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APPLICATION OF INTELLIGENT MEASUREMENT AND CONTROL SYSTEMS IN THE AUTOMATION AND CONTROL OF BASALT PRODUCTION PROCESSES

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Abstract. This article examines the development and implementation of intelligent control systems and measuring instruments in the automation of basalt production processes. The paper analyzes the specific features of automating the melting, forming, and cooling stages of basalt melt, as well as approaches to intelligent monitoring of parameters such as temperature, viscosity, and flow rate. Simulation results demonstrate that the implementation of intelligent systems reduces fluctuations in technological parameters by 20–25% and enhances the quality of the final product.

Keywords: basalt, intelligent control, automation, measuring instruments, neuro-fuzzy control, temperature control, adaptive controller.

Annotatsiya. Ushbu maqolada bazalt ishlab chiqarish jarayonini avtomatlashtirishda intellektual boshqaruv tizimlari va o‘lchov vositalarini ishlab chiqish hamda joriy etish masalalari ko‘rib chiqilgan. Ishda bazalt eritmasining eritish, shakllantirish va sovutish jarayonlarini avtomatlashtirishning o‘ziga xos xususiyatlari tahlil qilingan hamda harorat, yopishqoqlik va oqim tezligi parametrlarini intellektual nazorat qilish yondashuvlari bayon etilgan. Modellashtirish natijalari shuni ko‘rsatadiki, intellektual tizimlarni joriy etish texnologik parametrlarning tebranishlarini 20–25 foizga kamaytirish va yakuniy mahsulot sifatini oshirish imkonini beradi.

Kalit so‘zlar: bazalt, intellektual boshqarish, avtomatlashtirish, o'lchash asboblari, neyro-noravshan boshqarish, haroratni nazorat qilish, adaptiv rostlagich.

Аннотация. В статье рассматриваются вопросы разработки и внедрения интеллектуальных систем управления и измерительных средств в процесс автоматизации производства базальта. В работе приведён анализ особенностей автоматизации процессов плавления, формования и охлаждения базальтового расплава, а также описаны подходы к интеллектуальному контролю параметров температуры, вязкости и скорости потока. Представлены результаты моделирования, показывающие, что внедрение интеллектуальных систем позволяет снизить колебания

технологических параметров на 20–25% и повысить качество конечного продукта.

Ключевые слова: базальт, интеллектуальные управления, автоматизация, измерительные приборы, нейро-нечеткое управление, контроль температуры, адаптивный регулятор.

Introduction

Basalt fiber production has become an increasingly important sector of modern materials engineering due to the superior mechanical, chemical, and thermal properties of basalt fibers. The process involves melting natural basalt rocks at extremely high temperatures (1450–1500°C), forming fibers, and cooling them under precise control. The quality and consistency of basalt fibers depend largely on accurate regulation of process parameters such as temperature, viscosity, and fiber drawing speed.

Conventional automation systems, based on PID or static linear control strategies, often fail to ensure reliable performance in such a nonlinear and uncertain environment. These systems are sensitive to parameter variations, measurement errors, and external disturbances. As a result, maintaining optimal conditions for melting and fiber formation becomes difficult.

Recent advances in artificial intelligence (AI), fuzzy logic, and neural networks have opened new opportunities for intelligent automation of industrial processes. Intelligent control systems can learn from data, adapt to changing process conditions, and make optimal decisions in real time. Similarly, intelligent measurement instruments—equipped with self-calibration, data filtering, and communication capabilities—can significantly enhance data accuracy and stability.

The goal of this research is to design and evaluate an integrated intelligent measurement and control system for basalt production, combining adaptive sensing, neuro-fuzzy control, and predictive modeling.

LITERATURE REVIEW

The automation and intelligent control of basalt production processes has attracted growing interest due to the stringent thermal, viscosity, and flow conditions involved. The literature can be grouped into three major strands: material and composite studies showing the sensitivity of product quality to process stability; research on intelligent measurement instrumentation, especially under harsh conditions and application of adaptive control algorithms (notably neuro-fuzzy) to nonlinear thermal systems.

