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Research on Cold Atmospheric Plasma Jet Driven by Artificial Intelligence

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ABSTRACT

Cold atmospheric plasma jets, with their low temperature, high reactivity, and environmentally friendly characteristics, have shown broad application potential in biomedical treatment, material modification, and pollution control. However, the complexity of discharge mechanisms, strong parameter coupling, and spatial nonuniformity restrict their stability and controllability. The integration of artificial intelligence (AI) provides a new approach for this research, enabling intelligent regulation of the discharge process through data-driven modeling and optimization. This paper discusses the formation mechanism, dynamic characteristics, and AI applications in parameter optimization and discharge diagnostics of cold plasma jets, providing theoretical support for their intelligent and engineering development.

Introduction

Cold plasma, as a nonequilibrium discharge system, features high electron temperature and low gas temperature. It can generate abundant high-energy particles and reactive species under atmospheric pressure, offering unique technological advantages in material modification, biological sterilization, and gas purification. The cold atmospheric plasma jet (CAPJ), as a typical form, has attracted extensive attention due to its directed discharge and mild action characteristics. However, its discharge process is influenced by factors such as electric field distribution, gas dynamics, dielectric structure, and external disturbances, showing strong nonlinearity and randomness. Traditional experimental research heavily relies on empirical parameter adjustment, making it difficult to achieve stable control under complex conditions. With the development of artificial intelligence, data-driven models have shown great potential in solving nonlinear problems and optimizing complex systems. Combining AI with cold plasma jet research helps reveal its dynamic laws, optimize discharge parameters, and realize intelligent control and prediction of the system.

I. Physical Characteristics and Formation Mechanism of Cold Atmospheric Plasma Jets

(1) Energy Distribution Characteristics of Nonequilibrium Discharge

The core feature of cold plasma jets lies in their nonequilibrium nature. The electron temperature typically reaches tens of thousands of Kelvin, while the ion and neutral gas temperatures remain around 300–400 K, forming a highly nonuniform energy distribution. In this state, electrons are rapidly accelerated by the external electric

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field, colliding with gas molecules to induce ionization, excitation, and recombination reactions, thereby generating active particles and photons. The discharge process undergoes micro-scale temporal evolution, exhibiting multiple stages such as breakdown, discharge channel formation, and arc expansion. Due to uneven energy input and diffusion, the jet shows spatial nonuniformity, resulting in filamentary and branched discharges. The asymmetry of energy distribution significantly affects discharge stability and active species concentration, forming the basis for constructing subsequent control models.

(2) Gas Dynamics and Plasma Propagation Behavior

Cold plasma jets typically use helium, argon, or air as working gases, and their flow-field structures directly influence discharge morphology. Gas velocity, viscosity, and boundary-layer effects determine discharge channel formation and propagation paths. High-velocity gas flow effectively reduces channel temperature and suppresses thermal arc formation, while low flow rates enhance localization and lead to overheating. The jet propagation exhibits strong plasma–fluid coupling, where active particles mix and diffuse with background gases, forming complex reaction kinetics. By analyzing fluid parameters and electromagnetic field strength simultaneously, one can reveal the self-organizing behavior of the discharge front, providing physical input data for AI modeling.

(3) Synergistic Effect of Discharge Structure and External Electric Field

The generation of cold plasma jets depends on electrode configuration and external electric field design. Common structures include needle-ring, coaxial, parallel-plate, and dielectric barrier discharge (DBD) types. The waveform (sinusoidal, pulsed, or square) and frequency of the applied voltage determine the evolution of the electron energy distribution function (EEDF). The electrode geometry affects field concentration, thus influencing breakdown paths and discharge density. Experimental and numerical studies show that uneven electric field distribution can cause unstable jet expansion, while optimized dielectric configurations and electrode geometries significantly improve discharge uniformity and jet length.

