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Development of A Control System for Bitumen Production

E.A. Melikov, T.M. Maharramova

Azerbaijan State Oil and Industry University (Baku, Azerbaijan)

For correspondence:
Elchin Melikov / e-mail: elchin03@mail.ru

Abstract

The article examines the issues of enhancing the efficiency, safety, and productivity of technological processes in modern industry. In this regard, the effective control of complex chemical and technological processes, such as bitumen production, is not limited to practical experience and operational skills, but also requires the analysis and optimization of these processes using mathematical models. Within the framework of mathematical modeling, as applied to the bitumen production process, the technological sequence of the production under study, the heat and mass transfer processes occurring in one of the main technological apparatuses - the reactor, as well as the control algorithms used, were thoroughly investigated and analyzed in detail. In this regard, the expression of process parameters using mathematical models and their simulation allows for increasing the efficiency and safety of the entire production process. In the course of the research, energy and mass balance equations are formulated, and a dynamic model is developed in the form of differential equations that takes into account heat transfer, material diffusion, and reaction kinetics. The developed mathematical models were simulated in the MATLAB/Simulink environment and analyzed for various operating modes of the process under consideration. A comprehensive analysis of the automated control system used in the bitumen production process was conducted. The main regime parameters: temperature, pressure, flow rate, and level were monitored and regulated in real time, and the relationships between these process parameters were presented in the form of corresponding diagrams.

Keywords: mathematical model, optimal control, control system, bitumen production, technological process, regime parameters.

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Bitum istehsalında idarəetmə sisteminin işlənməsi

E.A. Məlikov, T.M. Məhərrəmova
Azərbaycan Dövlət Neft və Sənaye Universiteti (Bakı, Azərbaycan)

Xülasə

Məqalədə, müasir sənaye sahəsində texnoloji proseslərin səmərəliliyi, təhlükəsizliyi və məhsuldarlığının artırılması məsələləri araşdırılır. Bu baxımdan bitum istehsalı kimi mürəkkəb kimyəvi-texnoloji proseslərin idarə olunmasının yalnız praktiki təcrübə və əməliyyat bacarıqları ilə məhdudlaşmadığı, həm də bu proseslərin riyazi modellərlə təhlilini və optimallaşdırılmasını tələb etdiyi göstərilir. Bitum istehsalı prosesində tətbiq olunan riyazi modelləşdirilməsi çərcivəsində istehsalın texnoloji ardıcıllığı, əsas aparat – reaktor daxilində baş verən istilik və kütlə ötürmə prosesləri və tətbiq edilən idarəetmə alqoritmləri ətraflı şəkildə araşdırılmış və təhlil edilmişdir. Bu kontekstdə rejim parametrlərinin riyazi modellərlə ifadə edilməsi və onların simulyasiya olunması istehsal prosesinin daha effektiv və təhlükəsiz aparılmasına imkan verir. Tədqiqat çərçivəsində enerji və kütlə balansı tənlikləri qurulmuş, istilik ötürmə, maddə diffuziyası və reaksiyaların kinetikası nəzərə alınmaqla diferensial tənliklər formasında dinamik model hazırlanmışdır. Tərtib edilən riyazi modellər MATLAB/Simulink mühitində simulyasiya olunmaqla müxtəlif iş rejimləri üzrə analiz edilmişdir. Bitum istehsalı prosesində tətbiq edilən avtomatlaşdırılmış idarəetmə sistemi də geniş şəkildə təhlil olunurmuşdur. Əsas rejim parametrləri: temperatur, təzyiq, sərf və səviyyənin real vaxt rejimində izlənməsi və tənzimlənməsi, eyni zamanda onlar arasında asılılıqlar diaqram şəklində göstərilmişdir.

Açar sözlər: riyazi model, optimal idarəetmə, idarəetmə sistemi, bitumun alınması, texnoloji proses, rejim parametrləri, bitum reaktoru.

