DOI:10.18686/ahe.v8i9.13895

Chemical Engineering and Process Automation: Current Situation Analysis and Trend Forecast

Xu Xu
Guangdong Institute of Petrochemical Engineering, Maoming 525000, China

Abstract: The chemical industry is a crucial pillar of the national economy, essential for multiple sectors such as agriculture, healthcare, energy, national defense, and high-tech. It supplies vital materials for agriculture, forms the foundation of the modern pharmaceutical industry, aids in efficient energy utilization and new energy development, supports national defense security, and drives the growth of high-tech industries reliant on chemical innovation. Automation technology precisely controls key production parameters, enhancing efficiency, ensuring product quality stability, reducing safety risks, and guaranteeing continuous production. Simultaneously, it optimizes production processes, cuts energy consumption and waste, enables sustainable development, breaks down information silos, boosts the competitiveness of the chemical industry, and underpins technological progress and social development.

Keywords: Chemical Engineering and Process Automation

1. Key Technologies and Their Application Areas

1.1 Sensor and Detection Technology

In the field of chemical engineering, monitoring temperature and pressure is vital for ensuring production safety, improving product quality, and optimizing efficiency. Temperature and pressure sensors are essential for this monitoring. In the petrochemical industry, for example, the temperature and pressure inside reactors need to be precisely controlled. High-precision sensors can monitor and feed back data in real-time, and the control system adjusts accordingly to ensure stable reaction progress. If the parameters deviate from the safe range, the system will immediately issue an alarm and take emergency measures to prevent safety accidents and product quality issues, ensuring stable production.

Composition analysis and detection technology is crucial for quality control in chemical production, especially in the pharmaceutical and fine chemical industries. In pharmaceutical synthesis, chromatographic and mass spectrometric techniques are used to conduct in-depth analysis of raw materials and finished products to ensure drug purity and stable efficacy. In the finished drug stage, strict control of impurity content ensures drug quality, safeguards patient medication safety, and helps build enterprise brand reputation.

1.2 Control Theory and Optimization Methods

PID control is the core of classical control theory. Due to its simplicity, reliability, and ease of implementation, it is widely used in the chemical industry and is essential for the stable operation of production processes. Taking a distillation column as an example, the PID controller monitors key parameters such as the bottom temperature of the column in real-time, compares them with preset values to generate deviation signals. The proportional component quickly responds to temperature deviations, the integral component eliminates static errors, and the differential component predicts and suppresses temperature fluctuations to ensure product quality and energy consumption levels. PID control dominates in chemical production and is widely applied in temperature control, flow regulation, and other aspects, ensuring smooth and orderly production.

Model Predictive Control (MPC) addresses challenges such as multivariable coupling, nonlinearity, and large time delays in modern chemical production. It improves production efficiency through dynamic optimization and feedforward-feedback control. In complex processes like ethylene production, MPC predicts the dynamic behavior of the system based on an accurate process model and plans the optimal trajectory of key operating variables. In response to changes in market demand or raw material fluctuations, MPC can adjust the production plan in real-time, optimizing ethylene yield and reducing energy consumption. MPC also has a feedforward compensation function, enabling it to handle complex production environments. It is widely used in petrochemical and chemical plants, helping enterprises save energy, reduce emissions, improve economic efficiency, and promoting the intelligent and refined control of chemical processes.

1.3 Artificial Intelligence Technology

The stable operation of chemical equipment is crucial for production continuity and safety. Machine learning technology analyzes pump operation data, such as vibration spectra, temperature, pressure, and current, to establish an "equipment health baseline" model, enabling accurate fault diagnosis and predictive maintenance, thereby enhancing the stability of the chemical production process. Chemical reaction processes are complex, and traditional control methods struggle to ensure product quality and production efficiency. Deep learning models trained with historical data automatically extract features and construct a high-precision "digital model" of the reaction process, optimizing process parameter settings, improving product performance consistency, and driving the intelligent control of chemical processes.

2. Future Development Trend Forecast

2.1 Intelligent Development Direction

2.1.1 Comprehensive Construction of Intelligent Factories

In the process of the global chemical industry moving towards high-quality development, intelligent factories, as the core model of future chemical production, are leading a profound transformation. Taking BASF's flagship factory in Ludwigshafen, Germany, as an example, it is a model of an intelligent factory, fully demonstrating the excellent efficiency brought about by the deep integration of automation and intelligence.

In the production process, from the moment raw materials enter the factory, the intelligent warehouse management system, relying on the Internet of Things technology, tracks the type, quantity, storage location, and quality status of each batch of raw materials in real-time. Automated Guided Vehicles (AGVs) accurately deliver them to the production line, ensuring the timeliness and accuracy of material supply. In the core production process, highly integrated automated production lines widely adopt advanced sensors, Programmable Logic Controllers (PLCs), and Distributed Control Systems (DCSs) to accurately collect and real-time control a large number of parameters such as reaction temperature, pressure, and flow at the millisecond level, ensuring that chemical reactions are always in the optimal state. For example, in ammonia synthesis production, using Model Predictive Control (MPC) technology, the feed gas ratio and reaction temperature are dynamically adjusted according to the real-time working conditions, increasing the ammonia synthesis rate by more than 10% compared to the traditional process. In the product quality inspection process, an artificial intelligence-based machine vision system and a high-precision spectral analyzer work together to conduct comprehensive non-destructive testing on the appearance, size, and internal composition of the product, quickly identifying defective products and ensuring that the quality pass rate of the products leaving the factory is nearly 100%.

