Journal of Computer Technology and Software

ISSN:2998-2383

Vol. 4, No. 3, 2025

Integrating Artificial Intelligence and CFD to Analyze Inlet Parameter Effects in Vortex Pilot Gas Heaters

Drayden Lorne[1], Elric Maves[2]
[1]Indiana University South Bend, South Bend, USA
[2]Indiana University South Bend, South Bend, USA
*Corresponding Author: Drayden Lorne, d.lorne@iusb.edu

Abstract: The Vortex Pilot Gas Heater (VPGH) represents an innovative application of vortex tube technology within natural gas transmission and distribution pressure regulation systems. By sealing the hot end of the vortex tube and integrating an external vortex heater, a self-heating mechanism for pilot gas and vacuum nozzles is achieved, effectively preventing freezing blockages caused by the Joule–Thomson effect. In this study, computational fluid dynamics (CFD) simulations based on the standard k-epsilon turbulence model are conducted to analyze the internal flow field. Furthermore, by adopting a single-variable control method, the effects of key inlet parameters on the operational performance of the VPGH are systematically evaluated. In addition, this work discusses the potential of integrating AI-driven design optimization frameworks with CFD modeling to enhance predictive accuracy and design adaptability in complex flow systems.

Keywords: Computational Fluid Dynamics (CFD); Expansion Ratio; Inlet Flow Parameters; Working Medium Properties; AI-Assisted Simulation

1. Introduction

The Vortex Pilot Gas Heater (VPGH) represents a practical and innovative application of vortex tube technology within natural gas transmission and distribution pressure regulation systems. This device operates by utilizing the principles of gas expansion and temperature separation inherent to vortex tubes, effectively heating pilot gas and vacuum nozzles. Its primary purpose is to prevent freezing blockages induced by the Joule − Thomson effect, a phenomenon commonly observed during gas decompression under low-temperature conditions. By ensuring reliable thermal performance, the VPGH plays a critical role in maintaining the safety and continuity of gas flow, especially in cold climates or high-pressure drop scenarios.

In addition to its core functionality, the VPGH offers several distinct operational advantages that make it suitable for field deployment in diverse gas network infrastructures. These include high energy efficiency due to the absence of external power sources, environmental sustainability by eliminating combustion-related emissions, and a design free from moving parts, which significantly reduces wear, noise, and maintenance requirements. Furthermore, the device demonstrates a high tolerance to humid and unprocessed gas compositions, facilitating broader applicability across various gas quality conditions. Its ease of installation, zero gas loss during operation, and ability to maintain stable thermal output without the risk of overheating further underscore its practical value in industrial settings [1].

This study focuses on the VPGH-SP model developed by Universal Vortex Inc., examining its structural integrity and thermal characteristics using computational fluid dynamics (CFD) simulations. By employing CFD analysis, the research aims to capture the detailed flow dynamics, temperature distributions, and heat transfer mechanisms within the heater, thereby providing insights into performance optimization and design refinement.

In recent years, the rapid advancement of artificial intelligence (AI) has opened new avenues for enhancing traditional engineering analysis. The integration of AI-based data-driven modeling, such as machine learning (ML) and deep learning (DL) techniques, with CFD simulations presents a promising approach to improving the design, fault prediction, and real-time operational control of systems like the VPGH. For example, AI algorithms can be trained on historical simulation and field data to predict thermal performance under varying environmental and operational conditions, enabling predictive maintenance and anomaly detection. Furthermore, optimization techniques such as genetic algorithms, reinforcement learning, or Bayesian optimization can be employed to automatically identify optimal geometric configurations or operating parameters, thereby accelerating the design process and improving efficiency. This hybrid paradigm of combining physics-based models with AI-driven insights marks a significant step toward intelligent thermal management systems in natural gas infrastructure, capable of adapting to dynamic gas environments with enhanced robustness and precision.