Разработка системы управления получением битума

Э.А. Меликов, Т.М. Магеррамова
Азербайджанский Государственный Университет Нефти и Промышленности (Баку, Азербайджан)

Аннотация

В статье рассматриваются вопросы повышения эффективности, безопасности и производительности технологических процессов в современной промышленности. Показано, что управление сложными химико-технологическими процессами, такими как производство битума, не ограничивается только практическим опытом и эксплуатационными навыками, но также требует анализа и оптимизации этих процессов с использованием математических моделей. В рамках математического моделирования, процесса производства битума детально исследованы и проанализированы технологическая последовательность исследуемого производства, процессы тепло- и массообмена, в основном аппарате – реакторе, а также применяемые алгоритмы управления. В связи с этим математическое выражение режимных параметров и их имитационное моделирование позволяют повысить эффективность и безопасность производственного процесса. В ходе исследования составлены уравнения баланса энергии и массы, а также разрабатывается динамическая модель в виде дифференциальных уравнений, учитывающая теплопередачу, диффузию материалов и кинетику реакций. Разработанные математические модели были смоделированы в среде MATLAB/Simulink и проанализированы для различных режимов работы рассматриваемого процесса. Проведен всесторонний анализ автоматизированной системы управления, применяемой в процессе производства битума. Основные режимные параметры: температура, давление, расход и уровень – контролировались и регулировались в режиме реального времени, а взаимосвязи между указанными технологическими параметрами представлены в виде соответствующих диаграмм.

Ключевые слова: математическая модель, оптимальное управление, система управления, получение битума, технологический процесс, режимные параметры, битумный реактор.

Introduction

Bitumen is a highly viscous, heat-stable material widely used in road surfaces, waterproofing systems, and industrial materials. The technological sequence of its production includes raw material preparation, heating, chemical processing, as well as final modification and storage processes. Each of these stages requires precise control of multiple parameters, such as temperature, pressure, mixing speed, and the amount of additional reagents used.

Mathematical models can be used to analyze heat and mass transfer processes, chemical reaction kinetics, energy balance, and material flows in the system. This, in turn, allows identifying critical points in the process, developing optimal control strategies, and increasing overall production efficiency. In addition, modern automation systems such as SCADA, PLC, and PID controllers allow engineers to control the parameters of technological processes in real time, collect data, and make control decisions [1-6]. Automation of technological processes minimizes errors caused by the human factor, maintains stable product quality, optimizes energy and material consumption, and simultaneously increases the level of safety [7]. The following factors determine the relevance of the article: the use of models and automation systems in bitumen production is of great importance for reducing energy costs, stabilizing product quality indicators, and ensuring the safe and effective control of the technological process under study. The primary focus is on modeling the processes of heat and mass transfer, as well as chemical transformations, that occur in the bitumen production reactor using differential equations. This involves analyzing the results of the mathematical models and developing optimal control solutions [8-11, 14].

Comparative Analysis of Reactor Systems and Modeling Approaches.

Reactor systems used in the chemical industry are considered the heart of the process. Their design, operating principle, and control mechanisms play a key role in ensuring the quality and sustainability of the production in question. Reactor systems are typically used to carry out gas-phase, liquid-phase, and heterogeneous reactions and, according to their design, are known to be divided into such types as heat-exchange tubular reactors, stirred tank reactors, continuous flow reactors, and pressurized semiconductor reactors. Reactor modeling aims to mathematically express the physical and chemical processes occurring in them on a scientific basis. Various modeling approaches are used for this purpose:

• empirical models. The reactor behavior is determined solely based on experimental results. Although this approach is effective for simple processes, it may be inaccurate for complex dynamic systems;

• physically based models (based on source equations) are based on mass and energy balance, kinetic equations, and heat transfer laws. For example, the Fourier, Navier-Stokes, Arrhenius, and other classical equations allow us to reflect the real nature of the process;

• “black box” models: the relationships between inputs and outputs are established without taking into account the internal structure of the system (e.g., neural networks, regression models, etc.). Such models are developed quickly, but do not allow for deep analysis of the system;

• hybrid models: a combination of physical and statistical models. These model types have become increasingly popular in recent years because they optimize both computational accuracy and modelling speed.