2.1.2 Deep Integration of Human-Machine Collaboration

With the rapid development of artificial intelligence, robotics technology, etc., human-machine collaboration is becoming a key trend in the future development of the chemical industry, playing a central role in reshaping production processes, improving work efficiency and safety.

In the daily inspection operations of chemical workshops, intelligent inspection robots and workers cooperate closely, opening up a new working mode. In a large chemical enterprise, for example, the equipped intelligent inspection robot integrates a variety of advanced sensors, including high-precision infrared thermal imagers, combustible gas detectors, high-definition cameras, and vibration sensors. It travels regularly between equipment along the preset inspection path, monitoring parameters such as the temperature, pressure, gas leakage, and mechanical vibration of key equipment such as reactors, distillation columns, and pipelines in real-time, and transmitting the collected massive data to the central control room instantly. The operators in the central control room use artificial intelligence algorithms to conduct in-depth analysis of the data, quickly screening for abnormal information. Once potential fault hazards, such as local overheating of equipment or slight leakage, are detected, they immediately notify the on-site inspection workers. The workers, based on the instructions from the central control room and using their professional knowledge and experience, with the help of the high-definition images and real-time data transmitted back by the robot, accurately verify the fault points and perform fine operations such as tightening loose parts and repairing small leaks. The robot continuously monitors beside to ensure the safety of the workers' operations. Human-machine collaboration has achieved a comprehensive upgrade of inspection from traditional manual fixed-time inspection to intelligent, real-time, and accurate inspection, effectively improving equipment reliability and reducing equipment failure rates by 30%, ensuring the continuity of chemical production.

2.2 Green Development Path

Supercritical fluid technology, relying on the unique physical and chemical properties of supercritical fluids, shows great advantages in the field of treating chemical waste such as waste plastics and rubber. Taking the recycling of waste polystyrene plastics as an example, the traditional pyrolysis method has problems such as high reaction temperature and uneven heat transfer, which easily lead to carbon deposition of polystyrene and low recovery rate of styrene monomers. However, the supercritical fluid degradation technology uses supercritical carbon dioxide or supercritical water as the medium. It has both the strong solubility of liquids and the high diffusivity of gases, enabling waste polystyrene to rapidly depolymerize under relatively mild conditions. Within a specific temperature and pressure range, the supercritical fluid can quickly penetrate into the molecular chains of polystyrene, weaken the intermolecular forces, promote the breaking of chemical bonds, and efficiently convert polystyrene into styrene monomers. The recovery rate is more than 30% higher than that of the traditional pyrolysis method, and carbon deposition is effectively inhibited. The obtained styrene monomer has high purity and can be directly reused in polystyrene synthesis or other organic synthesis processes, realizing the closed-loop recycling of plastic waste.

In the treatment of waste rubber, supercritical fluid technology also performs excellently. By placing waste rubber products such as waste tires in a supercritical alcohol medium, such as supercritical methanol or ethanol, under precisely controlled temperature, pressure, and reaction time conditions, the rubber macromolecular chains depolymerize, generating a variety of high-value chemical raw materials, including valuable aromatic oil, carbon black, and sulfur-containing compounds such as carbon disulfide.

2.3 Multidisciplinary Cross-Fusion Trend

In the chemical production process, information technologies such as 5G, big data, and cloud computing empower the automation system to achieve comprehensive optimization of the production process. The low latency, high bandwidth, and wide connection characteristics of the 5G network enable the real-time transmission of massive sensor data in the chemical production site to the central control room at the millisecond level, providing instant feedback for precise control. In supply chain management, information technology helps chemical enterprises build an intelligent supply chain system. With the help of the Internet of Things technology, the entire life cycle of chemical raw materials and products in storage and transportation can be tracked in real-time. Sensors collect information such as the location, status, temperature, and humidity of the goods in real-time and upload it to a unified data platform. Enterprises and upstream and downstream partners share data to achieve visual supply chain management and control.

Conclusion

The current status and future trends of chemical engineering and process automation highlight its central position in enhancing the overall strength of the chemical industry and promoting green and sustainable development. Through continuous integration of interdisciplinary innovation achievements such as sensor and detection technology, advanced control theory, and artificial intelligence, chemical production is gradually moving towards a new stage of intelligence, environmental protection, and high efficiency. Looking ahead, with the continuous progress of technology and the extensive expansion of applications, chemical engineering and process automation will more closely align with national strategic needs, helping the chemical industry gain a competitive advantage in the global market and providing strong support for the sustainable and healthy development of the economy and society.

References:

[1] LI Chao. Analysis of Modern Chemical Instrumentation and Chemical Automation Process Control [J]. Product Reliability Report,2023(09).

[2] Zhang Chao; Li Tengfei; Zhao Fengnian; Wang Shanshan; She Yongxin; Kim Mo-jun; Liu Haijin; Jin Fen; Shao Hua; Zheng Lufei; Xu Ping; Wang J. Preparation of molecular-imprinted electrochemical sensor and its application for rapid detection of glyphosate residues in drinking water [J]. Journal of Analysis and Testing,2016(12).