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ARTIFICIAL NEURAL NETWORK-BASED PREDICTION OF IN-CYLINDER PRESSURE AND PRESSURE RISE RATE IN A PCCI DIESEL ENGINE

Summary. This study experimentally collected in-cylinder pressure data from a diesel engine operating under premixed charge compression ignition (PCCI) conditions. The input parameters included advanced ignition timings of 40°, 45°, 50°, 55°, and 60° CA BTDC, and a crank angle range of 320°-420° CA. Accordingly, pressure traces corresponding to each ignition timing were obtained, yielding a total of 505 data points, with 101 points per pressure trace. Based on the experimental dataset, an artificial neural network (ANN) model was developed for pressure prediction and accuracy assessment. The results indicate that the model achieves very high accuracy, with R^2 , RMSE, and MAE values of 0.9983, 0.9397 bar, and 0.6937 bar, respectively, for the training dataset, and 0.9981, 1.0115 bar, and 0.7268 bar for the testing dataset. These results confirm the strong generalization capability and reliability of the ANN model. Given the validated accuracy, the ANN model was further applied to predict four additional pressure traces at ignition timings of 30°, 35°, 65°, and 70° CA BTDC, corresponding to 404 predicted pressure points. By combining the experimental and predicted datasets (909 pressure points in total), the pressure rise rate was calculated and a three-

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dimensional (3D) model was established. This model clearly illustrates the distribution and variation patterns of key combustion-related parameters in a PCCI diesel engine, thereby providing a valuable database and scientific foundation for future studies on combustion analysis, optimization, and AI-based engine prediction and control.

Keywords: PCCI combustion, in-cylinder pressure, artificial neural network, pressure rise rate

1. INTRODUCTION

Emissions generated by internal combustion engine (ICE)-powered vehicles pose significant threats to both human health and the environment [1]. Nevertheless, more than 1.4 billion vehicles worldwide were still powered by ICEs as of 2023 [2], indicating their continued dominance in current transportation systems. Among these technologies, diesel engines remain difficult to replace due to their high thermal efficiency, durability, and operational reliability, particularly in heavy-duty applications. Consequently, improving diesel engine technologies to mitigate environmental impacts has become an urgent and widely studied research topic. High emissions from conventional diesel engines primarily originate from inhomogeneous air-fuel mixing and heterogeneous combustion processes, which simultaneously generate fuel-rich and fuel-lean regions as well as strong temperature gradients within the combustion chamber. To address these issues, low-temperature combustion (LTC) strategies have been extensively investigated. Among them, premixed charge compression ignition (PCCI) has attracted considerable attention due to its potential to improve combustion characteristics and significantly reduce emissions [3,4]. PCCI combustion, derived from the homogeneous charge compression ignition (HCCI) concept, involves early fuel injection to promote premixing before auto-ignition during the compression stroke. This approach leads to a relatively homogeneous mixture prior to ignition, resulting in lower peak combustion temperatures and reduced formation of nitrogen oxides (NO_x) and soot compared to conventional diesel combustion. In practical applications, PCCI operation is typically combined with injection timing control, exhaust gas recirculation (EGR), and multi-stage injection strategies to enhance mixture preparation and combustion controllability [5-7]. Although recent studies have demonstrated that optimized injection strategies and EGR rates can extend the operating load range and reduce HC/CO emissions, challenges related to combustion control and limited operating range remain [8-9]. With rapid advancements in computational technologies, internal combustion engine research has increasingly incorporated artificial intelligence (AI)-based approaches alongside traditional experimental methods. Artificial neural networks (ANNs), in particular, have demonstrated strong capabilities in modeling highly nonlinear systems with multiple interacting parameters. For instance, Foroutani et al. [10] successfully applied ANN models to predict performance and emissions of a heavy-duty diesel engine fueled with syngas, achieving high prediction accuracy across different operating conditions. Similarly, Odufuwa [11] developed an ANN-based predictive framework for small diesel engines, demonstrating significant improvements in performance optimization and emission reduction. AI-based approaches have also been applied to advanced combustion concepts such as PCCI. Cheng Ma et al. [12] combined long short-term memory (LSTM) networks with NSGA-II optimization to enhance performance and emission characteristics of a CNG/diesel dual-fuel engine operating in PCCI mode, achieving substantial reductions in NO_x and fuel consumption. Despite these advancements, studies focusing on ANN-based modeling and prediction of in-cylinder pressure

under PCCI combustion remain relatively limited. Given the strong nonlinear behavior and complex combustion kinetics inherent to PCCI operation, ANN models offer a promising solution due to their computational efficiency and adaptability. Motivated by this research gap, the present study develops an ANN-based model to predict in-cylinder pressure at new injection advance angles using experimentally measured pressure data. Furthermore, the predicted pressure data are utilized to calculate the pressure rise rate, providing deeper insights into combustion characteristics and enabling identification of optimal operating regions for PCCI diesel engines.

