frey, G. (2022). Numerical investigation of the adsorption process of zeolite/water in a thermochemical reactor for seasonal heat storage. Energies, 15(16), 5944. https://doi.org/10.3390/en15165944
[17] Zou, Y., Kuang, S., Wu, Y., & Yu, A. (2025). Particle-pore-scale modelling and analysis of heat transfer in packed beds: Effects of bed porosity and pore structure. Applied Thermal Engineering, 279, 127601. https://doi.org/10.1016/j.applthermaleng.2025.127601

БАГАТОКАНАЛЬНА ВИМІРЮВАЛЬНА СИСТЕМА НА БАЗІ RASPBERRY PI 5 ДЛЯ ДОСЛІДЖЕННЯ ОПОРУ ГАЗОВОМУ ПОТОКУ ТА МОНІТОРИНГУ ТЕМПЕРАТУРИ В ШАРІ ПРИРОДНОГО ЦЕОЛІТУ

Ґжегож Вальовські[1], Дорота Андерс[1], Барбара Дибек[1], Вадим Пташник[2], Сергій Сиротюк[2]*, Патрик Радек[3]
[1]Інститут технологічних та природничих наук — Національний дослідний інститут, вул. Грабська, 3, Фаленти, 05-090 Рашин, ПОЛЬЩА
[2]Факультет механіки, енергетики та інформаційних технологій, Львівський національний університет ветеринарної медицини та біотехнологій імені С. З. Ґжицького, вул. Володимира Великого, 1, м. Дубляни, 79083, УКРАЇНА
[3]Кафедра оптоелектроніки, Факультет електротехніки, Сілезька політехніка, вул. Болеслава Кривоустого, 2, 44-100 м. Глівіце, ПОЛЬЩА

АНОТАЦІЯ

Вступ. Експериментальне дослідження гранульованих шарів для сорбційного акумулювання теплової енергії потребує одночасного вимірювання опору газовому потоку та температури із застосуванням гнучкої багатоканальної системи збору даних. У роботі розроблено вимірювальну систему під керуванням Raspberry Pi 5 для дослідження шару природного кліноптилоліту.

Матеріали та методи. Експерименти проводили в теплоізольованому реакторі об'ємом 0,5 м³, що містив шар кліноптилоліту висотою 0,4 м із фракцією частинок 0,5–1,0 мм. Робочим газом був кисень. Сигнали тиску оброблялися підсистемою на базі miniSTM32, тоді як для моніторингу температури використовували десять датчиків Pt1000, мультиплексори ADG732 та перетворювач AD7124-4. Було виконано три повторні серії вимірювань за восьми значень витрати газу. Дані залежності тиску від витрати аналізували з використанням середніх значень, вибіркового стандартного відхилення та лінійної регресії; залежність температури від перепаду тиску оцінювали за допомогою лінійної регресії та коефіцієнта кореляції Пірсона. Для оцінювання температурної реакції використовували стаціонарну двовимірну модель, реалізовану в MATLAB.

Результати. Функціональну працездатність платформи було перевірено, зокрема шляхом порівняння трьох каналів вимірювання тиску в 41 контрольній точці, яке показало добру міжканальну узгодженість. Перепад тиску змінювався від 7,93 до 99,79 кПа, тоді як його середнє значення зросло від 25,49 до 93,41 кПа. Лінійна регресія показала статистично значущий позитивний зв'язок між витратою газу та перепадом тиску (R^2 = 0,840, p = 0,0014). Температура залишалася в межах 16,83–16,92 °C, при цьому статистично значущої залежності від перепаду тиску не виявлено. Середні значення температури, розраховані в MATLAB, відрізнялися від експериментальних не більше ніж на 0,08 %, а розраховане підвищення температури внаслідок в'язкої дисипації становило менше 0,005 °C.

Висновки. Розроблена система забезпечує інтегроване вимірювання опору газовому потоку та температури в шарі природного кліноптилоліту. Експериментальні та чисельні результати свідчать, що за досліджених умов суттєві зміни опору газовому потоку не супроводжувалися виявленою систематичною температурною реакцією. Запропонована архітектура може бути основою для подальших досліджень цеолітових шарів за контрольованих сорбційних умов, релевантних для систем акумулювання теплової енергії.

Ключові слова: вбудована вимірювальна система, Raspberry Pi 5, збір даних, опір газовому потоку, природний цеоліт, зернистий шар, акумулювання теплової енергії.

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