Comparative analysis shows that in thermodynamically active, highly viscous multiphase systems, such as bitumen production, the most effective approach is physical modeling. In this case, mass transfer, heat distribution, and reaction kinetics must be modeled interactively inside the reactor. This approach allows one to predict how the process will proceed under real conditions and serves as a basis for selecting optimal control parameters. To ensure the modeling accuracy, it is necessary to take into account the initial data obtained during laboratory experiments, the geometry of the reactor, the physicochemical raw material properties, and the reaction kinetics. A comparative block-scheme of the reactor models is shown in Figure 1.

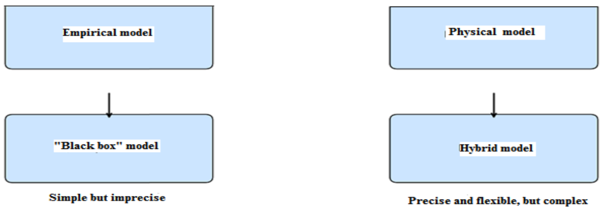

Figure 1 – Comparative block-scheme of reactor models

A comparative table of modeling approaches is presented in Table 1. This table compares four main approaches to modeling reactor systems: empirical, physically based, black-box, and hybrid models, according to various criteria. Empirical models, despite being simple and quick to use, have low accuracy; physically based models, despite being highly accurate, are complex. Black-box models, although based on artificial intelligence, do not take into account the internal physics of the process. Hybrid models, on the contrary, combine the advantages of both approaches and provide both accurate and flexible control.

Table 1 – Comparative table of approaches to modeling

Approach type	The main principle	Advantages	Disadvantages	Compatibility degree
Empirical model	Based on experimental results	Easy and quick setup	The accuracy is low and widespread use is difficult	Low
Physical model	Mass/heat balance, kinetics	Full compliance with the real process	Mathematical complexity, large parameters number	High
Black-box model	By input-output connection	Artificial intelligence methods are fast	The process essence is not taken into account	Average
Hybrid model	Physical + statistical	Combination of precision + speed	Complex setup and calibration required	High

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Bitumen Extraction Technology and its Industrial Application.

Technological processes automation is of great importance for optimizing production and increasing the efficiency of energy and raw materials use. The technological scheme for bitumen production reflects the sequence of processes covering all stages, from the primary processing of raw materials to obtaining the final product. This sequence includes the raw materials preparation, the distillation process, oxidation and quality monitoring of the finished product. Each process stage is carried out under certain technological conditions that allow regulating the chemical and physical bitumen properties. The technological scheme of bitumen production is shown in Figure 2.

The technology of bitumen production is one of the key components of deep oil refining and is based mainly on the processes of vacuum distillation and thermal oxidation. In this technology, the initially heavy fraction of oil obtained after atmospheric distillation, fuel oil, is distilled in a vacuum column at a temperature of 350÷400 °C and a pressure of 10÷50 mm Hg, during which the light and medium fractions are separated, and a residue containing high-molecular hydrocarbons, asphaltenes, resins and other complex compounds is formed in the cube. The resulting residue can be used directly as technical bitumen or subjected to further enrichment and conversion into oxidized bitumen. During the oxidation process, the tar is processed in special reactors at a temperature of 220÷280 °C and an air flow rate of 100÷150 m^3/h. In this case, intramolecular and intermolecular reactions of hydrocarbons occur, in particular, oxidation, condensation and polymerization, significantly changing their composition. As a result, the proportion of resins and asphaltenes in the composition of the resulting product increases, which improves its thermal and mechanical stability. The bitumen obtained type is divided into various categories depending on the area of use: viscoelastic road bitumen used in road construction, more elastic and heat-resistant oxidized bitumen intended for waterproofing and roofing, as well as technical bitumen for industrial purposes.

In modern technologies, especially in automated production systems, the oxidation process is regulated by maintaining the temperature, pressure, and flow rates of the reactor under full control, which creates conditions for obtaining a consistently high-quality product. In addition, in some industries, polymer additives are used to modify bitumen, which further increases its elasticity and strength properties, and ensures the wares production that are resistant to climate change.

