

INTISARI

Unit *Primary Reformer* merupakan komponen vital dalam pabrik amonia dengan konsumsi energi terbesar, di mana efisiensi proses sangat bergantung pada stabilitas kinerja katalis berbasis nikel. Seiring berjalannya waktu, maka deaktivasi katalis akibat *sintering*, *coking*, dan *poisoning* dapat terjadi yang antara lain dapat diobservasi melalui dinamika *Pressure Drop* dan *Methane Slip*. Keterlambatan dalam mendeteksi penurunan kinerja katalis dapat berdampak signifikan pada efisiensi konversi dan konsumsi energi pabrik. Penelitian ini bertujuan untuk mengembangkan model prediktif berbasis *Machine Learning* guna mengevaluasi kinerja reaktor melalui dua indikator kunci secara *real-time*, yaitu *Pressure Drop* sebagai indikator degradasi fisik dan *Methane Slip* sebagai indikator deaktivasi kimia, menggunakan data operasional historis industri.

Metodologi penelitian mengintegrasikan pendekatan berbasis data dengan validasi berbasis prinsip teknik kimia. Data sensor industri memiliki karakteristik *time-series* dan mengandung *noise* diproses melalui dua strategi pra-pemrosesan yang dievaluasi secara komparatif, yaitu pembersihan manual berbasis pengetahuan domain dan metode otomatis menggunakan algoritma *Isolation Forest*. Selanjutnya, tiga algoritma pemodelan dikembangkan dan diuji kinerjanya, yakni ARIMA sebagai *baseline* statistik linier, serta *Random Forest Regressor* dan *eXtreme Gradient Boosting* sebagai representasi metode *ensemble learning* non-linier. Validasi model dilakukan secara komprehensif menggunakan metrik evaluasi kesalahan statistik, uji signifikansi statistik, serta interpretasi fisik melalui analisis signifikansi fitur dan plot ketergantungan parsial untuk memastikan model mematuhi hukum kesetimbangan Le Chatelier dan persamaan Ergun.

Hasil menunjukkan bahwa metode pembersihan manual lebih unggul dalam mempertahankan integritas sinyal fisik data industri dibandingkan *Isolation Forest*, yang cenderung menghilangkan data operasional valid pada kondisi beban tinggi. Model *Random Forest Regressor* terbukti sebagai arsitektur paling andal dan *robust*, mencatatkan kinerja terbaik dalam *Root Mean Squared Error* (RMSE) sebesar 0,0336 $\text{kg/cm}^2 \cdot \text{G}$ untuk *Pressure Drop* dan 0,28 % CH_4 dalam gas alam untuk *Methane Slip*. Uji statistik mengonfirmasi *Random Forest Regressor* mengungguli model pembandingan lainnya. Analisis interpretasi model memvalidasi konsistensi prediksi terhadap prinsip fisik di mana Laju Alir *Steam* dan Laju Alir Gas Alam teridentifikasi sebagai variabel yang paling berpengaruh. Penelitian ini menyimpulkan bahwa model *Machine Learning* yang dikembangkan layak diimplementasikan sebagai sistem peringatan dini untuk mendukung strategi pemeliharaan dan optimasi energi di pabrik amonia.

Kata kunci: *primary reformer; machine learning; random forest regressor; pressure drop; methane slip*

ABSTRACT

The Primary Reformer represents a critical, energy-intensive unit in ammonia plant, where process efficiency heavily relies on the stability of nickel-based catalyst performance. Over time, catalyst deactivation caused by sintering, coking, and poisoning occurs, observable through the dynamics of Pressure Drop and Methane Slip. Delays in detecting such performance degradation can significantly impact conversion efficiency and overall plant energy consumption. This study aims to develop Machine Learning-based predictive model to evaluate reactor performance through two key indicators in real-time, namely Pressure Drop as an indicator of physical degradation and Methane Slip as an indicator of chemical deactivation, using historical industrial operational data.

The research methodology integrates a data-driven approach validation based on chemical engineering principles. Industrial sensor data, characterized by time-series properties and inherent noise, were processed using two comparative preprocessing strategies, using domain knowledge-based manual cleaning and an automated method using Isolation Forest algorithm. Subsequently, three modeling algorithms were developed and tested, using ARIMA as a linear statistical baseline, and Random Forest and eXtreme Gradient Boosting as representatives of non-linear ensemble learning methods. Model validation was conducted comprehensively using statistical error metrics, significance testing, and physical interpretation via feature importance analysis and partial dependence plots to ensure the model adheres to Le Chatelier's principle and the Ergun Equation.

Results indicate that the manual cleaning method outperformed Isolation Forest in maintaining the physical signal integrity of industrial data, as the automated method tended to eliminate valid operational data under high load conditions. The Random Forest Regressor model proved to be the most reliable and robust architecture, recording the best performance with a Root Mean Squared Error (RMSE) of $0.0336 \text{ kg/cm}^2 \cdot \text{G}$ for Pressure Drop and $0.028 \% \text{ CH}_4$ in natural gas for Methane Slip. Statistical tests confirmed that the Random Forest Regressor outperformed other comparative models. Model interpretation analysis validated the consistency of prediction against physical principles. Identifying Steam Flow Rate and Natural Gas Flow Rate as the most influential variables. This study concludes that the developed Machine Learning model is suitable for implementation as an early warning system to support maintenance strategies and energy optimization in ammonia plants.

Keywords: *primary reformer; machine learning; random forest regressor; pressure drop; methane slip*