Influence of aeronautical situations, water inoculation and fuel fraction on aerodynamic flame stabilization of a gas turbine

Ahmed Sayed A. Hassan
Mechanical of Engineering , collage of Engineering and Computer sciences, Jazan University, Saudi Arabia

Abstract

This research aims to improve gas turbine performance and suppress compressor rotating stall and surge. The effect of water spray at the compressor inlet on the stable operating range and performance of the gas turbine was examined. In gas turbines, combustion is a complex phenomenon that involves a variety of physical and chemical processes, changes in flow rate, turbulence intensity, and operating pressure and temperature variations. These phenomena cause inappropriate behaviors, like abrupt acceleration, stopping, and explosions, in continuous combustion processes within the combustion chamber. The blow-by phenomenon in aviation engines is greatly impacted by problems with combustion instability and flame continuity, especially at high altitudes. These engines must operate at low flame temperatures and in lean, difficult-to-ignite mixture conditions due to emissions regulations. This increases the opportunities and potential for extinguishing fires, contributing to the development of blow-off conditions. There isn't a comprehensive theory for how gas turbines burn, so this study must rely on empirical correlations and basic models. The results of laboratory tests showed that nitrogen oxide emissions from the gas turbine's exhaust gases into the atmosphere could be reduced by up to 25% and the temperature could be lowered by more than 30% by spraying water into the engine at a rate of 20% compared to the air. Theoretical studies have supported these findings. Excessive water injection above the designated percentage can cause fatigue cracking, decreased aerodynamic efficiency, long-term blade wear, and stress concentration. Differences in combustion chamber geometry influence flame stability and emissions by controlling turbulence, mixture formation, and residence time. In order to maintain the combustion stability margin and safe equivalence ratio, altitude-compensating fuel scheduling necessitates general design changes for burners.

Submitted: 28-Aug-2025

Accepted: 4-Nov-2025

Published: 23-Dec-2025

DOI:10.5455/jeas.2025120106

Keywords: *Water injection, Flammability limits - Aero gas turbines - Blowoff - Thermal energy.*

Highlights:

- Improve gas turbine performance
- Suppress compressor rotating stall and surge
- The effect of water spray at the compressor inlet on the stable operating range and performance of the gas turbine was examined

1. Introduction

The scheme of burning compartments in gas turbine machines represents serious challenge to engineers because of the environmental constraints, emission reduction requirements, and burning lean mixtures [1-7]. Because the combustion chambers located between two fast-moving parts of the compressor and the turbine [8], and also because of the difference in the intensity of the turbulence inside the combustion chambers [9, 10], thus the strength of the effect on the structure of the burning flame. Variations in physical and chemical parameters are another challenge that affects flame instability.

Chemical reactions, dynamic gas movements, thermodynamic properties of mixtures, temperature, and pressure will lead to flame initiation results of the interaction between these factors [11, 12]. This will lead to random flame behaviors when pressure and temperature increase, and the behavior may move from an unstable state [13], which has a noticeable effect on combustion rates, to a turbulent combustion state and complex phenomenon [14, 15]. Considering that combustion in gas turbines is an energy production process. Therefore, it is necessary to control combustion eddies in order to achieve maximum efficiency with the least amount of adverse environmental impact in terms of rate of gas ingesting and contaminant [16, 17]. Scientists are currently using several highly accurate programs, such as new design factors and tests on various fuel types, to determine the best combustion chamber design in light of the pressing need to produce gas turbines with high efficiency.

According to the new design requirements, the turbine elements must maintain thrust while in flight and refrain from altering the flame's size or shape as the gases burn in the combustion vessel, as this could result in engine power cutting off or increase the risk of a fire. To achieve maximum engine power, modern design must therefore use complex design elements such as fuel injection locations, injection angles, injection pressure, and speed in conjunction with excellent combustion efficiency. Enhancing the clouds' temperature, pressure, and humidity levels is necessary to maximize combustion efficiency and prevent flame extinguishment. Undoubtedly, variations in the humidity of the air entering the engine, along with the intake's pressure and temperature, have a big effect on combustion and the engine's overall condition, whether it is cold at ground level or warm at different elevations.

