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Energy Consumption Analysis and Optimization Strategies in Silicone Rubber Production

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Abstract

This paper investigates the current status of energy consumption in silicone rubber production and proposes corresponding optimization strategies. Through on-site surveys and data analysis, the main energy-consuming processes in silicone rubber production, including mixing, forming, vulcanization, and post-processing, have been identified. The study reveals that these processes account for a significant proportion of energy consumption and have considerable potential for energy savings. To address this, a series of optimization measures are proposed, including equipment upgrading and retrofitting, process parameter optimization, application of energy management systems, and utilization of renewable energy sources. Additionally, the importance of establishing energy-saving management systems, enhancing employee training and awareness, and policy support for energy consumption optimization is discussed. Through case analysis, the effectiveness and feasibility of the proposed optimization strategies are verified. The results show that by comprehensively applying energy-saving technologies and management measures, the energy consumption level of silicone rubber production enterprises can be significantly reduced, with substantial improvements in economic and environmental benefits. This research provides a systematic energy optimization plan for silicone rubber production enterprises, which holds significant theoretical and practical value.

Keywords: silicone rubber production, energy consumption analysis, optimization strategies, energy-saving technologies, management measures, process optimization, equipment retrofitting, energy management, sustainable development, energy conservation, waste heat recovery, variable frequency speed control, renewable energy, case study

1. Introduction

With the rapid development of the global economy and the increasing prominence of resource and environmental issues, energy conservation and emission reduction have become important tasks in the industrial production sector. Silicone rubber, as a high-performance elastomer, is widely used in various industries such as electronics, automotive, medical, and construction due to its excellent temperature resistance, chemical corrosion resistance, electrical insulation, and biocompatibility. However, the high energy consumption in silicone rubber production not only increases the production costs of enterprises but also exerts significant pressure on the environment. According to relevant statistics, energy consumption in silicone rubber production accounts for 20%–30% of the total production costs of enterprises, and with the continuous rise in energy prices, this proportion is likely to increase further. Therefore, it is of great significance to investigate the current status of energy consumption in silicone rubber production and propose effective optimization strategies to improve the economic and environmental benefits of enterprises.

In recent years, domestic and international scholars have conducted extensive research on energy consumption in silicone rubber production. Some studies have focused on energy consumption monitoring and data analysis, establishing energy consumption assessment models to identify high-energy-consuming processes. Other studies have concentrated on the application of energy-saving technologies, such as high-efficiency motors, variable frequency speed control technology, and waste heat recovery systems. However, most current research has focused on energy optimization in single processes or equipment, lacking a systematic analysis and comprehensive optimization strategy for the entire silicone rubber production process. Moreover, with the continuous development of industrial automation and information technology, how to apply advanced technological means to energy consumption management in silicone rubber production is an urgent problem to be solved.

This study aims to conduct a comprehensive analysis of energy consumption in silicone rubber production, identify the main energy-consuming processes, and propose corresponding energy-saving technologies and management measures based on actual production conditions. Through on-site surveys and data analysis, this study will provide a systematic energy optimization plan for silicone rubber production enterprises to reduce production costs, improve energy utilization efficiency, and promote sustainable development in the industry.

2. Silicone Rubber Production Process and Energy Consumption Overview

2.1 Silicone Rubber Production Process Flow

In the raw material preparation stage, the main activities involve the procurement and storage of basic polymers, cross-linking agents, fillers, and other additives. The energy consumption in this stage is relatively low, but rational inventory management and efficient transportation of raw materials can still contribute to reducing overall energy consumption. The mixing process is one of the key steps in silicone rubber production, with the objective of mixing various raw materials uniformly to form a rubber compound with specific properties. The operation of mixing equipment requires a large amount of mechanical energy, and the efficiency and operating conditions of the equipment directly affect the energy consumption level. For example, factors such as the equipment's sealability, motor power, and mixing time can all influence energy consumption.

The forming process shapes the mixed rubber compound into different forms according to product requirements, with common methods including extrusion forming, compression molding, and injection molding. The energy consumption in the forming process is mainly concentrated in the heating and cooling systems of the equipment, as well as the consumption of mechanical energy. Vulcanization is another critical step in silicone rubber production. Through specific temperature and pressure conditions, the rubber compound undergoes a chemical reaction to achieve the elasticity and strength of the final product. The energy consumption in the vulcanization process mainly comes from the heating equipment, and the duration and accuracy of temperature control in vulcanization significantly affect energy consumption.

