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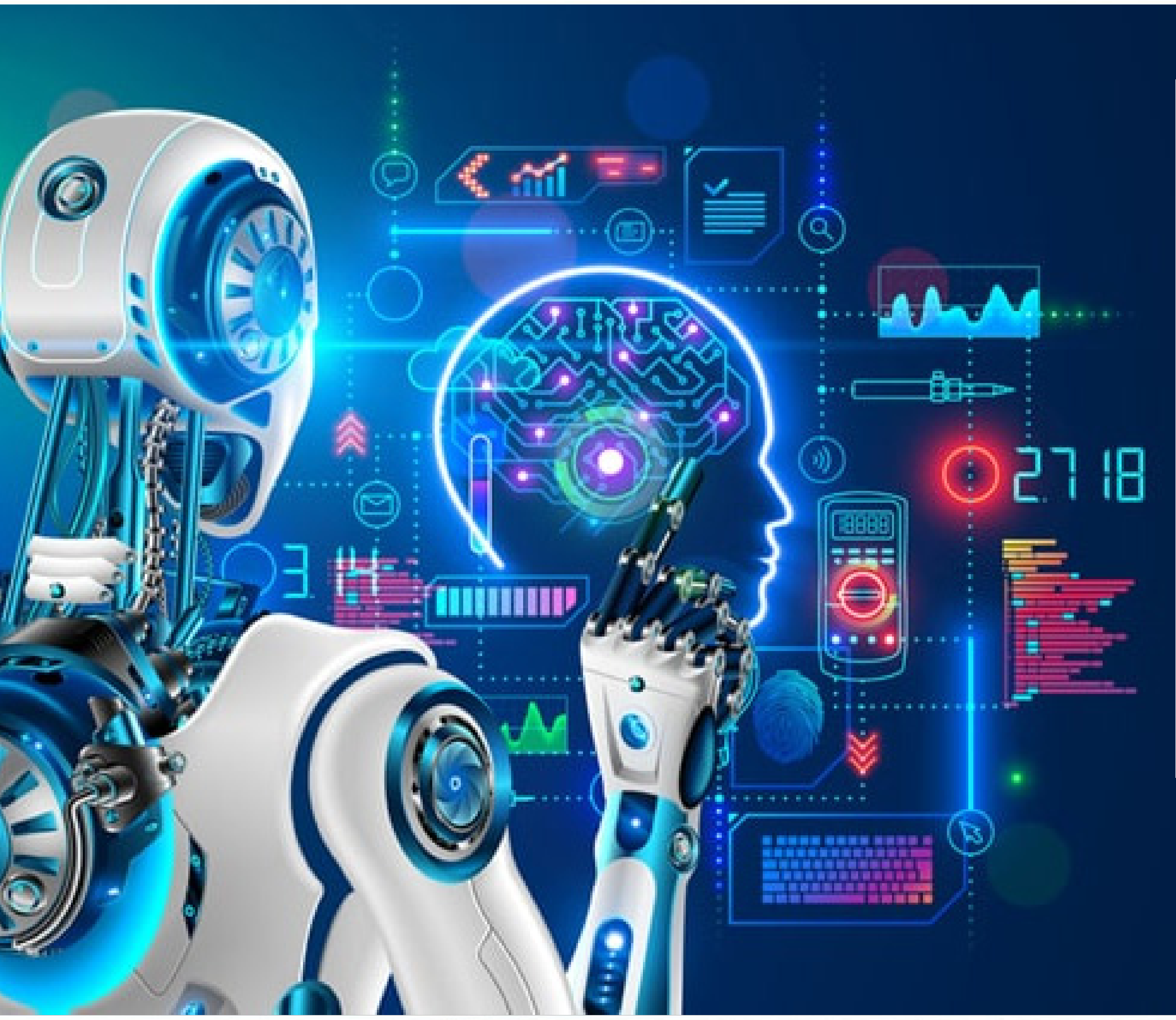