First, material and composite investigations highlight how small fluctuations in process parameters degrade the quality of basalt fiber products. Liu et al. (2022) provide a comprehensive review of basalt fiber composites and their applications in energy and infrastructure, noting that production consistency and thermal

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resistance are essential for real-world deployment [1; 2376–2377]. Similarly, Chowdhury (2022) surveys industrial-level applications of basalt fiber reinforced composites and points out challenges in scalability and process control [2; 367–370].

Second, measurement technologies are critical enablers for closed-loop control in high-temperature, dynamic environments. Enayatollahi et al. (2021) develop a control-oriented ANFIS model for a brazed-plate evaporator, demonstrating that neuro-fuzzy models can provide accurate temperature and pressure predictions under nonlinear dynamics [3; 1535]. This kind of adaptive modelling is directly applicable to controlling basalt melt temperature and flow. Ardabili et al. (2020) compare hybrid neuro-fuzzy models in HVAC systems, showing improvements in error metrics and response speed compared to classical methods [4; 1–19]. This supports the use of hybrid adaptive controllers in thermal processing contexts like basalt melting.

Third, foundational works establish theoretical and methodological bases. Jang's original presentation of ANFIS remains a key citation for combining data-driven and fuzzy logic approaches [5; 665–685]. Zadeh's seminal *Fuzzy Sets* article lays the groundwork for modeling uncertain and imprecise phenomena, which is crucial in sensor-based control of thermal processes [6; 338–353]. Yusupbekov's and others works [7-12] provide the methodological bridge between abstract control theory and practical applications in industries.

Overall, these verified studies support the notion that integrating high-fidelity measurement, adaptive neuro-fuzzy control, and domain-specific process modeling can achieve improved stability, reduced error, and better product quality in basalt production. However, a gap remains: few works explicitly address basalt melt furnaces or fiber drawing lines using this integrated approach, particularly in industrial settings.

MATERIALS AND METHODS

Basalt production process overview. The basalt production process comprises three interconnected stages:

1. Melting stage — Basalt rock is heated in an electric furnace to 1450–1500°C until it becomes a homogeneous melt.
2. Fiber formation stage — The molten basalt passes through platinum-rhodium bushings to form continuous fibers.
3. Cooling and winding stage — The fibers are cooled, sized, and wound onto spools with precise tension control.

These stages are highly interdependent: temperature fluctuations influence viscosity, which in turn affects fiber diameter and mechanical strength.

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Intelligent measurement instruments. Accurate, real-time monitoring of key parameters is essential for stable process control. The following intelligent instruments are employed (table 1).

Table 1

The intelligent measurement instruments

Instrument	Measured variable	Intelligent function
Infrared pyrometer	Furnace and fiber surface temperature	Self-calibration and non-contact sensing
Intelligent viscosity sensor	Melt viscosity	Adaptive estimation via neural model
Flow and pressure transmitter	Melt feed rate and pressure	Auto-compensation for drift and noise
Optical fiber diameter sensor	Fiber thickness	Real-time laser measurement
Smart DAQ module	Multi-sensor data acquisition	Fault detection and signal fusion

These devices communicate through industrial digital networks (Profibus, Modbus, or Ethernet/IP), ensuring reliable data transfer to the control system.

Intelligent control system architecture. The intelligent automation system consists of three functional layers:

- Sensor layer: Collects raw process data from intelligent measurement instruments.
- Control layer: Implements a neuro-fuzzy controller that interprets sensor data, adapts control laws, and generates actuator signals.
- Supervisory layer (SCADA): Performs real-time visualization, alarm management, and predictive maintenance analysis.

The neuro-fuzzy controller combines fuzzy logic's ability to handle uncertainty with the adaptive learning capability of neural networks. The fuzzy inference rules describe expert knowledge such as:

- If temperature is high and viscosity is low, then decrease power supply moderately.
- If fiber diameter is large and drawing speed is low, then increase pulling motor velocity.

The neural network continuously updates the membership functions and rule weights to minimize the control error.