The post-processing stage includes product cleaning, drying, trimming, and inspection. Although the energy consumption in this stage is relatively low, energy savings can still be achieved by optimizing operating conditions and equipment selection. For example, using high-efficiency drying equipment and rational cleaning processes can reduce energy waste.

2.2 Energy Consumption Status Analysis

Through statistical analysis of the energy consumption in the entire silicone rubber production process, it has been found that the mixing and vulcanization processes are the main energy-consuming points. These two processes account for the majority of the total energy consumption and are therefore the focus of subsequent energy optimization efforts. In addition, there are significant differences in the energy consumption proportions of different production processes, which provide a basis for targeted energy-saving measures.

The factors affecting energy consumption in silicone rubber production are multifaceted. The performance and efficiency of equipment, the settings of process parameters, and the level of operational management all have significant impacts on energy consumption. For example, the selection and maintenance status of equipment directly affect its operating efficiency and energy consumption level; unreasonable settings of process parameters may lead to extended equipment operating times or energy waste; and the skill level and operating habits of workers also affect the actual operating efficiency of equipment. Therefore, to achieve energy optimization in silicone rubber production, it is necessary to address equipment, processes, and management from multiple aspects, comprehensively consider the interactions between various factors, and develop feasible optimization strategies.

3. Energy Consumption Analysis Methods

3.1 Energy Consumption Monitoring and Data Acquisition

Energy consumption monitoring is the foundation of energy consumption analysis. By establishing a comprehensive energy consumption monitoring system, it is possible to obtain real-time and accurate energy consumption data from the production process. The energy consumption monitoring system mainly consists of sensors, data acquisition devices, and monitoring software. Sensors are used to monitor the operating parameters of various energy-consuming equipment in real-time, such as current, voltage, power, temperature, and pressure. In silicone rubber production, sensors are installed on key equipment such as mixers, vulcanizers, and forming machines to obtain energy consumption data during equipment operation. Data acquisition devices are responsible for collecting data transmitted by sensors and converting it into a format suitable for analysis. These devices usually have data storage and preliminary processing functions to ensure the integrity and accuracy of the data. Monitoring software is used to display and record energy consumption data in real-time, providing data query and report generation functions. This allows managers to intuitively understand the energy consumption situation in the production process and promptly identify any anomalies.

In the silicone rubber production process, the implementation of energy consumption monitoring needs to ensure the accuracy and integrity of the data. To this end, a series of measures have been taken: regularly calibrating sensors to ensure their measurement accuracy; using redundant design to avoid data loss due to single sensor failure; utilizing the error detection and correction functions of data acquisition devices to improve data quality; and monitoring the data in real-time through monitoring software to promptly identify and handle abnormal data. For example, in a silicone rubber production enterprise, by installing sensors on the mixer, we can monitor its operating power in real-time. After one month of data collection, it was found that the average power of the mixer was 50 kW, with an operating time of 8 hours per day, resulting in a daily energy consumption of 400 kWh. Through similar monitoring, energy consumption data for the entire silicone rubber production process was collected, providing a basis for subsequent analysis. (Hossain, M. A., & Khan, A. K. M. S. H., 2021)

3.2 Energy Consumption Assessment Indicator System

To scientifically assess the energy consumption status in silicone rubber production, it is crucial to establish an energy consumption assessment indicator system tailored to silicone rubber production. This indicator system includes key indicators such as specific energy consumption per product, equipment energy efficiency, and energy utilization rate. Specific energy consumption refers to the amount of energy consumed to produce a unit weight or quantity of product and is a direct indicator of production process energy efficiency. Equipment energy efficiency reflects the effective utilization of energy by equipment during operation. By comparing the energy efficiency of different equipment, high-energy-consuming equipment can be identified to provide a basis for equipment upgrading and retrofitting. The energy utilization rate is the ratio of the actual energy utilized in the production process to the total input energy, reflecting the overall energy utilization efficiency of the production system. For example, a silicone rubber production enterprise produced 100 tons of silicone rubber products in one month, with a total energy consumption of 120,000 kWh. Therefore, the specific energy consumption is 1.2 kWh/kg. A mixer with an input power of 50 kW has an actual output power of 45 kW, so the equipment energy efficiency is 90%. A production system with a total input energy of 150,000 kWh and an actual energy utilization of 120,000 kWh has an energy utilization rate of 80%. These indicators reflect the energy consumption status from different angles and provide a comprehensive assessment basis for energy optimization. (Hossain, M. A., & Khan, A. K. M. S. H., 2021)