Considering the influence of combustion theory on gas turbine engines, [18–21] assert that in order to optimize design and attain the highest combustion efficiency with the lowest levels of hydrocarbon oxides, precise and reliable modeling in addition to mathematical techniques must be used in conjunction with comparisons with laboratory results. Blowing is usually avoided by running the engine at a wide safety margin to ensure stability at a higher equivalence ratio. Reducing this margin leads to lower emissions. Based on the aforementioned, the capacity to detect or sense the onset of ignition offers significant and precise benefits for the consistent, stable operation of gas turbines with high efficiency for an extended period of time with reduced consumption and preserving engine life with the least amount of maintenance [22–25]. Published results of researchers [26-28] showed that it is possible to know the stable blowing factors by performing appropriate mathematical analyses or through visual observations of the flame or through the acoustic fingerprint.

2. Water Injection Impact Evaluation Tool

A twin-shaft Cussons P9005 gas turbine with a gas generator, power turbine, loader, gauges, and water pump is depicted in Figure 1. Water injection system is shown in Figure 2 in the left side, and a pollution meter for carbon monoxide, carbon dioxide, and

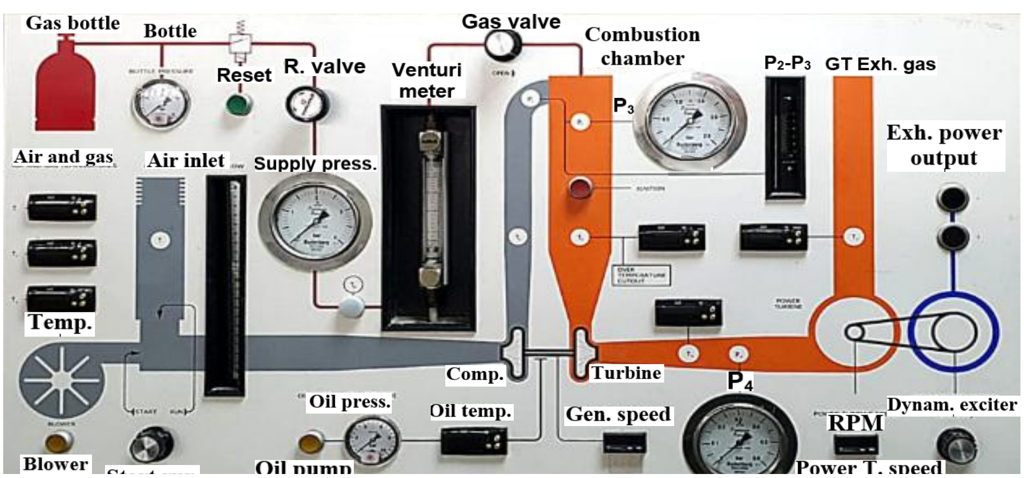


Figure 1. A twin-shaft gas turbine test bed

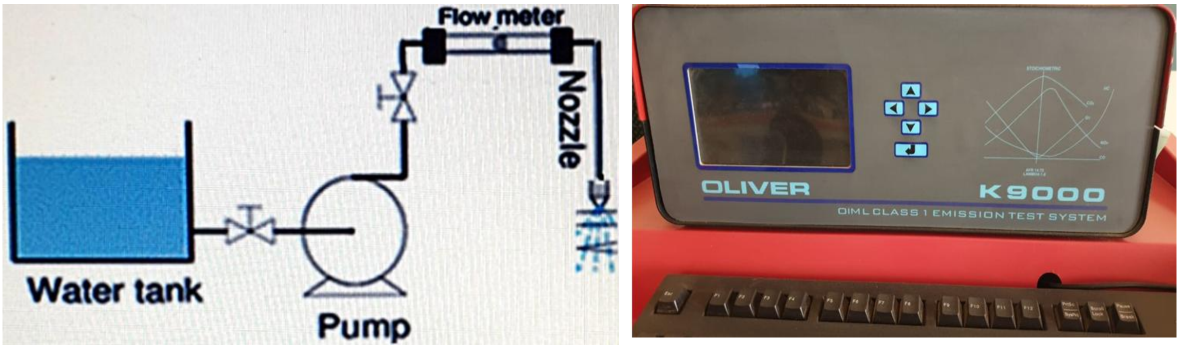


Figure 2. Water injection system (Left side) and Pollution measuring device (Right side)

nitrogen oxides, a computer control unit, and a stand-alone smoke analyzer is shown in Figure 2 on the right side.