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CONTENTS

CONTENTS

CONTENTS

INTELLIGENT SYSTEM FOR MONITORING AND MANAGEMENT OF THE VEGETABLE OIL REFINING PROCESS

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Abstract: This article examines the development and implementation of a system for optimal management of the multi-stage technological process of refining vegetable oils based on predictive models and virtual quality analyzers. It has been shown that traditional automatic control systems, based primarily on PID regulation, do not provide the required level of quality and energy efficiency under conditions of uncertainty in parameters, nonlinearity, and multidimensionality of the control object. An approach to building an improved management system using Model Predictive Control (MPC) methods and virtual analyzers that provide an operational assessment of product quality indicators in real-time has been proposed. The results of modeling and pilot production tests, confirming the increase in the stability of the technological regime, the quality of the final product, and the reduction of specific energy costs, are presented.

Key words: vegetable oil refining, optimal management, MPC, forecasting model, virtual analyzer, automation, product quality.

Annotatsiya: Maqolada bashoratli modellar va virtual sifat analizatorlari asosida o‘simlik moylarini qayta ishlashning ko‘p bosqichli texnologik jarayonini optimal boshqarish tizimini ishlab chiqish va amalga oshirish masalalari ko‘rib chiqiladi. Asosan PID-rostlashga asoslangan an’anaviy avtomatik boshqaruv tizimlari parametrlarning noaniqligi, chiziqli emasligi va boshqaruv ob’ektining ko‘p o‘lchovliligi sharoitida talab qilinadigan sifat va energiya samaradorligini zarur darajada ta’minlamasligi ko‘rsatilgan. Real vaqt rejimida mahsulot sifati ko‘rsatkichlarini tezkor baholashni ta’minlaydigan Model Predictive Control (MPC) usullari va virtual analizatorlardan foydalangan holda takomillashtirilgan boshqaruv tizimini yaratishga yondashuv taklif etiladi. Modellashtirish va tajriba-ishlab chiqarish sinovlari natijalari keltirilgan bo‘lib, ular texnologik rejim barqarorligini, yakuniy mahsulot sifatini va o‘ziga xos energiya sarfini pasayishini tasdiqlaydi.

Kalit so‘zlar: o‘simlik moylarini rafinatsiyalash, optimal boshqarish, MPC, bashoratlovchi model, virtual analizator, avtomatlashtirish, mahsulot sifati.

Аннотация: В статье рассматриваются вопросы разработки и реализации системы оптимального управления многостадийным технологическим процессом рафинации растительных масел на основе прогнозирующих моделей и виртуальных анализаторов качества. Показано, что традиционные системы автоматического управления, основанные преимущественно на ПИД-регулировании, не обеспечивают требуемого уровня качества и энергоэффективности в условиях неопределенности параметров, нелинейности и многомерности объекта управления. Предложен подход к построению усовершенствованной системы управления с использованием методов Model Predictive Control (MPC) и виртуальных анализаторов, обеспечивающих оперативную оценку показателей качества продукции в режиме реального времени. Приведены результаты моделирования и опытно-производственных испытаний, подтверждающие повышение стабильности технологического режима, качества конечной продукции и снижение удельных энергозатрат.

Ключевые слова: рафинация растительных масел, оптимальное управление, MPC, прогнозирующая модель, виртуальный анализатор, автоматизация, качество продукции.

INTRODUCTION

In the modern world, the oil and fat industry faces a growing demand for high-quality products, energy-saving technologies, and stable operation of production lines, taking into account the variability of raw material resources. The process of refining vegetable oils is a complex multi-stage system in which heat and mass transfer are closely intertwined with chemical, physicochemical, and hydrodynamic processes occurring in close interdependence. At any stage of refining, if the technological characteristics do not meet the standards, this will inevitably affect the properties of the finished product and the financial results of production [1-3].

In the traditional automation of refining vegetable oils, local control systems are used, most often with PID regulators designed to maintain the stability of individual quantities: temperature, reagent consumption, and level in reactors. However, such systems do not have the ability to analyze and adjust complex nonlinear relationships between process parameters, final product properties, and technological/economic factors. The control system operates reactively, which does not allow achieving optimal operating modes in the presence of interference and uncertainty [4,5].