2. METHODOLOGY

2.1. Experimental Setup

Figure 1 illustrates the schematic diagram of the experimental engine test bench, which consists of major components such as an AC electric dynamometer, an exhaust gas analysis system, a fuel supply system, an engine control system, and various measuring instruments. The test engine is a Changchai 192FA diesel engine (2), a single-cylinder four-stroke engine, directly coupled to a DW16 dynamometer (1) and equipped with a Common Rail fuel injection system. Intake air is drawn from the ambient environment through an air filter and an intake air flow meter (7), then passes through a surge tank (8) to attenuate pressure fluctuations caused by the cyclic intake process of the engine. Diesel fuel is supplied to the Common Rail injection system, where the fuel pressure is compressed to a high level, monitored by a pressure sensor (11), and controlled by the electronic control unit (ECU) (15). In-cylinder combustion is analyzed using a combustion analysis system, which employs signals from a speed sensor (3) and a crankshaft position sensor (4) to determine the engine speed and crank angle position, thereby enabling combustion analysis and measurement data synchronization. A lambda sensor (5) is installed in the exhaust line to measure the excess air ratio, while the exhaust gases are directed to an exhaust gas analyzer (6) to determine the emission components. The overall operation of the system is monitored and managed by the ECU (15) and the central control computer (14), allowing for data acquisition, processing, and synchronization throughout the experimental campaign.

Table 1 summarizes the main technical specifications of the Changchai 192FA engine used in the experimental study.

Tab. 1

Technical specifications of the test engine

Specification	Changchai 192FA engine
Cylinder bore, [mm]	92
Stroke [mm]	76
Displacement volume [cm ³]	504
Compression ratio	19
Rated power [kW]	8.2
Rated speed [rpm]	3600

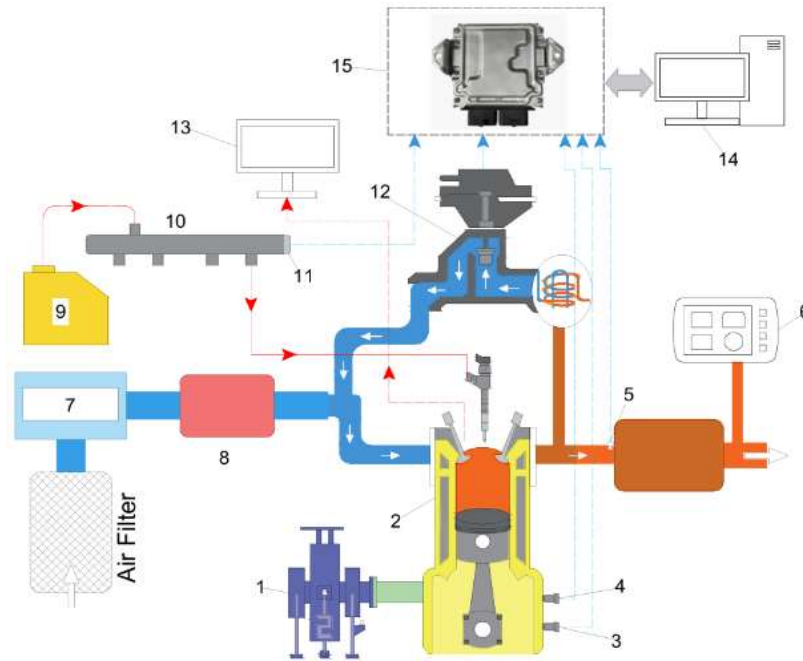


Fig. 1. Schematic diagram of the experimental engine test bench

2.2. Predictive Capability Evaluation

Artificial Neural Networks (ANNs) are machine learning models inspired by the structure and functional mechanisms of the human brain. ANNs are developed to efficiently address tasks such as prediction, classification, complex pattern recognition, and data processing, particularly in systems characterized by nonlinear relationships [13]. Evaluating the predictive capability and accuracy of any machine learning model, in general, and artificial neural network models, in particular, is a crucial step to ensure the reliability of the model. In this study, the model performance is assessed using the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE). These metrics are widely used to compare prediction errors in forecasting problems [14].