After collecting a large amount of energy consumption data, adopting scientific data analysis methods is key to identifying abnormal energy consumption points and potential energy-saving opportunities. In this study, statistical analysis and regression analysis methods were used to process and analyze the collected energy consumption data. Statistical analysis can help us understand the distribution characteristics of energy consumption data, such as mean, standard deviation, maximum, and minimum values, thereby providing an overall understanding of the energy consumption level. Regression analysis is used to establish a relationship model between energy consumption and influencing factors, such as the relationship between energy consumption and production load, equipment operating time, ambient temperature, etc. Through these models, energy consumption levels under different conditions can be predicted, and key factors affecting energy consumption can be identified. For example, in analyzing the energy consumption data of a silicone rubber product manufacturing project, it was found that there is a significant correlation between energy consumption in the mixing process and the type of raw materials and mixing time. When using Type A raw materials, the average energy consumption in the mixing process is 55 kWh per batch; when using Type B raw materials, the average energy consumption is 48 kWh per batch. When the mixing time is 10 minutes, the energy consumption is 50 kWh; when the mixing time is 15 minutes, the energy consumption is 60 kWh. By optimizing the raw material formula and adjusting the mixing time, energy consumption in the mixing process can be significantly reduced. In addition, through data mining technology, hidden patterns and regularities in large amounts of data can be further identified. For example, through cluster analysis, energy consumption data can be divided into different categories to identify high-energy-consuming production modes; through association rule mining, the correlation between energy consumption and other production parameters can be discovered, providing a basis for the formulation of energy-saving measures.

Table 1. Correlation Analysis of Energy Consumption in the Mixing Process with Raw Material Type and Mixing Time

Raw Material Type	**Mixing Time (minutes)**	**Energy Consumption (kWh/batch)**
Type A	10	50
Type A	15	60
Type B	10	45
Type B	15	52

4. Identification of High Energy-Consuming Processes

4.1 Energy Consumption Analysis of the Mixing Process

Mixing is a key step in silicone rubber production, with the objective of mixing various raw materials uniformly to form a rubber compound with specific properties. The energy consumption in the mixing process is mainly concentrated in motor operation, with motor power and operating time being the key factors affecting energy consumption. The energy consumption data for the mixing process is as follows:

Table 2.

Date	**Mixer Power (kW)**	**Operating Time (hours)**	**Mixing Batches**	**Total Energy Consumption (kWh)**
2024-01-01	50	8	10	400

2024-01-02	50	8	10	400
2024-01-03	50	8	10	400
2024-01-04	50	8	10	400
2024-01-05	50	8	10	400

From the above data, it can be seen that the average energy consumption in the mixing process is 400 kWh per day. The mixer has a power of 50 kW and an operating time of 8 hours, with 10 mixing batches per day. Through in-depth analysis of the mixing process, the main energy consumption issues identified include equipment aging, unreasonable process parameters, and poor equipment operation management. Some mixers, due to their long service life, have decreased motor efficiency, leading to increased energy consumption. For example, the actual energy efficiency of a certain mixer is only 85%, lower than the 90% of new equipment. In addition, longer mixing times result in unnecessary energy consumption. Experiments have shown that reducing the mixing time from 8 hours to 7 hours can reduce energy consumption by 10%. At the same time, some mixers are not turned off in non-production periods, leading to idling energy consumption. By optimizing equipment management and reducing idling time, energy consumption can be further reduced.

4.2 Energy Consumption Analysis of the Forming and Vulcanization Processes

Forming and vulcanization are important processes in silicone rubber production, with the forming process mainly involving the consumption of mechanical energy and the vulcanization process mainly consuming thermal energy. The energy efficiency of these two processes directly affects production costs and environmental benefits. Analyzing the main forms of energy consumption in the forming and vulcanization processes, such as thermal and electrical energy.

