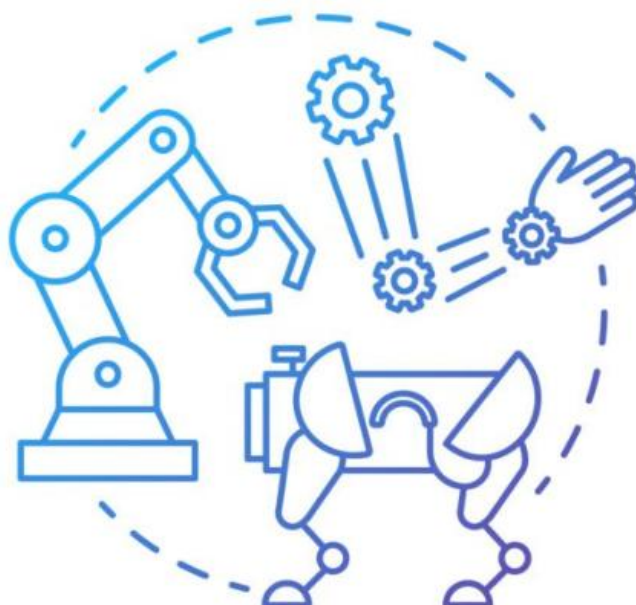


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У збірник включені тези доповідей, які присвячені сучасним автоматизованим технологіям Industry 4.0 та їх впровадження; інформаційні управляючі системи технологічного призначення; математичні методи в системах автоматизації; розробка та програмування в робототехніці; штучний інтелект та машинне навчання в автоматизації; інтеграція технологій у виробництві та промисловості; сенсорні технології та взаємодія людини з роботами в Industry 5.0; ефективність використання роботизованих систем у виробництві; етика та правові аспекти в робототехніці; Інтернет речей та Інтегровані системи в комп'ютерно-інтегрованих технологіях, автоматизації та робототехніки; технологічні виклики та інновації у світі робототехніки.

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AUTOMATION OF THERMOFIXATION IN THE PRODUCTION OF REFLECTIVE CLOTHING (REFLECTIVE DTF)

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Annotation: The work is devoted to the problem of ensuring the quality of reflective clothing elements manufactured using Reflective DTF technology. The technological process of applying reflective coatings is considered, and the critical dependence of the preservation of the optical properties of microspheres on the accuracy of the temperature regime at the thermofixation stage is revealed. A comparative evaluation of automatic temperature control methods is carried out according to the criteria of accuracy, speed, adaptability, and implementation complexity. The optimal approach to automation of thermofixation is determined to ensure the stability of the production process.

Key words: automation, thermofixation, Reflective DTF, reflective clothing, PID control, temperature control, microspheres, retroreflection.

АВТОМАТИЗАЦІЯ ТЕРМОФІКСАЦІЇ У ВИРОБНИЦТВІ СВІТЛОПОВЕРТАЛЬНОГО ОДЯГУ (REFLECTIVE DTF)

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Анотація: Робота присвячена проблемі забезпечення якості світлоповертальних елементів одягу, виготовлених за технологією Reflective DTF. Розглянуто технологічний процес нанесення світлоповертальних покриттів та виявлено критичну залежність збереження оптичних властивостей мікрокульок від точності температурного режиму на етапі термофіксації. Здійснено порівняльну оцінку методів автоматичного контролю температури за критеріями точності, швидкодії, адаптивності та складності реалізації. Визначено оптимальний підхід до автоматизації термофіксації для забезпечення стабільності виробничого процесу.

Ключові слова: автоматизація, термофіксація, Reflective DTF, світлоповертальний одяг, ПІД-регулювання, контроль температури, мікрокульки, ретрорефлексія.

Automation of technological processes is one of the key directions for increasing the efficiency of modern production, ensuring product quality stability, reducing the influence of the human factor, and optimizing resource costs [1-12]. In the context of the light industry and the production of personal protective equipment, these issues acquire particular importance as they directly affect human safety and health.

In particular, the problem of pedestrian safety at night in Ukraine is becoming critical due to the high mortality rate in conditions of insufficient lighting. The increase in the number of people with twilight vision disorders (nyctalopia) also requires the introduction of new methods of passive safety. One of the most effective ways to solve this problem is the use of clothing with reflective elements, which ensures human visibility at a distance of up to 150 meters compared to 20–30 meters without them.

Manual adjustment, which is used in most enterprises, is characterized by the lowest accuracy of maintaining the set temperature. The operator visually monitors the heat press readings and manually adjusts the heating parameters. This approach leads to a significant error ($\pm 8\text{--}10^\circ\text{C}$), since the operator's reaction to temperature changes has a delay, and subjective assessment does not ensure process stability. In addition, the human factor (fatigue, inattention) further reduces the quality of control, especially during long production cycles.