Root Mean Squared Error (RMSE) calculates the average deviation between predicted values and actual values.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - y'_i)^2} \quad (1)$$

Mean Absolute Error (MAE) calculates the average of the absolute errors between the actual and predicted values.

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i| \quad (2)$$

R^2 (Coefficient of Determination): A statistical indicator that shows the proportion of variance in the target to be predicted that is explained by the input variables in the model.

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (3)$$

y_i is the actual value and $\hat{y}_i$ is predicted value, $\bar{y}$ is the average of the actual values.

2.3. Theoretical Basis for Boost Pressure Calculation

The rate of pressure change with respect to the crank angle is determined to evaluate the pressure development during the combustion process. This parameter reflects the intensity of combustion and is commonly used to analyze the combustion characteristics of internal combustion engines. In this study, the rate of pressure rise with respect to the crank angle is calculated using the finite difference method. The influence of crank angle resolution on pressure-derived parameters has been thoroughly investigated by Brunt and Lucas [14].

$$\frac{dP}{d\theta} = \frac{P_2 - P_1}{\theta_2 - \theta_1} \quad (4)$$

where:

θ is the crank angle (°CA – crank angle);

P_1 is the in-cylinder pressure at crank angle θ_1 ;

P_2 is the in-cylinder pressure at crank angle θ_2 .

The above expression represents a finite-difference approximation of the derivative:

$$\frac{dP}{d\theta} \approx \frac{\Delta P}{\Delta \theta} \quad (5)$$

2.4. Dataset Used for the Model

Figure 2 shows the distribution of in-cylinder pressure as a function of crank angle for different advanced injection timings (40°, 45°, 50°, 55°, and 60° CA BTDC), corresponding to 101 data points for each injection timing. Consequently, a total of 505 pressure data points were collected during the experimental campaign. It can be observed that the pressure curves exhibit relatively similar shapes, with the peak pressure occurring around the TDC region (~360-370° CA), which is characteristic of PCCI combustion dominated by premixed combustion. Variations in injection timing result in only minor changes in the peak pressure magnitude, indicating that the compression and auto-ignition processes are relatively stable. This behavior is consistent with the low-temperature combustion and mixture stratification characteristics of PCCI. The experimental in-cylinder pressure data corresponding to injection timings ranging from 40° to 60° CA BTDC were selected for processing and analysis, as this range represents a stable operating region characteristic of the PCCI combustion mode. This injection timing interval clearly reflects premixed mixture formation, auto-ignition, and hybrid combustion characteristics (premixed-diffusive), while ensuring good repeatability and reliability of the experimental data. Therefore, this dataset was used as the basis for training and evaluating the predictive model, as well as for subsequent analyses of pressure rise rate and in-cylinder pressure trends. The dataset was divided into 80% for training (404 data points) and 20% for testing the predictive accuracy of the model (101 data points).

The evaluation results presented in Table 3 indicate that the ANN model achieves high accuracy and exhibits stable performance on both the training and testing datasets. Specifically, the coefficient of determination R^2 reaches 0.9983 for the training set and 0.9981 for the testing set, with a negligible difference of only 0.0002 (approximately 0.02%), demonstrating the excellent generalization capability of the model. The RMSE increases slightly from 0.9397 for the training dataset to 1.0115 for the testing dataset, corresponding to an increase of approximately 7.64%, while the MAE rises from 0.6937 to 0.7268, with a difference of about

4.77%. These deviations remain below 10%, which is within the acceptable range for nonlinear prediction models. These results confirm that the ANN model not only provides high prediction accuracy but also ensures good stability and reliability, with no evidence of overfitting, making it well suited for in-cylinder pressure prediction in PCCI engines. The discrepancies between the experimental and ANN-predicted pressure values are illustrated in detail in Figure 3.