2. Numerical Simulation

The The expansion ratio of the vortex tube—defined as the ratio between the high-pressure gas inlet and the low-pressure gas outlet pressures—is a critical parameter that governs the thermal and flow characteristics of the Vortex Pilot Gas Heater (VPGH) system. This ratio directly influences the degree of energy separation within the vortex tube, thereby affecting the heating efficiency of the pilot gas. To quantitatively evaluate the thermal performance under varying expansion ratios, several key temperature-based metrics are introduced: the heating effect of the pilot gas (ΔTp) is measured as the temperature difference between the pilot gas outlet and inlet; the cooling effect (ΔTc) refers to the temperature drop at the low-pressure gas outlet relative to the inlet; and the overall temperature separation effect (ΔTh) is defined as the difference between the maximum temperature at the hot end and the minimum temperature observed at the cold outlet of the vortex tube.

In this section, a series of CFD simulations is conducted across a range of expansion ratios from 2 to 8, while maintaining the outlet pressure constant at standard atmospheric conditions. As depicted in Fig. 1, the results indicate a clear trend: increasing the expansion ratio leads to significant enhancement in both the heating effect (ΔTp) and overall temperature separation (ΔTh). Specifically, within the studied range, ΔTp increases from approximately 3 K to 6 K, while ΔTh rises from about 9 K to 17 K, demonstrating the amplified energy separation effect at higher pressure differentials. This behavior underscores the sensitivity of the vortex-induced thermal gradient to the expansion ratio, highlighting its importance as a design and operational parameter.

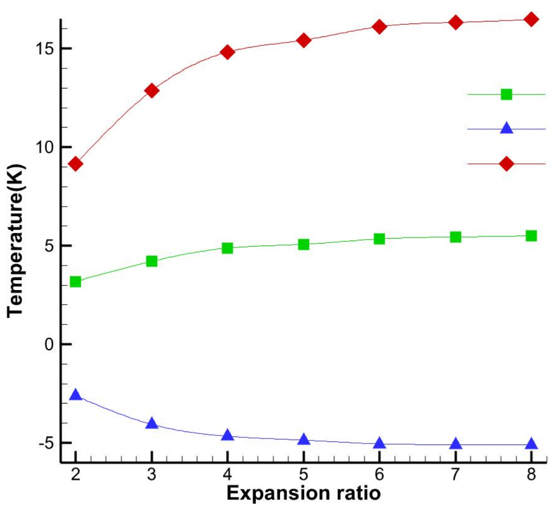

Fig 1. Influence of different expansion ratios on temperature

From a physical standpoint, the observed enhancement can be attributed to the greater pressure energy input at higher expansion ratios, which intensifies the internal vortex motion and enhances kinetic energy redistribution across the radial and axial directions of the tube. This leads to more efficient conversion of pressure energy into temperature gradients. Nevertheless, practical constraints such as internal wall roughness, frictional losses, turbulence saturation, and nozzle flow capacity introduce diminishing returns when the expansion ratio exceeds certain thresholds. Beyond this point, the system may no longer effectively utilize the additional pressure energy; instead, excessive input pressure may result in the expulsion of partially compressed gas, causing irreversible energy loss and ultimately reducing the net heating efficiency [2].

To address these challenges and facilitate adaptive system optimization, AI-based pattern recognition and surrogate modeling techniques offer a promising direction. By learning from a curated dataset of simulation or experimental results, machine learning models can be trained to identify non-linear response zones, detect performance plateaus, and predict optimal expansion ratios under varying boundary and operating conditions. For instance, ensemble learning or neural network regression models can approximate complex thermofluid behaviors without necessitating full CFD runs for each new condition. This approach not only accelerates parametric design exploration but also paves the way for real-time intelligent control strategies, where the VPGH system can dynamically adjust its operating parameters in response to environmental fluctuations, gas composition variations, or pipeline pressure changes. Ultimately, the convergence of computational fluid dynamics with AI-driven optimization establishes a new paradigm for the intelligent and energy-efficient operation of gas heating technologies in modern distribution networks.

2.1 Influence of Inlet Velocity of Pilot Gas on Performance

The internal structure of the Vortex Pilot Gas Heater (VPGH) relies on the principle of temperature separation within the vortex tube to generate high-temperature regions. These internal heat sources remain largely unaffected by changes in the external pilot gas flow. In contrast, the outer vortex heater serves as a passive heat exchanger, where thermal energy is transferred from the inner vortex tube to the flowing pilot gas without altering the internal vortex dynamics. As such, variations in the inlet velocity of the pilot gas primarily influence the degree of heat absorption, rather than the generation or distribution of the heat source.