II. Application Framework of Artificial Intelligence in Cold Plasma Jet Research

(1) Data-Driven Modeling of Discharge Characteristics

The nonlinear and multiscale features of cold plasma jets make traditional fluid–electromagnetic coupled models computationally intensive and unsuitable for real-time prediction. Data-driven modeling introduces a new pathway for intelligent discharge analysis. By collecting multi-source data such as voltage, current, optical emission spectra, and high-speed imaging, a multidimensional discharge feature space can be constructed. Algorithms such as deep neural networks (DNN), support vector machines (SVM), and convolutional neural networks (CNN) enable nonlinear mapping between input parameters and output responses. CNNs, in particular, excel at extracting discharge texture and energy distribution from high-dimensional data, allowing for recognition of unstable discharge patterns or local breakdown precursors. Moreover, incorporating deep reinforcement learning (DRL) frameworks enables “self-learning” optimization of discharge states within simulation environments, granting predictive control capabilities under complex conditions. Studies show that data-driven models can achieve over 95% accuracy in discharge state recognition, laying the groundwork for digital twin development and real-time plasma regulation.

(2) Parameter Optimization and Process Control Based on Machine Learning

Cold plasma jet systems involve multiple coupled parameters, including gas flow rate, discharge voltage, drive frequency, dielectric thickness, and electrode spacing—all of which significantly affect energy transfer and discharge stability. Traditional parameter tuning methods rely on manual experience and single-variable testing, which are inefficient and inadequate for complex conditions. Machine learning enables multi-objective optimization and adaptive control. Using algorithms such as genetic algorithms (GA), particle swarm optimization (PSO), and Bayesian optimization (BO), AI can efficiently search global parameter spaces with objectives like power efficiency, discharge uniformity, and active species yield. Additionally, reinforcement learning allows the system to autonomously adjust input parameters based on real-time feedback, forming a closed-loop control structure for self-adaptive optimization. Experimental verification demonstrates that this approach improves energy efficiency by over 20% and significantly reduces discharge instability, highlighting the intelligence and adaptability of AI-driven plasma process control.

(3) Intelligent Diagnosis and Anomaly Detection

During long-term operation, cold plasma devices are prone to discharge abnormalities and performance degradation due to voltage fluctuations, gas contamination, temperature drift, or dielectric aging. Establishing AI-based

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diagnostic frameworks is thus essential. Long short-term memory networks (LSTM) can model discharge time-series data to detect nonlinear variations in current and optical signals, providing early warnings for arc transitions or discharge collapse. Unsupervised learning methods such as autoencoders (AE) identify subtle feature deviations even in unlabeled data, enabling early fault detection. Combined with multisource sensor data fusion and feature importance analysis, AI models can distinguish between anomalies caused by external disturbances and those due to internal degradation. Experimental validation shows that this intelligent diagnostic framework achieves over 92% accuracy in anomaly identification, significantly reducing downtime risks and enhancing the operational reliability of cold plasma systems.

III. AI-Driven Multiphysics Coupling Analysis of Cold Plasma Jets

(1) Intelligent Integration of Electromagnetic and Fluid Dynamics

The discharge behavior of cold plasma jets results from coupling among electromagnetic fields, fluid flow, and gas-phase reactions. Their spatial nonuniformity and temporal nonlinearity pose challenges to conventional multiphysics simulations. AI provides a means for rapid prediction of coupled dynamics. By training deep neural networks on experimental and simulated datasets of electric field, charge density, and velocity distributions, surrogate models can approximate the coupled Maxwell and Navier–Stokes equations. These models achieve millisecond-level response times while maintaining accuracy within 3%, reducing computational costs by orders of magnitude. They enable real-time control of energy transport and flow dynamics under varying operating conditions, providing data-driven foundations for adaptive discharge control and jet stability optimization.

(2) Intelligent Prediction of Chemical Reactions and Reactive Species Evolution

Cold plasma involves hundreds of reactions, including electron collisions, ionization, recombination, and molecular excitation, forming complex reaction networks. Traditional rate-equation-based solvers are computationally demanding. AI shifts reaction kinetics from explicit computation to data learning. Random forest algorithms identify key reaction pathways, while graph neural networks (GNN) capture topological relationships among reactants and products to predict reaction evolution globally. This approach accurately estimates concentrations of radicals, ozone, and NOx under various gas ratios and voltage conditions, automatically adjusting discharge parameters for optimized performance. It demonstrates superior generalization compared to traditional models, greatly reducing experimental costs and energy waste, and supports applications in sterilization, waste gas treatment, and surface functionalization.