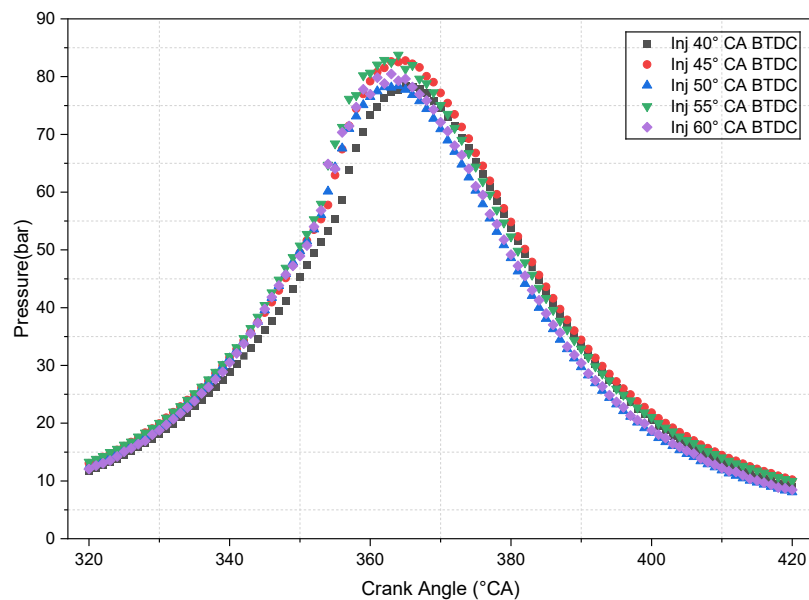


Fig. 2. In-cylinder pressure as a function of crank angle for different advanced injection timings

Tab. 2

Performance of the pressure prediction model

Pharse	R^2	RMSE	MAE
Train	0.9983	0.9397	0.6937
Test	0.9981	1.0115	0.7268

The error distributions for both the training and testing datasets are centered around zero, indicating the absence of systematic bias in the model. The mean error values of the two datasets are nearly identical, with a central deviation of less than 0.1 pressure units, reflecting the stability of the ANN model. The error distribution of the testing dataset is slightly wider than that of the training dataset, but the difference is not significant, as evidenced by the increase in RMSE (approximately 7.64%) and MAE (about 4.77%) compared to the training dataset. The majority of errors in both datasets fall within ± 1 pressure unit, accounting for approximately 98% of the data. Large errors ($|\text{error}| > 2$) occur only at a very low frequency in both datasets. Overall, the model exhibits very small error dispersion and high reliability.

Figure 4 presents a comparison between the experimental pressure and the predicted pressure for both the training and testing datasets. The results show that the predicted curves closely follow the variation trends of the experimental data in both datasets, demonstrating the model's strong capability to capture the nonlinear characteristics of the combustion process.

Discrepancies occur only locally at a few outlier points; however, their magnitudes are small and do not significantly affect the overall pressure range. Notably, the strong similarity in trends and fitting quality between the two datasets indicates that the model not only achieves high prediction accuracy but also exhibits good generalization capability, thereby confirming the reliability of the model for predicting subsequent in-cylinder pressure values.