Monitoring the quality of vegetable oils, including acid number indicators, the level of free fatty acids, phospholipids, and residual substances, presents us with specific tasks. Although laboratory analysis methods provide high accuracy, they are characterized by significant inertia. Such a shortcoming does not allow the application of the obtained results for the operational regulation of the process in dynamics, which leads to delays in making management decisions and reduces the overall effectiveness of management.

Recent years have witnessed the rapid development of Advanced Process Control (APC) systems, which actively utilize forecasting models and optimization approaches. Among APC methods, Model Predictive Control (MPC) management deserves special attention. This approach allows for the calculation of optimal control commands, taking into account not only the current state of the system, but also its future forecasts for a certain time interval. At the same time, MPC takes into account limitations that can be applied to both managed and controlled variables [6-8].

The real-time management system implemented using MPC relies on a forecasting model created based on existing experimental data. The accuracy and predictability of this model play a key role in ensuring the effectiveness of automatic control of the object.

With each cycle of the control system's operation, the following operations are performed:

− the control system receives current values of controlled parameters and recorded interference from sensors and automated systems.

− output characteristics are determined, which are an anticipatory forecast of the object's dynamics for future time intervals.

− the best set of control actions acting during the given forecast period is determined.

− in the absence of changes in the control actions compared to the current stroke, the adjustment of the control is not applied. Otherwise, management is transferred to the executive mechanism management systems.

To enhance the effectiveness of such systems, it is useful to use virtual quality analyzers. They are software systems that indirectly assess complex measurable indicators using existing data. Virtual analyzers ensure constant quality control of products and allow for the inclusion of quality indicators in the management system.

Creating and implementing a control system for refining vegetable oils using predictive models and virtual analyzers is a significant scientific and technical task with significant practical potential for the oil and fat industry.

REVIEW OF LITERATURE ON THE SUBJECT

The vegetable oil refining process is a complex, multi-stage technological system that requires continuous monitoring and precise control of key process parameters. Product quality, resource efficiency, and operational stability in oil refining are strongly dependent on the effectiveness of process control systems. Conventional control methods often fail to ensure stable performance due to process nonlinearity, multivariable interactions, time delays, and limited availability of real-time quality measurements. As a result, the development of intelligent monitoring and management systems has become a critical research direction in modern oil-processing industries.

The theoretical foundations of advanced process control are comprehensively presented in the works of Markman A. L. and Dozortsev V. M., who demonstrate that Advanced Process Control (APC) systems significantly improve stability, adaptability, and efficiency in complex industrial processes. Their studies emphasize the importance of model-based control, predictive algorithms, and integrated decision-making mechanisms, which are particularly relevant for multi-stage refining technologies characterized by strong interdependencies between technological variables.

The physicochemical principles of vegetable oil refining are thoroughly described in the fundamental work by Gunstone F. D., Harwood J. L., and Dijkstra A. J. Their research details the technological essence of degumming, neutralization, bleaching, and deodorization stages, as well as the factors affecting oil quality parameters. This knowledge forms the scientific basis for constructing reliable process models and selecting appropriate control variables within intelligent monitoring systems.

A significant contribution to the analysis of vegetable oil refining technology has been made by Samadov E.E., who conducted detailed studies of technological modes and multi-stage refining processes. His research highlights the dynamic behavior of refining systems, the influence of operating conditions on product quality, and the limitations of traditional measurement methods. These findings justify the need for intelligent systems capable of real-time monitoring and adaptive control.

An important direction in intelligent process management is the application of virtual analyzers. Samadov E.E. developed and experimentally validated virtual analysis methods for assessing refined vegetable oil quality indicators without direct laboratory measurements. His studies demonstrate that virtual analyzers enable real-time estimation of key quality parameters, thereby enhancing the responsiveness and reliability of control systems. Such tools play a central role in intelligent monitoring architectures by reducing delays in decision-making and improving overall process transparency.

The issues of modeling and optimization of edible oil refining processes were investigated by Gupta S. K. and Bhatia S., who proposed mathematical models for optimizing operating conditions. Their work shows that proper optimization of technological parameters can significantly improve product quality while reducing energy and material consumption. These approaches provide a methodological foundation for embedding predictive and optimization modules into intelligent control systems.