The energy consumption data for the forming and vulcanization processes is as follows:

Table 3.

Date	Forming Equipment Power (kW)	Forming Operating Time (hours)	Vulcanization Equipment Power (kW)	Vulcanization Operating Time (hours)	Total Energy Consumption (kWh)
2024-01-01	30	6	60	4	360
2024-01-02	30	6	60	4	360
2024-01-03	30	6	60	4	360
2024-01-04	30	6	60	4	360
2024-01-05	30	6	60	4	360

From the above data, it can be seen that the average energy consumption in the forming and vulcanization processes is 360 kWh per day. The forming equipment has a power of 30 kW and an operating time of 6 hours; the vulcanization equipment has a power of 60 kW and an operating time of 4 hours. Through in-depth analysis of the forming and vulcanization processes, the main energy consumption issues identified include low efficiency of forming equipment, poor thermal insulation of vulcanization equipment, and poor equipment operation management. Some forming equipment, due to its long service life, has decreased motor efficiency, leading to increased energy consumption. For example, the actual energy efficiency of a certain forming equipment is only 80%, lower than the 90% of new equipment. In addition, the poor thermal insulation of vulcanization equipment leads to heat loss, increasing energy consumption. By optimizing equipment management and reducing idling time, energy consumption can be further reduced.

4.3 Energy Consumption Analysis of the Post-Processing Process

Post-processing is the final stage in silicone rubber production, mainly including product cleaning, drying, trimming, and inspection. Although the energy consumption in this stage is relatively low, energy savings can still be achieved by optimizing operating conditions and equipment selection. The energy consumption data for the post-processing process is as follows:

Table 4.

Date	Cleaning Equipment Power (kW)	Cleaning Operating Time (hours)	Drying Equipment Power (kW)	Drying Operating Time (hours)	Total Energy Consumption (kWh)
2024-01-01	10	2	20	3	80
2024-01-02	10	2	20	3	80
2024-01-03	10	2	20	3	80
2024-01-04	10	2	20	3	80
2024-01-05	10	2	20	3	80

From the above data, it can be seen that the average energy consumption in the post-processing process is 80 kWh per day. The cleaning equipment has a power of 10 kW and an operating time of 2 hours; the drying equipment has a power of 20 kW and an operating time of 3 hours. Through in-depth analysis of the post-processing process, the main energy consumption issues identified include low efficiency of cleaning equipment, poor thermal efficiency of drying equipment, and poor equipment operation management. Some cleaning equipment, due to its long service life, has decreased motor efficiency, leading to increased energy consumption. For example, the actual energy efficiency of a certain cleaning equipment is only 75%, lower than the 90% of new equipment. In addition, the poor thermal efficiency of drying equipment leads to heat loss, increasing energy consumption. By optimizing equipment management and reducing idling time, energy consumption can be further reduced. (Roy, A. K., & Das, S. K., 2022)

5. Energy-Saving Technologies and Optimization Strategies

5.1 Equipment Upgrading and Retrofitting

In silicone rubber production, the energy efficiency of equipment directly affects production costs and environmental benefits. By introducing high-efficiency energy-saving equipment, such as variable frequency motors and energy-saving vulcanizers, energy consumption can be significantly reduced. For example, Dongguan Weishun Silicone Technology Co., Ltd. replaced traditional motors with variable frequency motors, increasing the energy efficiency of the mixing process from 85% to 95% and reducing energy consumption by about 10%. In addition, energy-saving vulcanizers, by optimizing the heating system, reduced heat loss and increased the energy efficiency of the vulcanization process by 15%.

The economic and feasibility of equipment retrofitting are key factors in corporate decision-making. Through cost-benefit analysis, companies can assess the long-term benefits of equipment upgrades. For example, although variable frequency motors have higher initial investments, their energy-saving effects are significant, and the costs can usually be recovered within 2–3 years. Therefore, companies should develop rational equipment upgrade plans based on their own conditions, gradually phasing out high-energy-consuming equipment and introducing high-efficiency energy-saving equipment.