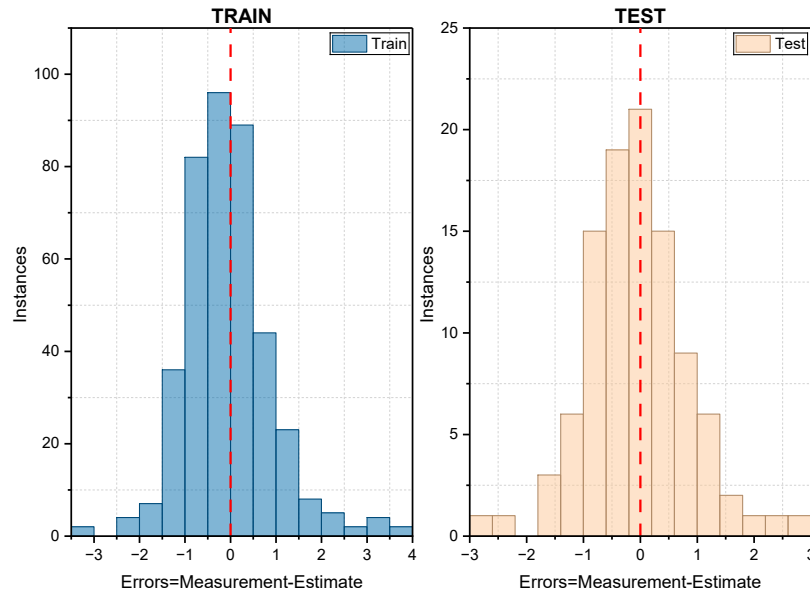


Fig. 3. Distribution of errors between experimental and ANN-predicted pressure

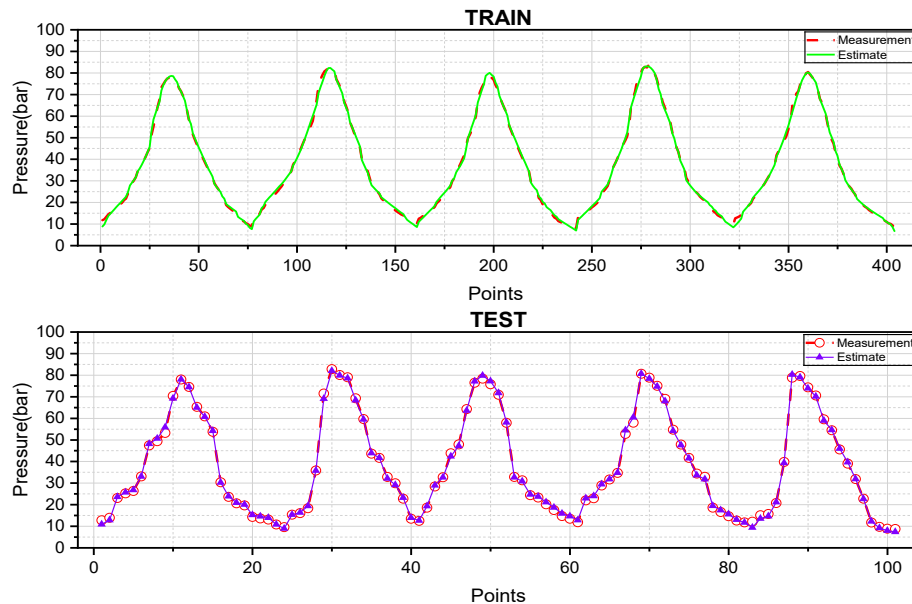


Fig. 4. Comparison of experimental and ANN-predicted in-cylinder pressure for the training and testing datasets

3. RESULTS AND DISCUSSION

The injection timing range of 40° - 60° CA BTDC was selected as the training dataset because it represents a stable and typical operating region of the PCCI combustion mode. Within this range, the premixing, auto-ignition, and hybrid combustion processes are clearly manifested and exhibit high repeatability in the experimental data, ensuring good data quality, low noise, and strong representativeness of the engine combustion kinetics. Based on 505 in-cylinder pressure data points collected at injection timings of 40° , 45° , 50° , 55° , and 60° CA BTDC, the ANN model was developed and its predictive accuracy was validated. Subsequently, the trained model was employed to predict an additional 404 pressure data points at new injection timings of 30° , 35° , 65° , and 70° CA BTDC, which lie at the boundaries of the data space, in order to evaluate the extrapolation capability, stability, and generalization performance beyond the training domain. This approach enables simultaneous assessment of prediction accuracy within the interpolation domain and forecasting capability under new operating conditions, thereby confirming the generalization ability, reliability, and practical applicability of the ANN model for in-cylinder pressure prediction in PCCI engines. Figure 6 presents the complete data distribution consisting of 990 pressure data points, including 550 experimental points and 440 points predicted by the ANN model. This combined dataset forms a large-scale input database that comprehensively covers advanced injection timings across the engine operating space. The dataset enables a continuous representation of pressure characteristics as a function of crank angle and injection strategy. Based on thermodynamic theory describing the relationship among pressure, volume, and crank angle, the 990 pressure data points are subsequently used to calculate the engine pressure rise rate.