To investigate this effect, simulations were conducted with inlet velocities ranging from 0.4 m/s to 4.0 m/s. As illustrated in Fig. 2, a monotonic decline in heating efficiency is observed as the velocity increases. This trend is attributed to the basic physics of convective heat transfer: at lower velocities, the gas remains in contact with the heat exchange surfaces for a longer duration, allowing more heat to be absorbed. Conversely, higher velocities reduce the thermal residence time, weakening the overall heat transfer and thus lowering the outlet temperature of the pilot gas.

Importantly, while the internal thermal field of the vortex tube remains constant under fixed inlet pressure conditions, the heat transfer rate is highly sensitive to flow rate. In practical systems, this implies a trade-off between flow rate and thermal gain, especially in environments requiring precise temperature regulation.

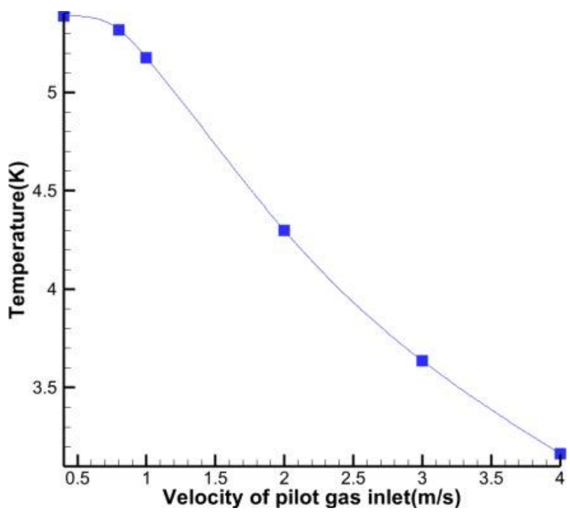

Fig 2. Influence of inlet velocity of pilot gas on heating effect of pilot gas

With the aid of artificial intelligence, particularly in regression modeling and data clustering, it becomes feasible to map the complex, nonlinear relationships between inlet velocity, residence time, and outlet temperature. AI-driven predictive models can rapidly estimate heating efficiency across a wide range of velocities without rerunning computationally expensive simulations. Furthermore, reinforcement learning algorithms may be used to identify velocity settings that optimize heat transfer performance under varying operational scenarios, contributing to the development of adaptive control systems for smart gas regulation equipment.

2.2 The Influence of Working Medium Type on Working Performance

To investigate the influence of working medium type on the thermal performance of the VPGH, dimensionless spatial parameters are introduced for clarity and scalability: $r^*=r/R$, where R is the radius of the vortex tube, and $L^*=l/L$, where L denotes the length of the hot-end segment. This normalization allows for a generalized analysis of axial temperature distributions across different gases. In the present simulation, the fluids examined include hydrogen, helium, nitrogen, oxygen, and chlorine. At a representative radial location ($r^*=0.9$), the temperature profiles along the tube's axial direction are plotted in Fig. 3.

The simulation results reveal a consistent temperature separation trend among different gases, but with clearly distinguishable magnitudes. Notably, gases with lower molar mass, such as hydrogen (2 g/mol) and helium (4 g/mol), demonstrate a more pronounced temperature gradient compared to heavier gases like chlorine (71 g/mol). This is attributed to the fact that lighter molecules are more responsive to the energy redistribution driven by the vortex flow field. In diatomic gases, this effect is enhanced further when the specific heat capacity is lower, allowing for more significant temperature shifts under the same input conditions. Although helium and hydrogen have similar molar masses, the monatomic structure of helium gives it a smaller heat capacity, resulting in a slightly more efficient energy separation.

These findings align with earlier research by Tang et al. [3] and Wu [4], which similarly noted the dependence of vortex tube performance on gas thermophysical properties. More broadly, the results suggest that gas selection for VPGH applications should consider not only molar mass but also specific heat, molecular structure, and compressibility effects, especially when operated under varying pressures and temperatures.

