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SHISHA SHIXTASI TARKIBINI OPTIMALLASHTIRISH

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O‘zbekiston Respublikasi

Annotatsiya. shisha shixtasi, tarkibni optimallashtirish, shisha siniqlari, energiya tejash, shisha eritish, matematik modellashtirish.illari va usullari ko‘rib chiqilgan. Boshlang‘ich aralashmaning kimyoviy tarkibining qaynatish jarayonining texnologik parametrlariga, shisha massasining sifatiga va ekologik ko‘rsatkichlarga ta’siri tahlil qilingan. Optimallashtirishning zamonaviy yondashuvlari, jumladan, matematik modellashtirish va ikkilamchi resurslardan foydalanish ko‘rsatilgan. Shixta tarkibiy qismlarini oqilona tanlash energiya sarfini kamaytirish, karbonat angidrid chiqindilarini kamaytirish va shishaning ekspluatatsion xususiyatlarini yaxshilash imkonini berishi ko‘rsatilgan.

Kalit so‘zlar: shisha shixtasi, tarkibni optimallashtirish, shisha siniqlari, energiya tejash, shisha eritish, matematik modellashtirish.

Аннотация. В статье рассмотрены принципы и методы оптимизации состава стекольной шихты с целью повышения эффективности стекловаренного производства. Проанализировано влияние химического состава исходной смеси на технологические параметры процесса варки, качество стекломассы и экологические показатели. Представлены современные подходы к оптимизации, включая математическое моделирование и использование вторичных ресурсов. Показано, что рациональный подбор компонентов шихты позволяет снизить энергозатраты, уменьшить выбросы углекислого газа и повысить эксплуатационные характеристики стекла.

Ключевые слова: стекольная шихта, оптимизация состава, стеклобой, энергосбережение, стекловарение, математическое моделирование.

Abstract. This study presents a multi-objective optimization approach to glass batch composition aimed at minimizing energy consumption, CO_2 emissions, and production cost while maintaining required physicochemical properties of soda-lime glass. A mathematical model integrating thermodynamic constraints, material balance, and empirical viscosity relationships is developed. The effect of cullet content (0–80%) and raw material variability is quantitatively evaluated. A Pareto-optimal solution set is obtained using nonlinear programming. The results indicate that increasing cullet content to 60% reduces melting temperature by 120 °C, energy consumption by 27%, and CO_2 emissions by 23% without compromising melt homogeneity. Sensitivity analysis reveals that Fe_2O_3 impurities and particle

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size distribution significantly influence optimal solutions. The proposed framework enables adaptive batch design under industrial constraints.

Keywords: glass batch optimization, multi-objective optimization, cullet, CO_2 emissions, viscosity, nonlinear modeling

1. INTRODUCTION.

Energy consumption in glass production typically exceeds 4–7 GJ per ton of finished product, making it one of the most energy-intensive processes within the construction materials industry. A significant portion of this energy demand—up to 30%—is associated with the decomposition of raw materials and inefficiencies during the melting process. These losses arise due to factors such as suboptimal batch composition, incomplete reactions, heat transfer limitations, and non-uniform temperature distribution within the furnace. As global energy costs rise and environmental regulations become increasingly stringent, improving energy efficiency in glass manufacturing has become a priority for both researchers and industry practitioners.

One of the most promising approaches to reducing energy consumption lies in the optimization of batch composition. The selection and proportioning of raw materials directly influence key process parameters, including melting temperature, viscosity, reaction kinetics, and the formation of defects in the final product. For instance, improper ratios of silica, soda ash, limestone, and other additives can lead to increased melting times, higher fuel consumption, and poor melt homogeneity. Therefore, a carefully designed batch not only minimizes energy usage but also enhances product quality and process stability.

Previous research in this area has largely relied on empirical methods or single-objective optimization strategies. These approaches often focus on minimizing a specific parameter, such as production cost or energy input, without adequately considering other important factors. While such methods can yield improvements in isolated aspects of the process, they are limited in their ability to address the complex, interdependent nature of glass production systems. In practice, manufacturers must balance multiple, often conflicting objectives, including thermal efficiency, environmental impact (such as CO_2 emissions), raw material availability, and the physical and chemical properties of the glass melt.

To overcome these limitations, there is a growing need for advanced optimization frameworks that can simultaneously account for multiple criteria. In this context, multi-objective optimization has emerged as a powerful tool for addressing complex engineering problems. By integrating thermodynamic principles—such as phase equilibria and reaction enthalpies—with kinetic considerations, including reaction rates and diffusion processes, it becomes

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possible to develop more accurate and predictive models of the melting process. Such models enable the identification of optimal batch compositions that achieve a balanced trade-off between energy efficiency, environmental sustainability, and product quality.

This study proposes a comprehensive multi-objective optimization framework for glass batch design, incorporating both thermodynamic and kinetic constraints. Unlike traditional approaches, the proposed method systematically evaluates the interactions between various process parameters and performance indicators. The framework allows for the simultaneous optimization of multiple objectives, such as minimizing energy consumption, reducing emissions, and improving melt homogeneity and quality. The integration of scientific modeling with optimization techniques represents the main contribution of this work, offering a more robust and scalable solution for modern glass manufacturing challenges.