3. Effect of water injection

Figure 3 illustrates the impact of water injection on the engine's exhaust gas temperature. It demonstrates that spraying a quantity of water that makes up 20% of the air can reduce the gas turbine exhaust temperature by up to 250°C, or 50%. As a result of increased engine cooling, Figure 4 illustrates a notable decrease in nitrogen oxide emissions when the water spray ratio is increased. Because of the prevailing cooling in the combustion chamber brought on by less water evaporation in the compressor, a 25% reduction happens at a 20% water-to-air ratio.

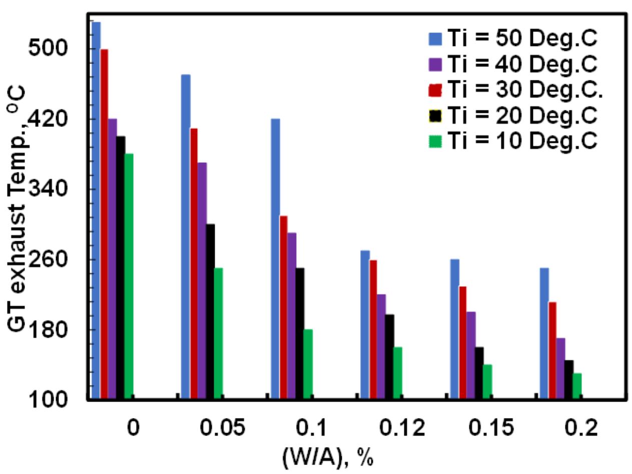


Figure 3. Reduced exhaust temperature

3. Analytical model

An analysis of pressure system modeling based on experimental data of experimental pressure rise versus flow rate can be used to infer the onset of sudden stop and sudden surge. The maximum characteristic of total pressure rise versus static pressure corresponds to the dynamic stability limit, which can be derived. The following is an expression for the pressure system's dynamic equations:

$$d\omega^2/\omega^2 = 2(W_T - W_C - W_G - W_{loss})/I \quad (1)$$

Taking into consideration the thermal efficiency and enthalpy difference between the turbine's inlet and exit, the energy generated is:

$$W_T = m_T \eta_T (h_o, T_i - h_o, T_e) \quad (2)$$

Utilize Euler's equation to determine the compressor's motive force:

$$W_c = \{\Delta Q + [(Vu)_{a,e} - (Vu)_{a,m}] - 0.5\lambda_c u_c^2\}(1+x)G_a/\eta_c \quad (3)$$

Where λ is the thermal conductivity ($G_a = \rho/lr_2$). The engine capacity is:

$$W_{net} = W_T - W_C = m_T h_T c_{pga} (T_{o,Ti} - T_{o,Te}) - (m_a + m_w) c_{paw} (T_2 - T_1)/\eta_c \quad (4)$$

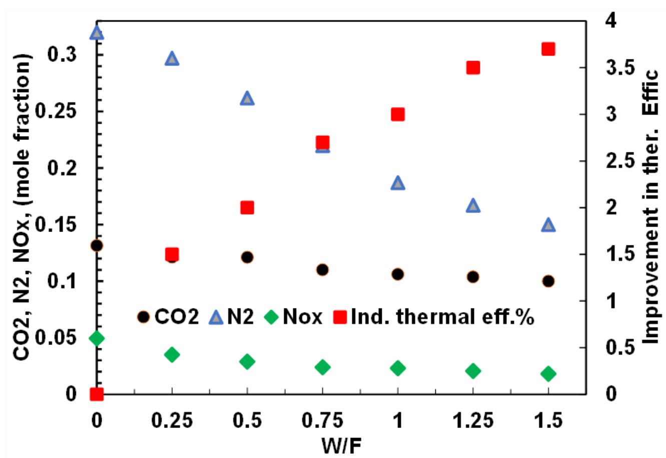


Figure 4. Reduced emissions of hydrocarbons from turbine exhaust

As a result of higher air density or humidity, Figure 6 illustrates how exhaust temperatures drop as the proportion of water injected into the compressor inlet rises.