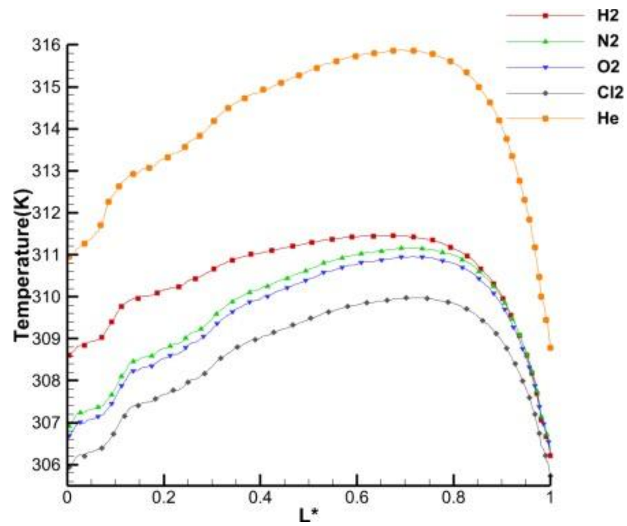

Fig 3. Axial distribution of temperature of different working media at r*=9

From an AI integration perspective, machine learning models trained on thermophysical databases and simulation outcomes could be employed to predict separation performance for untested or mixed working media. Feature engineering based on gas properties (e.g., molar mass, specific heat at constant pressure, molecular geometry) can inform supervised learning algorithms to estimate optimal working media under user-defined performance criteria. Furthermore, AI-driven inverse design frameworks may assist in identifying tailored gas mixtures or novel fluids (e.g., refrigerants, rare gases) that maximize separation efficiency while maintaining safety and environmental compliance.

3. Conclusion

This study employed computational fluid dynamics (CFD) simulations to evaluate the influence of key inlet parameters on the thermal and flow performance of the Vortex Pilot Gas Heater (VPGH). Based on systematic numerical experiments, the following conclusions are drawn:

Expansion Ratio: Under constant structural conditions, increasing the expansion ratio between the high-pressure inlet and low-pressure outlet significantly enhances the energy separation effect within the vortex tube. However, this effect exhibits diminishing returns beyond a certain threshold due to internal flow limitations and system pressure constraints.

Inlet Velocity: Higher inlet velocities of the pilot gas reduce the thermal residence time and thus decrease the heat absorption per unit volume. This leads to a measurable decline in outlet temperature, indicating a trade-off between flow rate and heating effectiveness.

Working Medium Properties: The energy separation effect is inversely correlated with the molar mass of the working medium. For gases with similar molar masses, those with lower specific heat capacities exhibit more pronounced temperature separation. These trends are consistent with previous findings in vortex tube research [3][4].

In addition to these findings, this study highlights the growing role of artificial intelligence in augmenting CFD-based thermal system design. AI techniques can be utilized to predict system behavior across broader parameter spaces, optimize working conditions in real time, and assist in selecting or synthesizing working media for tailored performance. By integrating AI-driven data modeling with traditional simulation tools, future research can move toward intelligent VPGH systems capable of adaptive operation and self-optimization in complex gas regulation environments.

References

[1] Behera, U., Paul, P. J., Kasthurirengan, S., Karunanithi, R., Ram, S. N., Dinesh, K., & Jacob, S. (2005). CFD analysis and experimental investigations on a vortex tube. International Journal of Heat and Mass Transfer, 48(10), 1961–1973.

[2] Ahlborn, B., Camire, J., & Keller, J. U. (1996). Low-pressure vortex tubes. Journal of Physics D: Applied Physics, 29(6), 1469 – 1472. https://doi.org/10.1088/0022-3727/29/6/038

[3] Aljuwayhel, N. F., Nellis, G. F., & Klein, S. A. (2005). Parametric and internal study of the vortex tube using a CFD model. International Journal of Refrigeration, 28(3), 442–450.

[4] Eiamsa-ard, S., & Promvonge, P. (2008). Review of Ranque – Hilsch effects in vortex tubes. Renewable and Sustainable Energy Reviews, 12(7), 1822–1842.