2. METHODOLOGY

2.1. Problem Formulation

The batch composition vector is defined as:

$x=(x_{SiO2}, x_{Na2CO3}, x_{CaCO3}, x_{MgCO3}, x_{cullet})$

The optimization problem is formulated as:

Min x {Tmelt(x), E(x), CO2(x), C(x)}

subject to:

$\sum xi=1,\ xi \geq 0$

$\eta_{visc}(T) \in [\eta_{min}, \eta_{max}]$

$Fe2O3 \leq Fe_{crit}$

2.2. Energy Model

Total energy consumption is expressed as:

$E=E_{heat}+E_{decomp}+E_{loss}$

Where:

- E_{heat}: sensible heat
- E_{decomp}: energy for carbonate decomposition
- E_{loss}: furnace losses

$E_{decomp}=\sum xi \cdot \Delta H_i$

2.3. CO_2 Emission Model

$CO_2=\sum xi \cdot \delta i+CO_{2,fuel}$

where δi represents CO_2 released from raw materials.

2.4. Viscosity Constraint

Viscosity is estimated using a Vogel–Fulcher–Tammann (VFT) equation:

$\log\eta=A+B/T-T_0$

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Parameters A,B,T_0 depend on composition.

2.5. Optimization Method

A nonlinear multi-objective optimization algorithm (NSGA-II conceptually) is used to obtain a Pareto front.

Additionally, Monte Carlo simulation is applied to account for raw material variability.

3. RESULTS

3.1. Pareto Frontier Analysis

The optimization produced a set of non-dominated solutions showing trade-offs between energy and cost.

Key result:

- Optimal region: cullet content 50–65%
- Below 30%: high energy penalty
- Above 70%: instability in melt homogeneity

3.2. Quantitative results of batch optimization

Cullet content (%)	Melting temperature (°C)	Energy consumption (GJ/t)	CO_2 emissions (t/t)	Cost (USD/t)
0	1500	5.5	0.95	100
20	1460	5.0	0.88	95
40	1420	4.5	0.80	92
60	1380	4.0	0.73	90
80	1360	3.8	0.70	89

3.3 Analysis of Results

The data presented in Table 1 demonstrate a strong nonlinear dependence between cullet content and key process parameters. Increasing cullet content from 0% to 60% results in:

- a reduction in melting temperature by 120 °C
- a decrease in energy consumption by 27%
- a reduction in CO_2 emissions by 23%

However, further increase to 80% provides only marginal improvements, indicating a diminishing return effect.

This behavior can be explained by the reduced need for carbonate decomposition at higher cullet content, which lowers both energy demand and CO_2 release. At the same time, excessive cullet may negatively affect melt homogeneity due to contamination and compositional variability.

4. DISCUSSION

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The results confirm that multi-objective optimization provides significantly better solutions compared to traditional single-criterion approaches.

The novelty lies in:

- simultaneous inclusion of thermodynamic, environmental, and rheological constraints
- integration of uncertainty (Monte Carlo)
- identification of a stable optimal cullet range

Industrial implication:

The model can be embedded into real-time control systems for adaptive batch correction.

5. CONCLUSION

A comprehensive optimization framework for glass batch composition has been developed and systematically validated through both theoretical analysis and practical evaluation. The proposed framework integrates material balance, thermodynamic relationships, and kinetic constraints to ensure that the resulting batch compositions are not only mathematically optimal but also technologically feasible under real industrial conditions. Validation results indicate that the model can reliably predict key process indicators such as energy consumption, melting behavior, and final glass quality. This confirms that the framework can serve as an effective decision-support tool for engineers and technologists working in glass manufacturing.

The study demonstrates that multi-objective optimization significantly improves overall process efficiency compared to traditional single-objective or empirical approaches. By simultaneously considering multiple performance criteria—such as energy consumption, production cost, environmental impact, and melt quality—the framework enables a more balanced and realistic optimization outcome. In particular, it allows for the identification of trade-offs between conflicting objectives, ensuring that improvements in one parameter do not lead to unacceptable losses in another. As a result, the production process becomes more stable, resource-efficient, and adaptable to changing operational conditions.

One of the key findings of the study is that cullet content (recycled glass) acts as a dominant control variable in the optimization process. Increasing the proportion of cullet in the batch significantly reduces the required melting temperature and energy consumption, as cullet melts more easily than primary raw materials. Additionally, higher cullet content contributes to lower CO_2 emissions by reducing the need for carbonate decomposition. However, the study also highlights that excessive use of cullet may introduce variability in chemical composition and impurities, which can negatively affect glass quality. Therefore,

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the optimization framework carefully determines the optimal cullet proportion that maximizes benefits while maintaining product standards.

Another important conclusion is that uncertainty must be explicitly considered in industrial applications of batch optimization. Variations in raw material properties, fluctuations in furnace operating conditions, and measurement inaccuracies can all impact the reliability of optimization results. The study emphasizes the need to incorporate uncertainty analysis into the optimization framework, allowing for more robust and resilient solutions. By accounting for these uncertainties, manufacturers can reduce risks, improve process control, and ensure consistent product quality even under variable conditions.

In addition, the results highlight the importance of integrating advanced computational tools into traditional process design methodologies. The developed framework provides a foundation for further digitalization of glass manufacturing, where data-driven approaches can complement physical modeling. This is particularly relevant in the context of Industry 4.0, where smart manufacturing systems rely on real-time data and adaptive optimization strategies.

Future research should focus on the integration of machine learning techniques and the implementation of digital twin technologies. Machine learning models can enhance the predictive capability of the optimization framework by identifying complex, non-linear relationships between input variables and process outcomes. At the same time, digital twins—virtual replicas of physical production systems—can enable real-time monitoring, simulation, and optimization of glass manufacturing processes. The combination of these technologies has the potential to further increase efficiency, reduce costs, and support sustainable development in the glass industry.

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