From an economic perspective, modern control strategies such as Economic Model Predictive Control (EMPC), developed by Grosso J. M. and Ocampo-Martinez C., offer effective tools for balancing technological performance and economic efficiency. EMPC integrates process dynamics with economic objectives, allowing industrial systems to minimize costs while maintaining product quality. This concept is particularly valuable for vegetable oil refining, where energy efficiency and raw material utilization are critical performance indicators.

Additionally, the joint work of Yusupbekov N.R. and Samadov E.E. demonstrates the successful implementation of APC systems based on virtual analyzers in industrial conditions. Their results confirm that the integration of intelligent monitoring tools with advanced control algorithms enhances process stability, improves quality management, and supports compliance with modern industrial standards.

Overall, the reviewed literature indicates that the integration of advanced process control, virtual analyzers, mathematical modeling, and economic optimization provides a strong scientific and practical basis for developing intelligent systems for monitoring and management of vegetable oil refining processes. The convergence of these approaches enables real-time quality control, improved resource efficiency, and sustainable operation of modern oil-refining facilities.

RESEARCH METHODOLOGY

The technological cycle of multi-stage refining of vegetable oils is analyzed. It includes phospholipid hydration, alkaline neutralization of unsaturated acids, washing procedures, adsorption purification, and filtration. This process is characterized by complex hydrodynamics, interaction of various phases, and rapid heat and mass transfer processes [9,10].

The research is based on the principles of a systematic approach, which is applied to the analysis and synthesis of automated systems that control complex technological processes. The work utilized mathematical models of chemical-technological processes, concepts of automatic control theory, methods for identifying dynamic systems, as well as concepts borrowed from artificial intelligence.

Modeling the neutralization dynamics of free fatty acids is based on a system of nonlinear differential equations that account for both chemical reactions and transport phenomena. The adsorption refining model takes into account the sorption characteristics, temperature, and parameters of the adsorbent.

$$\frac{dC_{FFA}}{dt} = -k(T) \cdot C_{FFA} \cdot C_{NaOH}, \qquad (1)$$

where: C_{FFA} – concentration of free fatty acids, C_{NaOH} – concentration of alkaline solution, $k(T)$ – temperature-dependent reaction coefficient.

The reaction coefficient, which determines the rate of a chemical reaction, changes with temperature, and this relationship is expressed using the Arrhenius equation:

$$k(T) = k_0 \exp\left(-\frac{E_a}{RT}\right), \quad (2)$$

where: E_a – activation energy, R – universal gas constant.

Adsorption purification is modeled using Langmuir's isotherm equations that describe adsorption processes:

$$q = \frac{q_{max} \cdot K \cdot C}{1 + K \cdot C}, \quad (3)$$

where: q – amount of adsorbed substance, C – concentration of impurities, K –adsorption constant.

As a tool for assessing the quality of vegetable oils, virtual analyzers built on neuro-fuzzy models proposed by Takagi and Sugeno are used. These models input parameters such as temperature, pH level, chemical consumption, and processing time, and output the acid number and impurity concentration in the oil as a result. Their training was conducted using experimental and production data, using methods of parametric determination and improvement of parameters.

Predictive control is implemented using an MPC controller, which determines the best control signals. For this, it uses an optimization approach, minimizing the objective function. This function takes into account both the difference between the actual and specified values of the regulated parameters, and the restrictions imposed on the control actions.

$$J = \sum_{i=1}^{N_p} (y_{ref}(k+i) - y(k+i))^2 + \lambda \sum_{i=0}^{N_c} \Delta u(k+i)^2, \quad (4)$$

where: N_p – forecasting horizon, N_c – management horizon, λ – weighting factor.

MPC, based on a predictive model, represents a type of adaptive control system where self-regulating elements act as regulators. These systems are characterized by the application of an internal model that predicts the future status of the system within a given timeframe (forecasting horizon). To achieve optimal control, the system calculates a number of control values within the control horizon, striving to minimize the objective function. In practical application, only the first value of the obtained sequence is used, which is equivalent to using the long-term forecasting horizon.