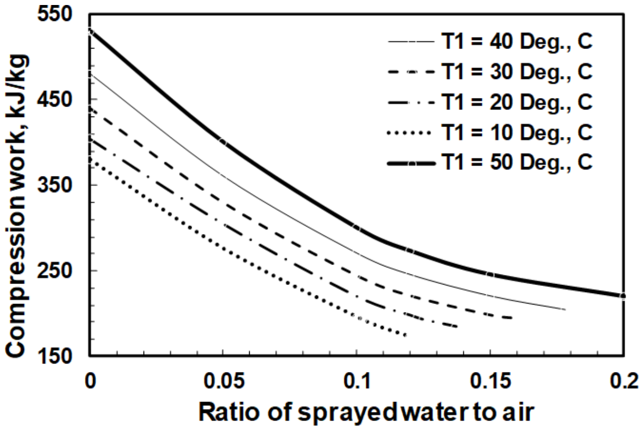


Figure 5. Compressor power consumption decreases with increasing water injection

4. Chemical and physical parameters affecting combustion efficiency

Turbine engines need to have very high-quality combustion chambers. By choosing the right fuel and employing techniques that lower combustion oxides by introducing water into the combustion chambers, this can be accomplished and engine operation can be made safe. The equation that states that combustion time = fuel evaporation time + fuel-air mixing time + chemical reaction time is the foundation of the model that [35] presented for efficient combustion processes inside gas turbines. The following is a list of definitions for burning competence [36]:

η_c = Actual burning time / Ideal burning time (5)

Equation (5) makes it abundantly evident that the working situations throughout the alteration from perfect thrust to complete shove regulate entirely of the quantified limitations. And the combustion efficiency can be written as:

$$\eta_c = \frac{\rho_g\, A_f\, u_t\, C_{pg}\, \Delta T}{(FAR)\, \dot{m}_A\, \Delta h^o} \qquad (6)$$

In case of $C_p \Delta T = (FAR)\Delta h^o$, this gives

$$\eta_c = \frac{\rho_g\, A_f\, u_t}{\dot{m}_A} \qquad (7)$$

The analysis of Equation [7] demonstrates that the air mixture and fuel densities, the air mass flow rate, the flame area, the flame propagation velocity or turbulent combustion, and the air mass flow rate all affect or are influenced by combustion efficiency. Notably, equation (7) is derived from a direct model that provides a direct expression for the laminar combustion velocity, $u_t = f(T, P)$, as well as a relationship for the turbulent combustion velocity that describes Lewis number effects.

$$\eta_c = f\left(\frac{p3^{1.75}\, A_{ref}\, D_{ref}^{0.75}\, exp\left(\frac{T_3}{b}\right)}{\dot{m}_A}\right)\left(\frac{\Delta P_L}{q_{ref}}\right)^{0.375} \qquad (8)$$

The definition of b is a constant whose numerical value is 300. based on the gas turbine combustion vessel design parameters, which are defined by low pollution rates, effective performance, and ease of design ($\Delta P_L / q_{ref})^{0.375}$ is small, therefore

$$\eta_{c,\theta_L} = f\,(\theta_L) \qquad (9)$$

$$\eta_c = f\left(\frac{p3^{1.75}\, A_{ref}\, D_{ref}^{0.75}\, exp\left(\frac{T_3}{300}\right)}{\dot{m}_A}\right) \qquad (10)$$

Another important fact, is that flying conditions (altitudes), will influence the burning rates of the combustible mixtures in the combustion chambers. When flying at low altitudes, temperatures and pressures will be higher, therefore, allowing for complete burning due to temperature drop by addition of air gradually, which enhances oxidation in the combustion process and hence, reduces residence time. As the aircraft's altitude above the ground increases, it is well known that the pressure drops. Consequently, the air pressure entering the gas turbine engine drops, which causes combustion to slow down as the residence time increases [25, 26]. According to researchers [33–35], it is essential to maintain the combustion process while in flight and boost ignition efficiency by distributing fuel evenly throughout the combustion chamber's main section and extending the residence time. This ensures high chamber pressure and temperature as well as reduced emissions from the engine outlet.