The technological scheme of bitumen production has a complex structure, including various important stages. This process begins with the receipt of raw materials and their feeding into the system by a pump. This is followed by initial heating in a tubular furnace, and then the main chemical transformations occur in the reactor block. The reaction products are cooled to a certain temperature using a cooling system, and gas separation is carried out by condensation. After this, the distillation process and separation of various fractions occur. Actuators ensure the coordinated operation of these stages. In this case, heat exchangers are used to improve energy efficiency. At the end of the process, the obtained bitumen is sent to storage systems and stored there under appropriate conditions. The process taking place in the bitumen reactor occurs in an environment with high temperature, viscosity, and low thermal conductivity. Therefore, a physically based mathematical model was chosen for correct modeling and optimal process control. The technological scheme of bitumen production is presented in Figure 2.

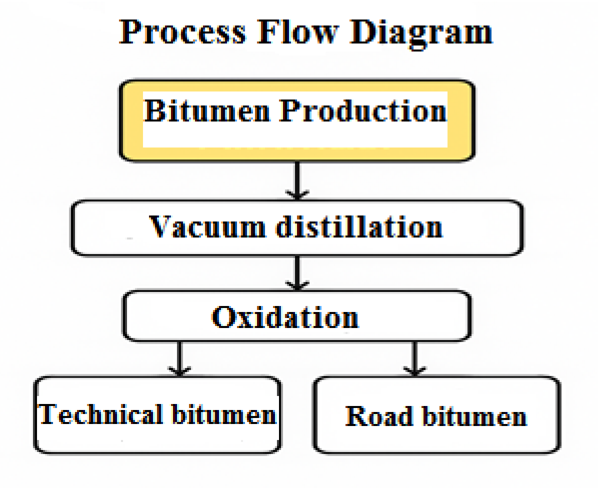

Figure 2 – Technological scheme of bitumen production

For example, the change in temperature during thermal conversion of bitumen in a reactor can be expressed by the following differential equation:

$$H = C_p \cdot \frac{dT}{dt} Q_{inp} - Q_{loss} + Q_{reac} \qquad (1)$$

where C_p is the heat capacity, Q_{inp} is the amount of supplied energy (electricity/fuel), Q_{loss} is the heat loss to the environment, Q_{reac} is the heat released/absorbed during the reaction.

In conjunction with this equation, Arrhenius-type expressions for reaction kinetics are used:

$$k = A \cdot e^{-E_a/RT} \qquad (2)$$

where k is reaction rate constant, A is frequency factor, E_a is activation energy, R is gas constant, T is temperature (in degrees Kelvin).

This model predicts how the temperature will change over time, how much energy will be needed, and how efficient the reaction will be.

Bitumen reactor automation scheme

Oxidation reactors used in bitumen production are complex technological apparatuses operating at high temperatures and under changing rheological conditions. For the efficient and safe operation of these reactors, automated control systems are required. Automation ensures both the stability of the technological process and the quality of the product by the standards' requirements.

The purpose and importance of automation. During the bitumen oxidation process, a number of key parameters must be continuously monitored: temperature, air flow, reaction time, reactor level, pressure, and mixing mode. Minor changes in these parameters have a significant impact on the properties of the product: for example, increasing the oxidation temperature can change the softening point and brittleness bitumen limit. Automation systems allow these parameters to be measured and controlled in real time using sensors.

Elements of a typical control scheme. The automated control scheme for bitumen reactors consists of the following main functional blocks:

- thermal control (PID controller). The temperature inside the reactor must be maintained with high accuracy. For this purpose, electric/gas heating systems or thermal oil circulation systems with PID controllers are used. Temperature sensors (thermocouples or resistance thermometers) are installed at various points in the reactor and transmit data to the SCADA system;

- automatic air flow regulation. During the oxidation process, air is supplied to the reactor under high pressure. The amount of air is measured by mass flow sensors (e.g., coriolis or Ventura) and controlled by automatic regulation valves;

- level and pressure monitor. The reactor filling level is monitored by ultrasonic or radar level sensors. Pressure sensors and safety valves are provided to prevent an increase in pressure within the system. Automatic signaling and blocking devices shut down the reactor in emergencies;

- regulating the blending mode. To ensure the oxidation process is homogeneous, the number of stirrer revolutions is regulated by high-speed electric motor controllers. The mixing intensity can be adaptively changed depending on the rheological parameters.