Figure 1 shows the structural diagram of the control system, where the forecasting regulator plays a key role. This regulator consists of two interdependent components: a forecasting model and an optimizer (Figure 1).

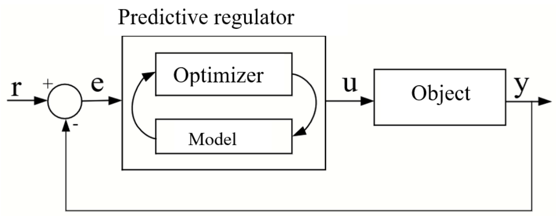

Figure 1. Block diagram of the control system with a forecasting regulator

Forecasting regulators are presented in several modifications, each of which has a unique set of characteristics. Their differences are manifested in aspects such as the applied model, model parameter setup algorithms, and optimization problem-solving algorithms.

ANALYSIS AND RESULTS

The study of current approaches to the theory and practice of real-time monitoring for objects controlled by automated systems revealed several promising directions for improving the accuracy of monitoring and forecasting.

Diagnostics, first in order, can be characterized as identifying the root causes of changes recorded during distributed parameter monitoring. Its peculiarity lies in the expansion of measurement boundaries and the complication of the process of analyzing controlled quantities at technological posts. This approach necessitates limited implementation of effective distributed monitoring and accurate diagnostics systems in earlier versions of systems responsible for optimization and operational management.

Another approach involves advanced preventive diagnostics, where independent algorithms identify defects in the early stages of their appearance at each control point. This approach allows for preventative management of the development of identified defects throughout the object's life cycle. For the effective implementation of preventive diagnostics monitoring, it is necessary to improve the methods of analysis and synthesis, as well as to increase the number of measurement and control units. The absence of the need to configure measuring transducers for signals opens the way to more advanced systems. Instead of traditional simplified systems focused on emergency protection, we can transition to distributed monitoring systems capable of predicting and preventing malfunctions [11].

The modern architecture of systems that track the technological processes of refining vegetable oils and fats, as shown in Figure 2, includes a number of interconnected components. These include local systems responsible for control and management, operational dispatch platforms (MES, ERP, EAM), the core of the automated technological process control system (ATPCS), data visualization systems, real-time information storage facilities, and programmable input-output controllers (Figure 2).

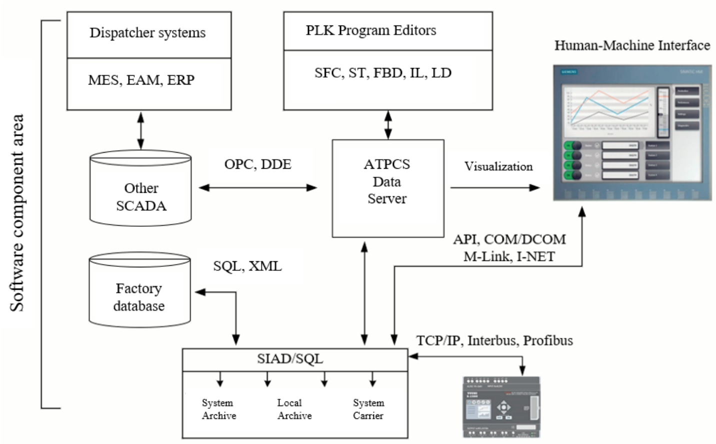

Figure 2. Generalized architecture of distributed monitoring systems for technological processes and production

The development of distributed monitoring software is not critical for computational resources, however, it is necessary to adhere to the parameters on a real time scale, ensuring reliability and accessibility. Information, which makes the selection of components and their interaction algorithms open during the integration of system components.

Figure 3 shows the dynamics of pH during neutralization and change in acid number using various control strategies (Figure 3).

