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Kinetic Aspects of Nitrogen Removal during Vacuum Treatment of Low-Alloy Steels

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Abstract

This study investigates the kinetic features of nitrogen removal during vacuum treatment of low-alloy steels under industrial conditions. The removal of dissolved nitrogen during vacuum treatment is a critical stage in the production of low-alloy steels, as excessive nitrogen content negatively affects mechanical properties and service performance. Although thermodynamic conditions under vacuum are favorable for nitrogen desorption, industrial practice shows that degassing efficiency is often limited by kinetic factors. The analysis is based on industrial data obtained from vacuum degassing operations and is supported by classical mass transfer theory and kinetic modeling concepts. Nitrogen removal is considered as a diffusion-controlled process described by a first-order kinetic approach, with particular attention given to the influence of vacuum stability, bubble dynamics, and metal–gas interaction mechanisms. The results demonstrate that stable vacuum conditions significantly enhance nitrogen removal efficiency, whereas pressure fluctuations reduce mass transfer effectiveness and may lead to partial nitrogen reabsorption. Comparison with published numerical and industrial studies confirms that kinetic limitations play a decisive role in determining the final nitrogen content after vacuum treatment. The findings highlight the importance of integrating theoretical models with real industrial data to ensure stable and reproducible refining results. The proposed approach provides a practical basis for optimizing vacuum degassing parameters and improving the quality of low-alloy steels in industrial steelmaking.

Keywords: vacuum treatment, nitrogen removal, low-alloy steels, degassing kinetics, mass transfer, industrial steelmaking

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Azlegirli poladların vakuum emalı zamanı azotun kənarlaşdırılmasının kinetik aspektləri

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Xülasə

Bu tədqiqat azlegirli poladların vakuum emalı zamanı azotun kənarlaşdırılmasının kinetik xüsusiyyətlərinin sənaye şəraitində araşdırılmasına həsr olunub. Azlegirli poladların istehsalında vakuum emalı zamanı həll olmuş azotun kənarlaşdırılması mühüm texnoloji mərhələdir, çünki azotun yüksək miqdarı poladın mexaniki xassələrinə və istismar göstəricilərinə mənfi təsir göstərir. Vakuum şəraitində azotun kənarlaşdırılması üçün termodinamik imkanlar əlverişli olsa da, sənaye təcrübəsi göstərir ki, prosesin effektivliyi çox vaxt kinetik amillərlə məhdudlaşır. Tədqiqat vakuum qazsızlaşdırma qurğularında aparılmış sənaye müşahidələrinə əsaslanır və kütlə mübadiləsinin klassik nəzəri müddəaları ilə dəstəklənir. Azotun kənarlaşdırılması birinci dərəcəli kinetik model əsasında diffuziya ilə məhdudlaşan proses kimi qiymətləndirilib, vakuumun sabitliyinin, qabarcıq dinamikasının və metal–qaz qarşılıqlı təsirinin rolu təhlil olunub. Nəticələr göstərir ki, vakuumun sabit saxlanılması azotun kənarlaşdırılmasının effektivliyini artırır, təzyiq dəyişkənliyi isə prosesin intensivliyini azaldır və azotun yenidən udulmasına səbəb ola bilər. Alınmış nəticələr vakuum rafinasiyası proseslərinin optimallaşdırılması və polad keyfiyyətinin yüksəldilməsi üçün praktiki əhəmiyyət daşıyır.

Açar sözlər: vakuum emalı, azotun kənarlaşdırılması, azlegirli poladlar, qazsızlaşdırma kinetikası, kütlə mübadiləsi, sənaye polad istehsalı.

Кинетические аспекты удаления азота при вакуумной обработке низколегированных сталей