PLC and SCADA systems are widely used to control bitumen reactors in industry. PLC collects, processes all signals (analog and digital) and executes the assigned control algorithms. SCADA, as an operator interface, provides real-time data monitoring, archiving and event recording. Typical industrial software includes:

- Siemens SIMATIC S7 (PLC);
- WinCC or Wonderware (SCADA);
- LabVIEW (used for visual interfaces in some research and educational systems).

A typical automation system used in modern bitumen oxidation reactors is divided into the following blocks:

- a temperature control block that is connected to a PID controller;
- air supply block (mass flow meter + actuator valve);
- level and pressure block (with built-in safety systems);
- production data is stored in a database (SCADA system);
- operator panel (HMI) - the ability to control and intervene in the process using a touch screen.

Practical results have shown that in bitumen reactors equipped with automated control systems:

- energy consumption is reduced by 10÷15%;
- the stability of product quality has increased by 25÷30%;
- operator intervention is kept to a minimum;
- the security level has been significantly increased.

In addition, some plants use related control systems. For example, the rheological properties of bitumen (penetration, softening temperature) are determined by automatic analyzers, and based on these results, the process parameters are dynamically regulated. This is a high-level form of control, operating on the principle of “closed loop optimization”. The automated structural scheme of a bitumen reactor is shown in Figure 3. The main parameters in the reactor are measured by temperature, level, pressure, and mass flow sensors, and the valve is controlled by a PID controller. The collected data are transmitted to the SCADA system, and from there to both the PLC and the operator panel. The operator can monitor the process in real time and intervene in it. This system ensures quality monitoring and product safety.