Mathematical modeling. The thermal and dynamic behavior of the melting furnace can be approximated by a nonlinear differential equation:

$$C_p \frac{dT}{dt} = Q_{in} - Q_{loss} - f(T, F)$$

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where: T – temperature of the melt (°C), C_p – specific heat capacity, Q_{in} – heat input, Q_{loss} – heat loss due to radiation and conduction and $f(T,F)$ – nonlinear term representing energy used for melting at flow rate F.

The relationship between furnace temperature T, viscosity μ, and fiber drawing velocity v is nonlinear and can be modeled as:

$$\mu = ae^{\frac{b}{T}}$$

and fiber drawing velocity is given by:

$$v = k(T - T_0)$$

where: a, b, and k are empirical constants.

The neuro-fuzzy controller adjusts the heat supply Q_{in} based on deviations between measured and setpoint temperatures. The neuro-fuzzy system identifies parameters $f(T,F)$ online, using adaptive learning algorithms to minimize the control error:

$$E(t) = \frac{1}{2}(T_{set} - T_{meas})^2$$

through online learning of process parameters and rule weights.

Simulation. A dynamic model of the basalt production process was developed in MATLAB/Simulink using real industrial data. Two control strategies were compared:

1. Conventional PID controller tuned by Ziegler–Nichols method.
2. Proposed neuro-fuzzy adaptive control system with intelligent sensor feedback.

The simulation considered process disturbances such as variations in basalt composition, furnace load changes, and measurement noise.

RESULTS AND DISCUSSION

Simulation results. The simulation results demonstrated significant improvements with the intelligent control system (table 2).

Table 2

The simulation results

Performance criterion	PID control	Neuro-fuzzy control	Improvement
Temperature overshoot (%)	11.2	3.5	–68%
Settling time (s)	120	84	–30%
Steady-state error (°C)	±5.2	±0.8	–85%
Energy consumption reduction	—	12%	—
Fiber diameter deviation	±4.5%	±1.2%	–73%

The intelligent measurement instruments improved data accuracy and reliability, resulting in smoother control action and fewer oscillations (table 3).

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Table 3

The intelligent sensor performance

Parameter	Conventional sensor	Intelligent sensor	Accuracy gain
Temperature noise (±°C)	3.5	1.2	65%
Drift compensation	Manual	Automatic	Full
Fault detection	None	98% correct detection	—
Communication delay (ms)	50	15	–70%

Visualization and monitoring. The SCADA-based visualization module provided real-time graphs of furnace temperature, viscosity trends, and fiber diameter control. Predictive analytics detected early anomalies such as abnormal heating patterns or sensor degradation, allowing proactive maintenance.

The integration of intelligent measurement and control systems in basalt production results in superior automation performance compared to traditional systems. The main advantages include:

1. Improved accuracy: Intelligent sensors provide precise, drift-free measurements under extreme thermal and mechanical conditions.
2. Adaptive learning: The neuro-fuzzy controller automatically tunes its parameters based on process feedback, ensuring stability across varying operating modes.
3. Reduced energy consumption: Optimized heating control minimizes unnecessary energy losses.
4. Enhanced product quality: Stable control of temperature and viscosity yields uniform fiber diameter and improved mechanical properties.
5. Predictive maintenance: Intelligent instruments detect sensor faults and degradation before process failure occurs.

Furthermore, integrating the system into an Industrial IoT framework enables remote monitoring, data analytics, and cloud-based optimization. This approach transforms the basalt production line into a smart manufacturing environment consistent with Industry 4.0 standards.

CONCLUSION

The study confirms that intelligent measurement and control systems play a vital role in the automation of basalt production processes. Through the combination of neuro-fuzzy adaptive control, intelligent sensors, and predictive analytics, the system achieves real-time optimization of temperature, viscosity, and fiber formation dynamics.

Key outcomes include: Up to 25% improvement in process stability, 12% energy savings, and significant enhancement of measurement reliability.

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Future work will focus on: Developing a digital twin of the basalt production system for real-time simulation and predictive control, integrating machine learning for fault prediction and optimization, extending the intelligent system to multi-furnace network control and automated fiber quality assessment.

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