Relay (On/Off) control is the simplest method of automation, where the heating element is turned on when the temperature drops below a set threshold and turned off when it exceeds it. Despite the simplicity of implementation and low cost, a significant drawback of this method is significant temperature fluctuations around the set value (hysteresis effect). Even with minimal hysteresis ($\pm 2\text{--}3^\circ\text{C}$), relay control does not provide smooth temperature maintenance, which is critical for uniform thermofixation of microspheres in the narrow range of $155\text{--}165^\circ\text{C}$. Such fluctuations can lead to periodic exceeding of permissible limits and partial destruction of the optical layer.

PID control (proportional-integral-derivative) provides high accuracy of temperature maintenance due to a combined approach to control. The proportional component generates a control action proportional to the current deviation from the set value, the integral component eliminates the accumulated error, and the derivative component takes into account the rate of temperature change, preventing overshoot. This allows reducing the error to $\pm 1\text{--}2^\circ\text{C}$ and ensuring smooth regulation without sharp temperature fluctuations. PID controllers are widely used in industry and have a well-developed theoretical basis for parameter tuning. However, the classical PID controller requires preliminary adjustment of coefficients and may lose efficiency when operating conditions change (for example, changes in film thickness, mains voltage fluctuations, workshop temperature), which justifies the feasibility of developing adaptive control algorithms.

Fuzzy logic represents an intelligent control method based on expert knowledge that does not require a precise mathematical model of the controlled object. The system makes decisions based on linguistic rules such as «if the temperature is slightly below the setpoint and decreasing rapidly, then significantly increase the heating power». The main advantage is adaptability to changes in process conditions and the ability to operate effectively under uncertainty. However, the complexity of configuration, the need to form a rule base, and significant computational costs make this method more labor-intensive to implement compared to classical PID control. Furthermore, implementing fuzzy logic on microcontrollers with limited computational resources (e.g., Arduino) may require algorithm simplification or reduced control frequency. The results of the comparative analysis of temperature control methods are presented in Table 1.

Table 1 – Comparative analysis of temperature control methods

Control method	Accuracy, $^\circ\text{C}$	Implementation complexity	Speed	Adaptability	Energy efficiency	Suitability for Reflective DTF
Manual	$\pm 8\text{--}10$	Low	Low	None	Low	Непридатный
Relay (On/Off)	$\pm 4\text{--}6^1$	Very low	Medium	None	High	Обмежено придатний
Classical PID	$\pm 1\text{--}2$	Medium	High	Low	High	Придатний
Fuzzy logic	$\pm 1\text{--}2$	High	Medium	High	High	Придатний

Notes: ¹ The accuracy of relay (On/Off) control depends on the inertia of the system and the hysteresis value; for systems with low inertia, fluctuations can reach $\pm 5\text{--}8^\circ\text{C}$.

Analysis of the data in Table 1 shows that for Reflective DTF technology, the most suitable methods are classical PID control and fuzzy logic, as they provide the required temperature maintenance accuracy within $\pm 1\text{--}2^\circ\text{C}$. Manual control is completely unsuitable due to its high error

($\pm 8-10^{\circ}\text{C}$), which exceeds the permissible deviation range for preserving the retroreflective properties of microspheres. Relay control has limited suitability due to significant temperature fluctuations ($\pm 4-6^{\circ}\text{C}$), which can lead to periodic excursions outside the critical range of $155-165^{\circ}\text{C}$. Classical PID control proved to be the optimal solution for automating the thermofixation process due to its combination of high accuracy, speed, and energy efficiency with moderate implementation complexity. Fuzzy logic, despite its higher adaptability, requires more complex configuration and the formation of a rule base, making its implementation economically impractical for this technological process.

CONCLUSIONS. The paper analyzes the problem of automating temperature control in the production of reflective clothing using Reflective DTF technology. It has been established that the critical stage of the technological process is thermofixation at a temperature of $155-165^{\circ}\text{C}$, deviation from which leads to thermal degradation of the optical layer of microspheres, a decrease in the intensity of retroreflection by 40–60 %, and an increase in the defect rate up to 25–30 %. It was found that most existing equipment does not provide the required accuracy of temperature maintenance (error $\pm 8-10^{\circ}\text{C}$), and manual adjustment does not allow synchronizing process parameters with temperature changes. This substantiates the need for the implementation of automated temperature control systems to ensure stable product quality and reduce production losses. A comparative analysis of four temperature control methods was carried out: manual, relay, classical PID control, and systems based on fuzzy logic. Based on the analysis results, it was established that classical PID control is the optimal solution for automating the thermofixation process, as it provides the required temperature maintenance accuracy ($\pm 1-2^{\circ}\text{C}$), high speed, and energy efficiency with moderate technical implementation complexity. The research results can be used for the development of microcontroller-based automation systems for heat presses in the production of reflective clothing, which will improve product quality, reduce defect rates, and ensure the stability of the technological process.

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