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Аннотация

В данной работе исследуются кинетические особенности удаления азота при вакуумной обработке низколегированных сталей в промышленных условиях. Удаление растворённого азота при вакуумной обработке является важнейшим этапом производства низколегированных сталей, поскольку повышенное содержание азота отрицательно влияет на их механические свойства и эксплуатационные характеристики. Несмотря на благоприятные термодинамические условия вакуумирования, промышленная практика показывает, что эффективность дегазации в значительной степени определяется кинетическими факторами. Анализ основан на данных, полученных в процессе промышленной вакуумной дегазации, и опирается на классические представления теории массопереноса. Процесс удаления азота рассматривается как диффузионно-ограниченный и описывается кинетической моделью первого порядка с учётом влияния стабильности вакуума, динамики газовых пузырьков и взаимодействия металл–газ. Установлено, что стабильный вакуум существенно повышает эффективность дегазации, тогда как колебания давления снижают интенсивность массопереноса и могут приводить к повторному насыщению металла азотом. Сопоставление результатов с опубликованными исследованиями подтверждает определяющую роль кинетических ограничений в процессе вакуумной обработки. Полученные выводы могут быть использованы для оптимизации параметров вакуумной дегазации и повышения качества низколегированных сталей.

Ключевые слова: вакуумная обработка, удаление азота, низколегированные стали, кинетика дегазации, массоперенос, промышленная металлургия.

Herald of the Azerbaijan Engineering Academy
2026, vol. 18, ONLINE
I. A. Behbudlu

Introduction

The quality of steel and its service performance are strongly influenced by the content of dissolved gases, particularly nitrogen and hydrogen, which adversely affect mechanical properties, ductility, and fatigue resistance. In low-carbon and low-alloy steels, excessive nitrogen content may lead to strain aging, embrittlement, and reduced formability, making effective gas removal an essential stage of secondary steel refining [1–3]. As a result, vacuum treatment has become one of the most important technological operations in modern steelmaking, enabling the reduction of dissolved gases to levels unattainable under atmospheric conditions.

The fundamental principles governing gas–metal interactions during steel refining are determined by thermodynamic equilibria and kinetic limitations. According to classical steelmaking theory, the removal of dissolved gases under vacuum conditions is driven by the decrease in partial pressure above the melt surface and is controlled by diffusion and mass transfer processes in both the liquid metal and the gas phase [1, 2]. However, despite favorable thermodynamic conditions, the actual efficiency of degassing processes in industrial units is often limited by kinetic factors, including melt stirring intensity, bubble formation and growth, interfacial area, and residence time under reduced pressure [3].

Industrial experience demonstrates that vacuum degassing units such as vacuum tank degassers and circulating vacuum degassers are capable of significantly reducing nitrogen and hydrogen content when process parameters are properly controlled. Studies conducted under industrial conditions at large steel plants confirm that the kinetics of gas removal depend not only on pressure level but also on melt circulation, bubble dynamics, and the stability of vacuum conditions throughout the treatment cycle [4,5]. Fluctuations in pressure or insufficient mass transfer may lead to incomplete degassing or even reabsorption of gases during treatment.

Recent research has increasingly focused on numerical and analytical modeling of vacuum degassing processes in order to better understand the mechanisms of gas removal and to optimize industrial practice. Numerical studies of hydrogen and nitrogen removal in vacuum tank degassers indicate that mass transfer coefficients and bubble behavior play a decisive role in determining degassing efficiency [6]. Investigations of bubble growth and flotation in molten steel systems further reveal that the dynamics of gas bubbles directly influence the effective interfacial area and, consequently, the rate of gas desorption [7]. Mathematical models developed for vacuum degassing processes have shown good agreement with experimental data and provide valuable tools for predicting gas removal under varying technological conditions [8].

At the same time, the practical implementation of vacuum refining technologies requires adaptation to specific industrial environments, equipment configurations, and steel grades. In this context, studies carried out at industrial enterprises, including steel plants operating in Azerbaijan, emphasize the importance of integrating theoretical models with real production data to achieve stable and efficient refining processes [9]. Previous investigations of vacuum refining of low-carbon and low-alloy steels have demonstrated that a combined thermodynamic and kinetic approach is necessary for a reliable assessment of degassing performance under industrial conditions [10].

Herald of the Azerbaijan Engineering Academy
2026, vol. 18, ONLINE
I. A. Behbudlu

Therefore, a comprehensive analysis of nitrogen removal during vacuum treatment of low-alloy steels, based on both industrial data and kinetic considerations, remains a relevant scientific and practical task. Such studies contribute to improving process stability, enhancing steel quality, and optimizing the operation of vacuum degassing units in modern steelmaking practice.