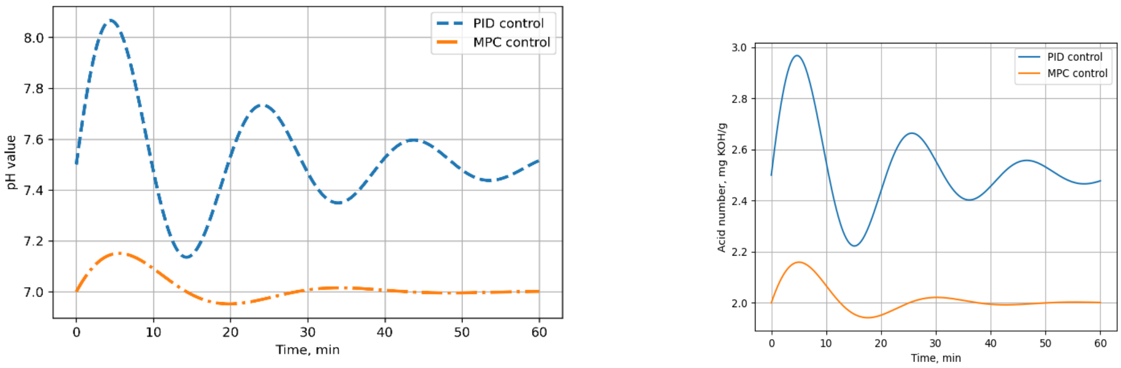

Figure 3. pH dynamics in the neutralization process and acid number under PID and MPC control

Mathematical models and numerical calculations confirmed the effectiveness of the optimal control system based on predictive models for refining vegetable oils. Using such a system made it possible to significantly increase the dynamic and static parameters of this process. Among the results achieved are: reduction of the change in the acid number of the finished product, enhancement of the stability of the technological cycle, and reduction of the duration of transient phases.

The practice of applying mathematical models of virtual analyzers mainly reduces to the use of regression equations. Although this approach has its own time costs, a significant drawback is the possibility of the constructed model not corresponding to the object being studied by the time it is completed. The modeling process includes the stage of statistical data analysis and subsequent selection of regression methodology, culminating in obtaining finite regression functions. This model is applicable only within certain limits of the object's functioning. Any significant change in the properties of the modeled object requires adjustments to the model used, which entails a repeated, labor-intensive process of its development.

Virtual analyzers, as a rule, are integrated into systems designed to improve management efficiency. Thanks to them, it is possible, in the shortest possible time, with partial automation, to conduct an analysis of the object under study, determine the cause-and-effect relationships, identify zones for optimization, and implement the found solutions in the form of recommendations or regulators. Later, the model is adjusted online or offline based on its own accuracy indicators and data obtained from a virtual analyzer, as well as laboratory tests. When creating a large-scale ATPCS complex, the key point is the consistent implementation of each stage based on the analysis of statistical indicators and comparison with the current management system. To conduct such an analysis, it is effective to use the Proficy CSense software from GE Intelligent Platforms. The successful completion of the analysis, confirming its effectiveness, opens the way for the implementation of the next stage, which ultimately contributes to improving the performance of the optimal management system [12].

The introduction of virtual analyzers has ensured constant monitoring of product quality, replacing traditional laboratory methods. Thanks to this, it was possible to adjust the neutralization and adsorption parameters more precisely, which led to a reduction in the consumption of alkaline reagents and adsorbents.

The virtual analyzer can be integrated into the automated technological process control system (ATPCS) or operate autonomously, acting as an intelligent component of the control system. Usually, this is a software-algorithmic system capable of extracting important information from existing data, determining patterns in the dynamics of ongoing processes, and displaying them graphically on the displays of operational personnel (Figure 4).

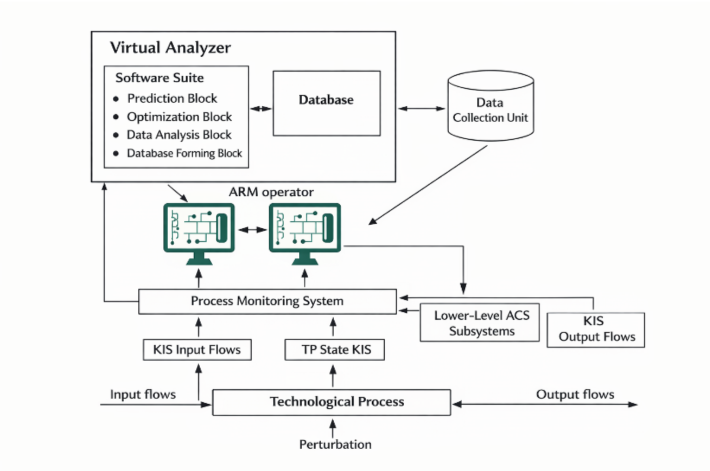

Figure 4. Diagram of interaction between the technological process, ATPCS and virtual analyzer

In this regard, its functionality is available on any network machine that has the ability to receive data on the current state of the TP, online analyzers, and laboratory measurements of material flows.