(3) Dynamic Coupling of Thermal and Radiative Effects

Although termed “cold,” local hotspots may form within cold plasma microregions, leading to radiation enhancement and thermal degradation risks. AI-based modeling excels in monitoring and predicting these phenomena. Convolutional neural networks (CNN) extract thermal and radiative features from infrared and optical images for noncontact temperature reconstruction and anomaly localization. Combined with ARIMA and LSTM temporal models, these methods enable dynamic temperature tracking and early warning of unstable discharge zones. Results show prediction errors below 2%, allowing real-time thermal management during plasma operation. Integrated modeling of radiative intensity and energy distribution further optimizes power input strategies, prevents overheating, and enhances overall thermal stability and operational safety of plasma devices.

IV. AI-Based Optimization and Engineering Application of Cold Plasma Jets

(1) Jet Morphology Control and Energy Distribution Optimization

The morphology of plasma jets determines energy distribution and interaction effects, serving as a key indicator of system stability and functionality. AI enables real-time morphology recognition and dynamic classification through multidimensional image feature extraction. Generative adversarial networks (GAN) excel in discharge image reconstruction, predicting jet propagation patterns under different electrode and voltage configurations. Studies indicate that the nonlinear coupling of gas velocity, voltage waveform, and frequency determines jet energy uniformity. Optimization algorithms can autonomously tune parameters for even energy density, preventing local overheating or collapse. AI-driven morphology prediction and energy control thus enhance jet uniformity and ensure stable operation under complex environments.

(2) Construction of AI-Based Adaptive Control Systems

Cold plasma jets are sensitive to power fluctuations,

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gas disturbances, and environmental variations. AI-driven adaptive control systems enable real-time monitoring and dynamic adjustment. Through multisensor data fusion, signals such as voltage, current, optical intensity, and temperature are collected and processed via edge computing before being analyzed by deep learning models. Reinforcement learning-based control frameworks use feedback to autonomously regulate discharge parameters, forming a closed-loop "perception–analysis–decision–execution" mechanism. Experimental evidence shows that these systems maintain discharge stability under disturbances, enhance response speed by over 30%, and improve power utilization, demonstrating high adaptability and robustness of AI in plasma process control.

(3) Intelligent Integration Toward Practical Applications

AI accelerates the transition of cold plasma jets from laboratory research to industrial application. Through scenario-based learning and adaptive optimization, AI systems automatically adjust parameters to match operational requirements. In surface modification, AI selects optimal energy density and treatment duration based on material characteristics, achieving high-precision processing. In biomedical applications, AI models analyze cellular responses and tissue properties to optimize dosage and treatment modes, ensuring safety and efficacy. In environmental treatment, predictive AI systems adapt power input to pollutant type and concentration for efficient degradation with minimal energy consumption. Algorithmic optimization and hardware integration thus drive cold plasma jets toward intelligent, green, and systematized engineering development.

V. Conclusion

As an interdisciplinary frontier technology, cold atmospheric plasma jets face challenges due to complex multiphysics coupling, which limits their controllability and precision. The integration of artificial intelligence introduces a new paradigm for mechanism research and engineering applications. Data-driven modeling and optimization enable precise discharge control and predictive regulation, significantly enhancing system adaptability and reliability. Future studies should focus on high-dimensional data fusion, multi-objective optimization, and intelligent feedback control, while developing interpretable AI models to uncover underlying physical mechanisms. The deep integration of AI with sensors, computational fluid dynamics, and plasma diagnostics will establish closed-loop intelligent control frameworks. With continuous advances in algorithms and computational hardware, AI-driven cold plasma jet research will play a pivotal role in achieving low-energy, high-efficiency, and high-stability plasma technologies, injecting new momentum into sustainable development in energy, manufacturing, biomedical, and environmental fields.

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