Purpose of the Study

The purpose of this study is to investigate the kinetic features of nitrogen removal during vacuum treatment of low-alloy steels under industrial conditions. Particular attention is given to the influence of process parameters on the efficiency of degassing, including vacuum level, mass transfer conditions, and melt–gas interaction mechanisms. The study aims to evaluate the role of kinetic limitations in nitrogen removal and to substantiate approaches for improving the stability and effectiveness of vacuum refining processes based on industrial data and established theoretical concepts.

Problem Statement

Despite the widespread application of vacuum degassing technologies in modern steelmaking, the efficient removal of nitrogen from low-alloy steels under industrial conditions remains a complex and insufficiently resolved problem. Although thermodynamic conditions under reduced pressure are favorable for gas desorption, practical steelmaking experience shows that achieving stable and predictable nitrogen removal is often limited by kinetic factors rather than equilibrium constraints [1–3]. As a result, significant discrepancies are frequently observed between theoretically attainable and actually achieved nitrogen concentrations after vacuum treatment.

Industrial studies conducted on circulating and vacuum tank degassers demonstrate that nitrogen removal efficiency is highly sensitive to process conditions, including vacuum stability, melt circulation intensity, and the dynamics of gas–metal interaction [4,5]. In real production environments, pressure fluctuations, non-uniform stirring, and variations in bubble formation may lead to reduced mass transfer rates and, in some cases, partial reabsorption of nitrogen into the molten steel. These effects complicate process control and reduce the reproducibility of refining results.

Existing numerical and analytical models of vacuum degassing processes provide valuable insight into hydrogen and nitrogen removal mechanisms; however, many of these models are based on idealized assumptions that do not fully account for the variability of industrial operating conditions [6–8]. In particular, the influence of transient vacuum regimes and kinetic limitations on nitrogen removal in low-alloy steels requires further clarification. The lack of sufficiently validated kinetic data obtained under industrial-scale conditions limits the practical applicability of theoretical models in steel plant operations.

Furthermore, the adaptation of vacuum refining technologies to specific steel grades and production facilities remains an important challenge. Studies performed at industrial enterprises emphasize the need to integrate theoretical approaches with real production data to ensure process stability and consistent steel quality [9]. Previous investigations of vacuum refining of low-carbon and low-alloy steels confirm that nitrogen removal kinetics must be evaluated in close connection with

Herald of the Azerbaijan Engineering Academy
2026, vol. 18, ONLINE
I. A. Behbudlu

industrial process parameters rather than considered solely from a thermodynamic perspective [10].

In this context, there is a clear need for a focused analysis of nitrogen removal kinetics during vacuum treatment of low-alloy steels based on industrial conditions. Addressing this problem is essential for improving the reliability of vacuum degassing processes, optimizing technological parameters, and enhancing the overall efficiency of secondary steel refining.

Solution and Methodology

The solution to the stated problem is based on a combined analytical and industrial approach to the study of nitrogen removal during vacuum treatment of low-alloy steels. The methodology integrates classical kinetic concepts of gas–metal interaction with data obtained under industrial operating conditions, allowing for a realistic assessment of nitrogen removal efficiency in vacuum degassing units.

The investigation considers vacuum treatment processes carried out in industrial vacuum degassers used for secondary steel refining. The analyzed steels belong to the class of low-alloy grades commonly produced under vacuum conditions. Nitrogen content in the molten steel was monitored before and after vacuum treatment cycles using standard industrial analytical methods. The vacuum pressure, treatment duration, and general operating parameters of the degasser were recorded to ensure consistency and comparability of the analyzed data.

From a theoretical perspective, nitrogen removal during vacuum treatment is described as a mass transfer–controlled process governed by diffusion mechanisms in the molten steel and at the metal–gas interface. In accordance with established steelmaking theory, the rate of nitrogen removal can be expressed using a first-order kinetic model, where the change in nitrogen concentration over time depends on the mass transfer coefficient and the effective interfacial area between the molten steel and the gas phase [1–3]. This approach is widely applied in the analysis of vacuum degassing processes and provides a practical framework for evaluating kinetic limitations under industrial conditions.

To account for the influence of gas bubble formation and motion on nitrogen removal, the methodology incorporates concepts related to bubble growth and flotation behavior in molten steel. The presence of ascending gas bubbles during vacuum treatment enhances the interfacial area available for mass transfer and intensifies degassing kinetics [6,7]. Variations in bubble dynamics, caused by changes in vacuum level or melt circulation intensity, were considered as factors affecting the overall efficiency of nitrogen removal.