Figure 5 shows a comparison of the alkali reagent flow rate under different control algorithms (Figure 5).

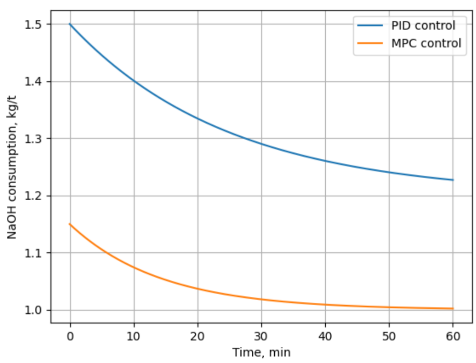

Figure 5. Comparison of NaOH consumption under PID and MPC control

Intelligent virtual analyzers additionally extract information from knowledge bases. Such databases can exist as classical databases or act as information repositories where technological experience is accumulated in multidimensional data. It can be implemented in various ways, combining different approaches. For example, it can be constructed using a multidimensional thematic data window that will function as a superstructure over the relational base [13-15].

Practical tests conducted under industrial production conditions have shown that the mathematical models and predictive control algorithm operate accurately and effectively. As a result, it was possible to reduce energy consumption per unit of product and improve the quality stability of the resulting refined oil (Figure 6).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2} \leq 5\%$$

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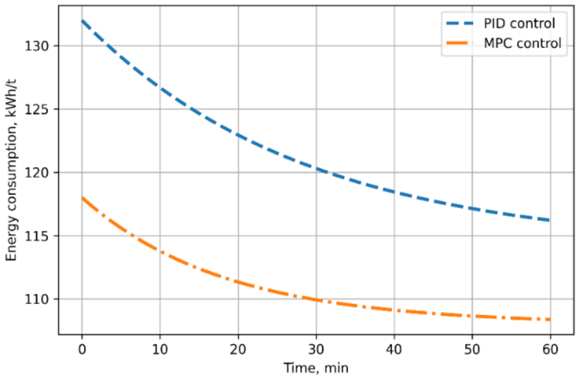

Figure 6. Energy consumption with different management strategies

During the pilot production tests, a reduction in the consumption of the alkaline reagent by 8-12% due to more precise dosing, as well as a reduction in specific energy consumption by 6-9%, was recorded.

The application of optimal control systems based on predictive models in the process of refining vegetable oils demonstrates a high degree of efficiency. This method, unlike outdated regulating systems, allows for comprehensive consideration of the interdependencies between various parameters of the technological process and the properties of the final product.

The use of virtual analyzers plays a key role in implementing distributed quality monitoring online. This approach allows for the prompt detection of deviations in the technological process and the introduction of corrective measures, preventing the emergence of defective products.

The implementation of such systems is justified, as the achieved results, such as improving product quality and reducing operating costs, justify the costs. It is important to understand that for successful implementation, a well-developed measurement base and reliable data for accurate model identification are required. The application of the MPC method demonstrates high efficiency in conditions where raw material markets and external factors are subject to fluctuations, which is a typical feature of the oil and fat industry.

CONCLUSIONS AND SUGGESTIONS

The study made it possible to create and confirm the effectiveness of a control system for refining vegetable oils, which is based on predictive models and virtual quality control systems. The application of MPC algorithms and intelligent data processing approaches contributes to increasing the stability of the technological cycle, improving the characteristics of the final product, and optimizing the use of material and energy resources.

The obtained results can be used in the design and modernization of automated control systems for technological processes in the oil and fat industry and related industries.

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