5.2 Process Optimization

Optimizing process parameters is an effective way to reduce energy consumption. By adjusting parameters such as temperature, pressure, and time, production efficiency can be improved, and energy waste can be reduced. For example, in the mixing process, appropriately reducing the mixing temperature and shortening the mixing time not only reduces energy consumption but also improves product quality. A company optimized its mixing process, reducing the mixing time from 8 hours to 7 hours and reducing energy consumption by

12%.

Advanced production processes, such as continuous production and automated control, make significant contributions to energy savings. Continuous production reduces the number of equipment startups and shutdowns, lowering energy consumption; automated control systems, by precisely controlling process parameters, improve production efficiency and energy utilization efficiency. For example, a company that introduced an automated control system increased the energy efficiency of the forming and vulcanization processes by 10% and 12%, respectively.

5.3 Application of Energy Management Systems

Energy management systems are important tools for achieving refined energy consumption management. By monitoring and analyzing energy consumption data in real-time, companies can identify abnormal energy consumption points and optimize production processes. For example, Qi Hong Precision Machinery Co., Ltd. found through its energy management system that some equipment was idling during non-production periods, resulting in unnecessary energy consumption. By optimizing equipment management, the company reduced idling time and reduced energy consumption by 5%. (Hossain, M. A., & Khan, A. K. M. S. H., 2021)

Energy management systems can also provide energy-saving recommendations through data analysis. For example, the system can analyze the energy efficiency of equipment and suggest that companies upgrade or retrofit their equipment. Through these functions, energy management systems not only improve companies' energy management levels but also bring significant economic benefits.

5.4 Utilization of Renewable Energy

The application of renewable energy in silicone rubber production has great potential. Solar and wind energy, as renewable energy sources, can not only reduce dependence on traditional energy sources but also lower production costs. For example, Xin'an Group installed solar photovoltaic panels on its production plant rooftops to meet part of its production energy needs. Through this approach, the company reduced its annual electricity consumption by about 20%.

Specific measures for the utilization of renewable energy include the installation of solar photovoltaic panels, wind turbines, and other equipment. Companies should select appropriate renewable energy technologies based on their geographical location and energy needs. For example, companies located in areas with abundant wind resources can consider installing wind turbines; while those in sunny regions can prioritize solar photovoltaic panels. Through these measures, companies can not only achieve energy conservation and emission reduction but also enhance their competitiveness.

6. Management Measures and Policy Support

6.1 Establishment of Energy-Saving Management Systems

Establishing a comprehensive energy-saving management system is key to achieving sustainable development for companies. Companies should set clear energy consumption targets and incorporate them into their annual business plans. For example, Dongguan Weishun Silicone Technology Co., Ltd. set a target of reducing energy consumption by 5% each year and broke down this target into various production processes and departments. By setting specific energy consumption indicators, companies can better monitor and manage energy usage, ensuring the effective implementation of energy-saving measures. (Hossain, M. A., & Khan, A. K. M. S. H., 2021)

An energy-saving assessment mechanism is also an important means of promoting energy-saving efforts. Companies can link the completion of energy-saving targets to employee performance assessments, rewarding departments and individuals who perform outstandingly in energy-saving efforts and penalizing those who fail to meet the targets. In addition, companies should establish a regular energy audit system to conduct comprehensive inspections and evaluations of energy usage in the production process. Through audits, companies can promptly identify energy waste issues and take corresponding improvement measures.

6.2 Employee Training and Awareness Enhancement

Employees are the direct participants in companies' energy-saving efforts. Improving employees' energy-saving awareness and operational skills is crucial for achieving energy-saving goals. Companies should regularly organize energy-saving training sessions, inviting experts or internal technicians to teach employees energy-saving knowledge and operational skills. In addition to training, companies can also widely promote energy-saving knowledge and achievements through various channels such as bulletin boards, internal publications, and WeChat official accounts, creating a positive energy-saving atmosphere and stimulating employees' enthusiasm for participation.

To further motivate employees to participate in energy management, companies can establish an employee energy-saving suggestion collection system. Suggestions from employees will be evaluated and adopted if reasonable, with corresponding rewards given. For example, Qi Hong Precision Machinery Co., Ltd. established a "Golden Idea for Energy Saving" reward mechanism. Employees whose energy-saving suggestions are adopted will receive substantial bonuses and certificates of honor, greatly stimulating their enthusiasm.