The influence of vacuum stability on nitrogen removal during treatment is illustrated in Figure.

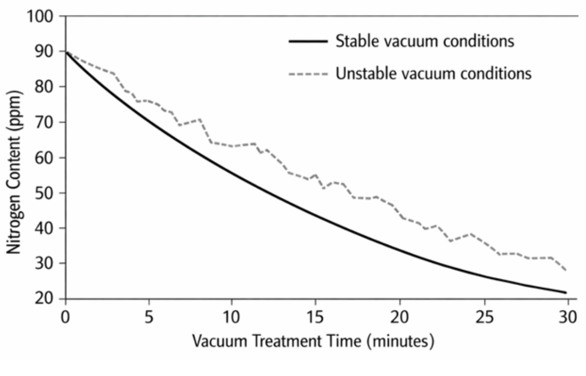

Figure – Effect of vacuum stability on nitrogen removal kinetics during vacuum treatment of low-alloy steels

As shown in Figure, stable vacuum conditions ensure a continuous and more

Herald of the Azerbaijan Engineering Academy
2026, vol. 18, ONLINE
I. A. Behbudlu

intensive decrease in nitrogen content over time, whereas unstable vacuum conditions result in slower removal rates accompanied by fluctuations. This behavior confirms the dominant role of kinetic limitations and mass transfer efficiency in determining the effectiveness of nitrogen removal during industrial vacuum treatment. The trends presented in Figure represent generalized industrial behavior and are used to illustrate the influence of vacuum stability on nitrogen removal kinetics.

In addition, numerical and analytical modeling results reported in the literature were used to support the interpretation of industrial observations. Mathematical models describing hydrogen and nitrogen removal in vacuum degassers served as a reference for evaluating the consistency of experimental data with theoretical predictions [6–8]. This comparative analysis made it possible to identify deviations associated with non-ideal industrial conditions, such as pressure fluctuations and transient vacuum regimes.

Special attention was given to the role of vacuum stability during treatment. Industrial data were analyzed with respect to the consistency of reduced pressure over time, as vacuum instability is known to negatively affect mass transfer conditions and may lead to partial reabsorption of nitrogen into the molten steel [4,5]. The methodology thus emphasizes the importance of maintaining stable vacuum conditions to achieve reproducible and efficient nitrogen removal.

Finally, the obtained results were compared with previously published data on vacuum refining of low-carbon and low-alloy steels to ensure methodological continuity and validation of the applied approach [10]. This integrated methodology provides a reliable basis for assessing nitrogen removal kinetics under industrial conditions and for formulating practical recommendations aimed at improving vacuum degassing performance.

Conclusion

The analysis of nitrogen removal during vacuum treatment of low-alloy steels has shown that, despite favorable thermodynamic conditions under reduced pressure, the efficiency of degassing is primarily governed by kinetic factors. Industrial data confirm that nitrogen removal cannot be reliably predicted based solely on equilibrium considerations and requires a detailed assessment of mass transfer conditions during vacuum treatment.

It has been established that the stability of vacuum conditions plays a decisive role in the kinetics of nitrogen removal. Fluctuations in pressure and non-uniform operating regimes reduce the effectiveness of gas–metal interaction and may lead to partial reabsorption of nitrogen into the molten steel, thereby decreasing the overall efficiency of the refining process.

The applied first-order kinetic approach, combined with industrial observations, provides a practical framework for evaluating nitrogen removal under real production conditions. Consideration of bubble dynamics and interfacial mass transfer mechanisms allows for a more accurate interpretation of degassing behavior in vacuum degassers and explains deviations from idealized theoretical models.

Comparison with previously published data on vacuum refining of low-carbon and low-alloy steels confirms the validity of the adopted methodology and highlights the necessity of integrating theoretical models with industrial-scale data. Such integration is essential for achieving stable and reproducible refining results.

The findings of this study can be used to optimize technological parameters of vacuum degassing units, improve process stability, and enhance the quality of low-alloy steels. The proposed approach contributes to the development of more efficient secondary steel refining practices and provides a basis for further investigations into the kinetics of gas removal under industrial conditions.

Conflict of Interests

The author declares there is no conflict of interests related to the publication of this article.

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