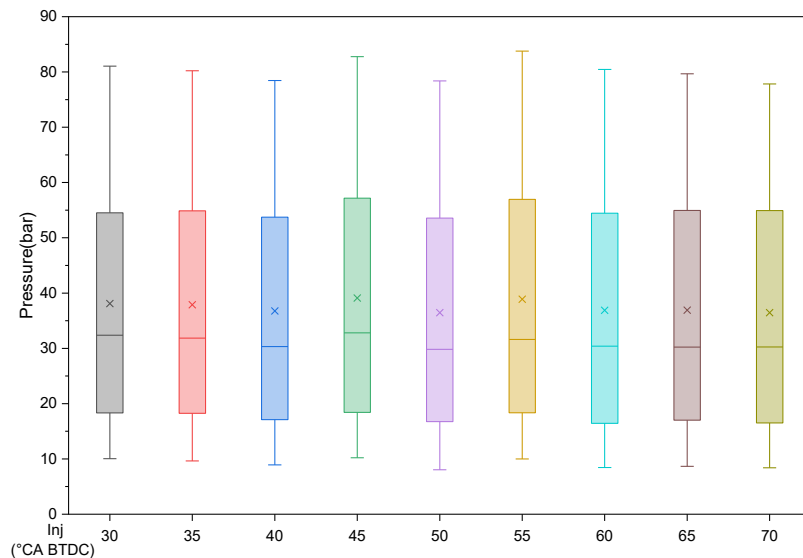


Fig. 5. Distribution of experimental and predicted pressure data

The in-cylinder pressure distribution of the PCCI engine reveals the formation of a distinct and continuous high-pressure band for all advanced injection timings, primarily concentrated within the range of 360° - 380° CA, with peak values reaching approximately 85-90 bar. Notably, this high-pressure region does not occur at a single operating point but extends across a control parameter domain, reflecting a characteristic feature of premixed combustion in which a relatively homogeneous fuel-air mixture is formed prior to auto-ignition. During the crank

angle interval of 320° - 355° CA, the pressure rises rapidly from approximately 8 bar to about 65-68 bar due to the combined effects of compression and low-temperature chemical reactions. The pressure then increases sharply and reaches its maximum within the 360° - 380° CA range, corresponding to the main heat release phase associated with volumetric auto-ignition throughout the combustion chamber. Subsequently, in the range of 400° - 420° CA, the pressure gradually decreases as a result of expansion work, reduced combustion reaction rates, and thermal energy dissipation. The presence of a broadened peak pressure region across the control domain, rather than a localized maximum, indicates that PCCI combustion tends to distribute energy more uniformly, with a controlled pressure rise rate and lower peak temperatures compared to conventional diesel combustion. These characteristics contribute to reduced NO_x and soot formation while improving combustion quality and overall engine efficiency. The relationship between the in-cylinder pressure curve (Figure 6) and the pressure rise rate (PRR) curve (Figure 7) demonstrates a direct mathematical and physical dependence; therefore, the shape of the PRR curve is inherently governed by the geometry of the pressure curve. During the crank angle interval of 320° - 355° CA, the in-cylinder pressure increases rapidly from approximately 8 bar to about 65-68 bar due to the combined effects of compression and early heat release, with the corresponding PRR rising from approximately $-0.076 \text{ MPa}/^{\circ}\text{CA}$ to about $3.3 \text{ MPa}/^{\circ}\text{CA}$. As the combustion process enters the main heat release phase around 360° CA, the pressure increase rate reaches its maximum, resulting in a peak PRR of approximately $5.860 \text{ MPa}/^{\circ}\text{CA}$. After the pressure reaches its maximum, the pressure curve enters a saturation region, and the slope decreases, causing the PRR to drop toward zero. Following the pressure reversal, the PRR becomes negative and reaches a minimum of approximately $-2.620 \text{ MPa}/^{\circ}\text{CA}$ at around 380° CA, reflecting the decreasing pressure with respect to crank angle. The pressure continues to decline at subsequent crank angles; however, the rate of decrease becomes more gradual, with PRR values ranging from approximately -0.9240 to $-0.0760 \text{ MPa}/^{\circ}\text{CA}$ between 390° CA and 400° CA. Consequently, the characteristic trend of the PRR curve increase $\rightarrow$ peak $\rightarrow$ decay to zero $\rightarrow$ negative region $\rightarrow$ gradual recovery is an inevitable consequence of the geometric form of the pressure curve as a function of crank angle. This behavior fully reflects the physical stages of the PCCI combustion cycle and confirms the strong consistency between combustion kinetics and in-cylinder pressure dynamics.