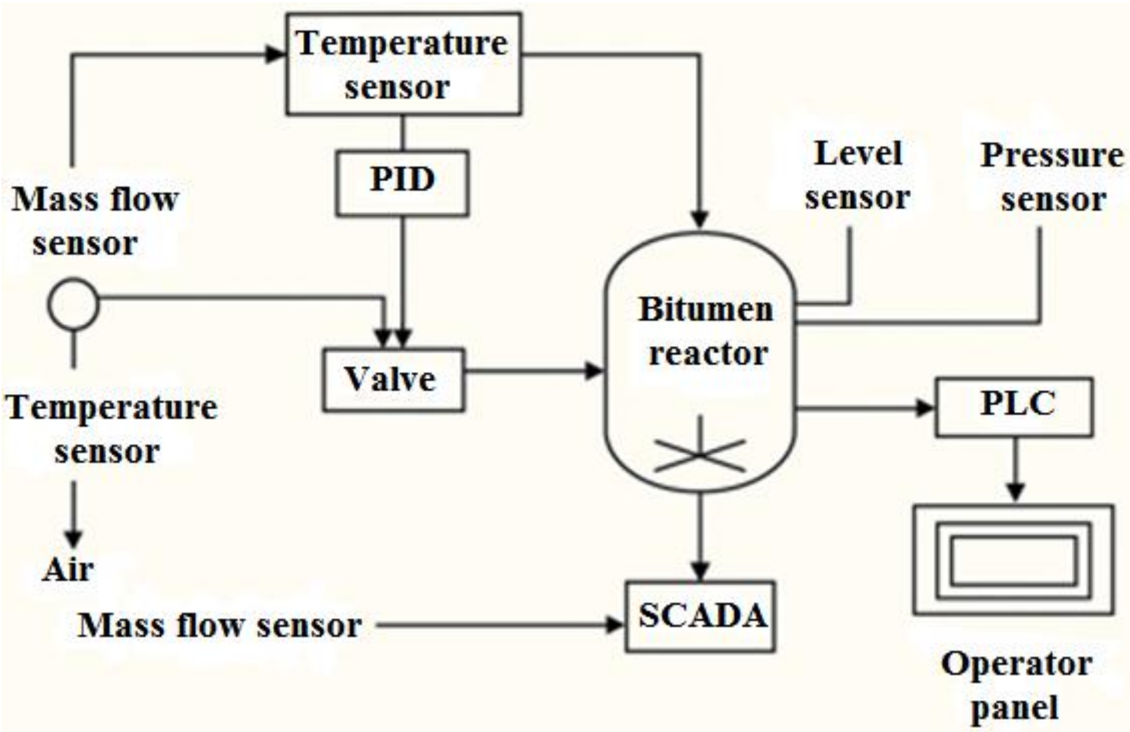

Figure 3 – The automated structural scheme of a bitumen reactor

Selection and justification of process mode parameters

It is known that the technological mode is a set of physical and technical parameters (temperature, pressure, speed, time, product movement speed, etc.) necessary for the optimal implementation of a certain technological process. The correct choice of the technological mode leads to increased productivity, reduced energy and material consumption, and improved product quality. The technological mode parameters are divided into the following categories.

When selecting the process mode parameters, the following basic principles must be taken into account:

- physical and chemical product properties (e.g., melting point of the material, sensitivity to moisture);
- equipment design and technical capabilities;
- performance and quality requirements;
- energy and resource consumption minimization;
- safety and environmental protection.

The correct selection and justification of technological parameters is the basis for optimal control of each process. This is achieved through the automation systems use and ensures high quality, safety and efficiency of production. The correct selection of technological mode parameters in a bitumen reactor directly affects the quality of the product, reaction rate and energy saving. The main technological goal here is to convert raw materials into a bitumen product with specified rheological and chemical properties. The reactor operates primarily by heating, mixing and uniformly introducing additives.

The main technological parameters of the reactor and their justification are given in Table 2. The correct choice of technological mode parameters in the bitumen reactor has a significant effect on the physicochemical properties, shelf life and quality of the product. Optimum temperature choice, mixing speed and reaction time guarantees the economic and technological efficiency of the process. Automated control, maintaining these parameters constant, ensures the required output quality. A visual scheme of the modification process using styrene-butadiene-styrene (SBS) in a bitumen reactor is shown in Figure 4. In Figure 4, bitumen is heated inside the reactor located in the center, and the SBS polymer is added from above. The mixing mechanism inside the reactor ensures uniform mixing of the added polymer with bitumen. In the outer part, a constant temperature is maintained using an oil bath and heating systems, which ensures the mixture stability. In the reactor shown in the figure, the bitumen is first heated to 180-190 °C using a heating system. Then the SBS polymer is added and mixed until homogeneous using an internal mixer. During the process, a constant temperature is maintained and the mixture is converted into high-quality, elastic modified bitumen.

Table 2 – The main technological parameters of the reactor and their justification

Parameters	Ranges	Technical justification
Temperature	160÷200 °C	Ideal for softening bitumen and efficient mixing of modifying reagents
Mixing speed	40÷80 rpm	Used to ensure homogeneous mixing and prevent phase separation
Reaction time	2÷4 hour	Sufficient for complete reaction of added reagents (polymer, paraffin, etc.)
Pressure (if applicable)	1.5÷3 bar	Preventing loss of volatile components and ensuring process safety
Reagent dosage	1÷10 % (by polymer)	Selected depending on the modification degree

The modification process using SBS in a bitumen reactor is mainly aimed at improving the physicochemical properties of bitumen by homogeneously combining polymer additives with it. In this process, bitumen is first heated to a temperature of 180÷190 °C using a heating system located inside the reactor, which increases its fluidity and creates optimal conditions for effective polymer mixing. Then, a certain amount of SBS polymer is added from above, and the substances are mixed until homogeneous using mechanical mixers inside the reactor. The temperature is maintained constant during the mixing process, and negative effects such as evaporation and oxidation are prevented due to the closed nature of the system. To maintain thermal stability, PID-type automatic control systems are used, as a result of which the modified bitumen acquires the required elasticity, high thermal stability, and mechanical strength. This technology is especially used in the production of bitumen compositions resistant to high loads on road surfaces and climate change.