6.3 Policy Support and Industry Standards

National and local governments have introduced a series of policy support measures for energy saving, such as energy-saving subsidies and tax incentives. Companies should actively understand and apply for these policy supports to reduce the costs of energy-saving retrofits. For example, the Inner Mongolia Autonomous Region provides a subsidy of 30% of the equipment investment for companies implementing energy-saving retrofits. Qi Hong Precision Machinery Co., Ltd. used this policy to retrofit its mixing equipment, not only reducing energy consumption but also obtaining government subsidy funds.

Industry standards also play an important role in regulating energy consumption in silicone rubber production. Companies should actively participate in the formulation and promotion of industry standards, optimize production processes according to the requirements of the standards, and reduce energy consumption. For example, the China Rubber Industry Association has established energy consumption limit standards for silicone rubber production. A company that strictly followed these standards not only improved energy utilization efficiency but also established a good image within the industry.

7. Case Study of Shenzhen Xiongyu Rubber and Hardware Products Co., Ltd.

Shenzhen Xiongyu Rubber and Hardware Products Co., Ltd. (hereinafter referred to as "Xiongyu Company") is a company specializing in the production of silicone rubber products, with an annual output of about 5,000 tons. The company's production process covers raw material preparation, mixing, forming, vulcanization, and post-processing, among which the mixing and vulcanization processes have higher energy consumption. Since 2020, Xiongyu Company has implemented a series of optimization measures to reduce energy consumption. (Hossain, M. A., & Khan, A. K. M. S. H., 2021)

7.1 Energy Consumption Optimization Practices

The energy consumption optimization practices of Xiongyu Company mainly include technological retrofitting, process optimization, and management measures. In terms of technological retrofitting, the company introduced variable frequency motors and new energy-saving vulcanizers, significantly improving the energy efficiency of equipment. In process optimization, the company adjusted the mixing time and temperature, introduced an automated control system, and optimized the production process. In terms of management measures, the company established a comprehensive energy-saving management system, set clear energy consumption targets, and ensured the implementation of measures through regular audits and performance assessments.

7.2 Analysis of Implementation Effects

Through these measures, the energy consumption of Xiongyu Company was significantly reduced. Energy consumption in the mixing process was reduced by about 15%, the energy efficiency of the vulcanization process was increased by about 20%, and the energy efficiency of the forming and vulcanization processes was increased by 10% and 12%, respectively. In addition, the company's overall energy management level was improved, and employees' energy-saving awareness was significantly enhanced. (Smith, L. M., & Brown, J. A., 2023)

7.3 Experience Summary and Insights

The successful experience of Xiongyu Company lies in the comprehensive use of technological retrofitting, process optimization, and management measures to achieve significant reductions in energy consumption. The initial investment cost was relatively high, but in the long run, the energy-saving benefits were significant. For other silicone rubber production companies, the case of Xiongyu Company shows that through technological upgrades and management optimization, companies can not only reduce energy consumption but also improve product quality and market competitiveness.

8. Conclusions and Future Work

8.1 Research Conclusions

This study has thoroughly analyzed the current status of energy consumption in silicone rubber production, identified high-energy-consuming processes such as mixing, forming, vulcanization, and post-processing, and proposed corresponding energy-saving technologies and optimization strategies. Through on-site surveys and data analysis, it was found that the mixing and vulcanization processes are the main energy-consuming points. In response to these issues, the study proposed energy-saving measures such as equipment upgrading, process optimization, application of energy management systems, and utilization of renewable energy. These measures not only effectively reduced energy consumption but also improved production efficiency and economic benefits, with significant innovation and practical application value.

8.2 Research Limitations and Future Work

Despite the achievements in energy consumption analysis and optimization strategies, there are still some limitations in this study. For example, the study mainly focuses on case analysis of specific companies, with a limited number of samples, which may affect the universality of the conclusions. In addition, the application of renewable energy in silicone rubber production is still in its infancy, lacking in-depth technical and economic evaluations.

Future research can further expand the sample range to cover more silicone rubber production companies of different types and sizes to verify the wide applicability of the optimization strategies. At the same time, in-depth studies on the integration of renewable energy sources and exploration of more innovative energy-saving technologies and management methods will contribute to the sustainable development of the silicone rubber industry.

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