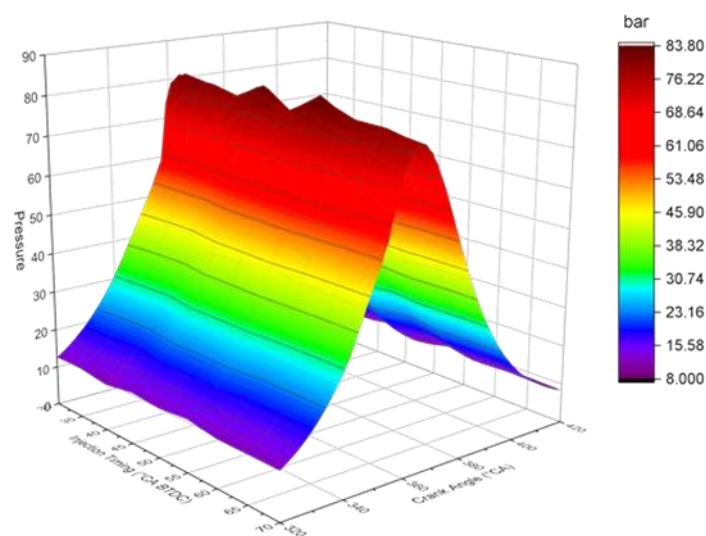


Fig. 6. Comparison between experimental and predicted values for the training and test datasets obtained from the ANN and GBM models

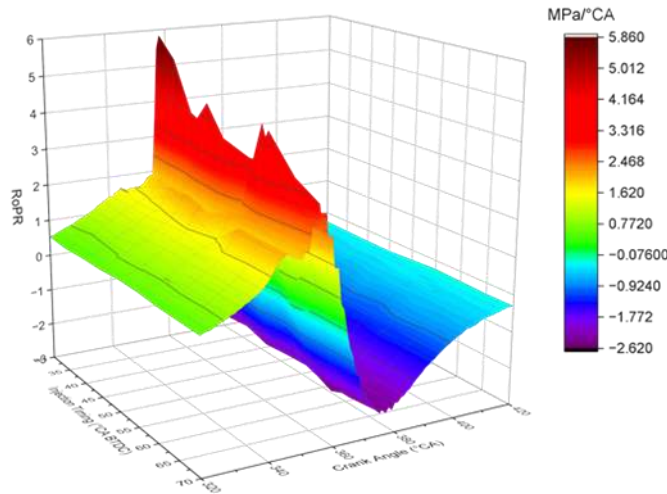


Fig. 7. Residual error distributions of the ANN and GBM models

4. CONCLUSION

This study applied an artificial neural network (ANN) to evaluate the accuracy of an in-cylinder pressure prediction model for a PCCI engine under advanced ignition timing conditions ranging from 40° to 60° CA BTDC, within a crank angle domain of 320-420° CA, corresponding to a total of 505 data points. The results demonstrate that the ANN model achieves very high prediction accuracy, as confirmed by the statistical metrics R^2 , RMSE, and MAE. Specifically, for the training dataset, the model yielded $R^2 = 0.9983$, RMSE = 0.9397 bar, and MAE = 0.6937 bar. Similarly, the testing dataset maintained comparable performance, with $R^2 = 0.9981$, RMSE = 1.0115 bar, and MAE = 0.7268 bar, indicating strong generalization capability and the absence of overfitting. Based on these results, it can be concluded that the ANN model is reliable and well suited for predicting in-cylinder pressure in PCCI engines using ignition timing and crank angle as input parameters. Leveraging the validated accuracy, the model was further trained and employed to predict new pressure profiles at the boundary regions of ignition timing, namely 30°, 35° and 65°, 70° CA BTDC, while maintaining the same crank angle range of 320-420° CA. For each ignition timing condition, 101 pressure data points were predicted, resulting in a total of 404 newly generated pressure data points, thereby substantially expanding the pressure dataset beyond the original training domain. Following the construction of the generalized pressure dataset, three-dimensional (3D) models were established to represent the distributions of the heat release rate (HRR) and the pressure rise rate, based on established thermodynamic formulations. These models describe the variation of HRR and pressure rise rate as functions of ignition timing within the range of 40°-60° CA BTDC and crank angle from 320° to 420° CA. The results reveal smooth and continuous distributions of both parameters, which are consistent with the combustion dynamics of PCCI engines. Overall, the study confirms the high accuracy and reliability of the ANN-based pressure prediction model and further demonstrates its capability for extrapolation beyond the original training dataset. The proposed approach contributes to reduced experimental costs and computational time for processing large datasets while providing effective input data for calculating key engine parameters, particularly the pressure rise rate. However, the present study is limited to characterizing the distribution of the pressure rise rate derived from

the predicted pressure data and does not yet identify the optimal operating regions of the engine at specific pressure levels. Therefore, this work serves as a scientific foundation for future research on AI-based combustion optimization, aiming to determine optimal pressure distribution regions to enhance engine power, improve thermal efficiency, and reduce emissions in PCCI engines.

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