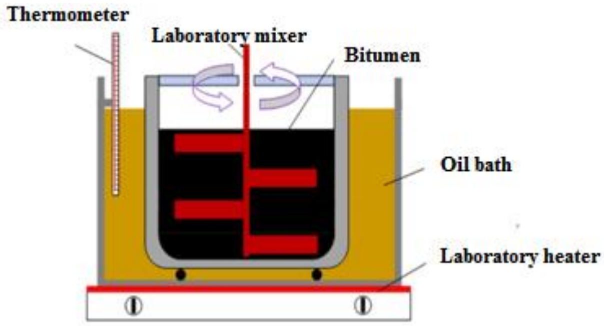

Figure 4 – Visual scheme of the SBS modification process in a bitumen reactor

Modeling for the thermo-casting mode of the reactor using differential equations.

The thermal casting mode in a bitumen reactor is determined by the thermal conductivity of the incoming flow, the exothermic reactions occurring in the reactor, and the heat losses to the environment. Since it is important to manage energy in a balanced manner in these systems, the analysis of the process behavior using mathematical models is a key tool for establishing the optimal operating mode. The dynamic change in heat in the reactor can be expressed by the following differential equation:

$$\rho c_p V \frac{dT}{dt} = \dot{m} c_p (T_{in} - T) + \Delta H \cdot R(T) - hA(T - T_{env})$$

The conventional designations used in the reactor pressure thermo-casting mode are given in Table 3.

Table 3 – Symbols used in the thermo-casting mode of the reactor

Symbols	Explanation
ρ	Reaction mass density (kg/m³)
c_p	Specific substance heat capacity (J/kg·K)
V	Reactor volume (m³)
m	Mass flow rate of the input stream (kg/s)
T_{in}	Inlet flow temperature (°C)
T	Current temperature inside the reactor (°C)
ΔH	Heat released as a chemical reaction (J/mol)
$R(T)$	Temperature dependent reaction rate function
h	Convective heat transfer coefficient (W/m²·K)
A	Heat transfer area (m²)
T_{env}	Температура окружающей среды (°C)

In the modeling and analysis of the model, the following assumptions were made to obtain a model of real industrial processes:

1. The temperature distribution inside the reactor is assumed to be uniform (i.e., mixing occurs completely).

2. The chemical reaction obeys the Arrhenius law:

$$R(T) = k_0 \cdot e^{-\frac{E_a}{RT}}$$

- k_0 is the reaction rate coefficient (1/s);
- E_a is activation energy (J/mol);
- R is the universal gas constant (8.314 J/mol·K).

3. Heat loss occurs mainly through convection and is characterized by a constant value h.

Modeling of the thermal casting mode in a bitumen reactor is shown in Figure 5.

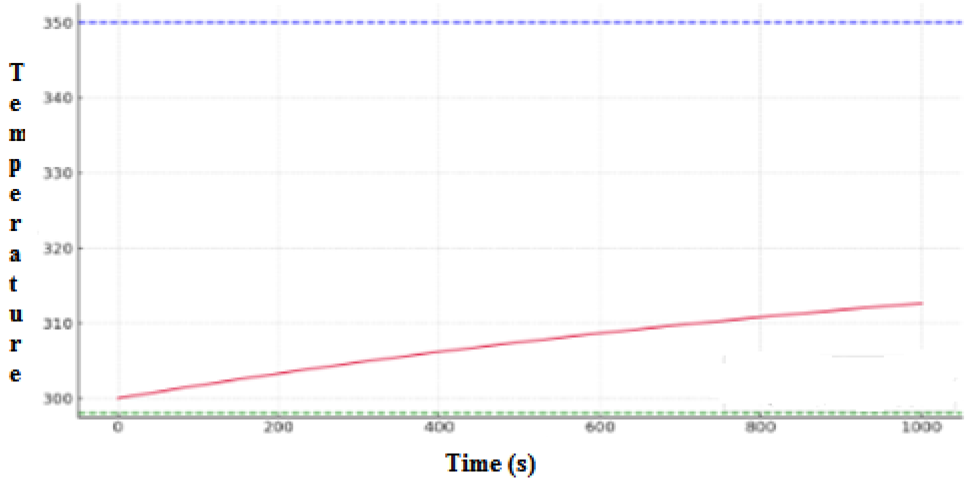

Figure 5 – Modeling of the thermal casting mode in a bitumen reactor

The above graph simulates the temperature change in the bitumen reactor over time. The simulation results show that:

- initially, the temperature in the reactor is lower than the inlet temperature (350 K), and over time, this temperature begins to increase;

- due to the heat released by the reaction and the energy of the flow, the temperature rises rapidly over a period;

- as a result of heat loss (convective transfer) and the thermal system balance, the temperature stabilizes over time and the system approaches thermal equilibrium.

These results clearly demonstrate the main factors' role (flow rate and inlet temperature) influencing the thermochemical processes in the reactor:

- the more energy is introduced into the system (due to temperature or mass flow rate), the faster the process stabilizes;

- this also indicates which parameters should be selected to speed up and improve the industrial processes efficiency [12, 13].

The dynamics of the reactor temperature under different conditions are shown in Fig. 6.

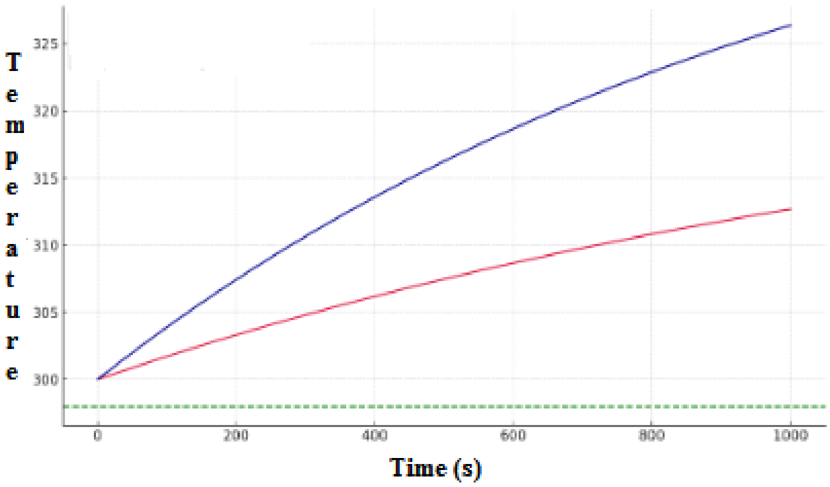

Figure 6 – Reactor temperature dynamics under different conditions

The above graph simulates the reactor temperature over time in two different regimes:

- model 1. Standard conditions:
  - mass flow: 0.5 kg/s;
  - inlet temperature: 350 K.
- model 2. Increased energy input:
  - mass flow: 0.8 kg/s;
  - inlet temperature: 370 K.

In model 1, the temperature increases more slowly and reaches a certain steady state. In this case, the reaction and heat release in the system reach a certain equilibrium.

In model 2, the temperature increases more rapidly and reaches a higher steady state because more energy is supplied. This reflects the higher temperature and faster reaction in the environment.

In both cases, the system approaches a stable temperature regime.

Conclusions

Thus, this article is an important study that contributes to the in-depth scientific analysis of industrial processes and increases their practical efficiency. The technological process of bitumen production was analyzed, and the regime parameters (temperature, pressure, flow rate, and level) influencing the process under consideration were determined. Mathematical models of heat and mass transfer processes occurring in the reactor were constructed using differential equations, and the dynamics of the process were analyzed using the modeling results. Optimization of the process in terms of accuracy, safety, and energy efficiency through the use of automated control systems (PID, SCADA, PLC) was shown.

The obtained results provide a significant scientific foundation for future technological advancements and industrial applications.

Conflict of Interests

The authors declare there is no conflict of interests related to the publication of this article.

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