5. Improving combustion efficiency through inlet and flight conditions

Changes in the rate of fuel and air consumption, inlet temperature and pressure, inlet air density and humidity, flame size and speed, and chemical reaction rates that influence the volumetric heat release rate (VHRR) within the gas turbine combustion chamber are examples of operating variables that have an impact on combustion efficiency. It is noted how operating conditions affect the gas turbine's internal combustion efficiency using Equation (5). According to the researchers [36-40], if the operating conditions are renamed by the factor (Θ_L), whether in the engine's combustion chamber fire instability processes or re-ignition, this results in variations in the behavior of the power generated from combustion, or what is known as the volumetric heat release rates.

6. Prediction of flame quenching conditions

The rate of heat release in volumetric (*RHRV)* inside a gas turbine's combustion chamber can be determined using a simple formula [36]. At that point, the compressor must run continuously to force the fluid away from rotating stall formation and reverse flow (surge) conditions and ensure the fire's continuity.

$$VHRR = total\ q(\theta) = comb.\ energy + hotwalls\ energy = q(\theta)\text{comb} + q(\theta))\text{ hot walls} \quad (11)$$

To determine the amount of heat required for re-ignition of a particular aero-gas turbine engine, Figure 6 illustrates the regions where a turbo-compressor operates at steady flow as well as the extremes of steady-state operation sufficient to sustain combustion within the combustion chamber of a gas turbine engine. The operating point is the point where the operating lines and the heat release rate graph intersect. The graph illustrates that instability arises at the intersection of these curves.

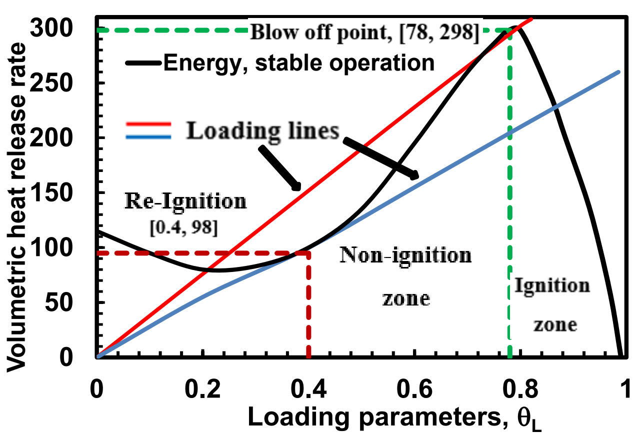


Figure 6. Effect turbo-compressor performance and expected stable and unstable operating areas on combustion stability

The irregularity of the flame inside the combustion chamber when the compressor is operating close to the surge line is depicted in the previous figure. This causes the flame to interrupt, which ultimately results in the gas turbine's stable operation failing. Consequently, it has been noted in numerous references that when a compressor operates in the presence of vortices or a servo line, the flame extinguishes and chemical reactions are not completed because there is insufficient air to finish the combustion process. This phenomenon is called Damköhler phenomenon. According to researcher [37], the blowing time and limit will be calculated by applying the following equation:

$$Da = \tau_{res} / \tau_{chem} \quad (12)$$

If the combustion chamber is kept at a temperature high enough for the re-ignition process, the amount of compressed air produced by the compressor operating away from the surge line reaches a level that chemically induces complete combustion, and the phenomenon known as blow-off happens instantly. As the compressor continues to operate in the safe operating area, fuel injection continues, and the mixture continues to move into the chamber, but at a lower temperature. Both the amount of heat stored as a result of the gases produced from a previous combustion process leading to re-ignition and the total amount of heat stored in the combustion chamber walls can be known using the empirical relationship $150(\Theta_b - \Theta)$ MWm^3. Recall that all of the fuel's characteristics, such as its density at specific pressures and temperatures, flammability limits, temperature at which it spontaneously ignites in air, fuel-to-air equivalency ratio, and combustion velocity, must be precisely known.

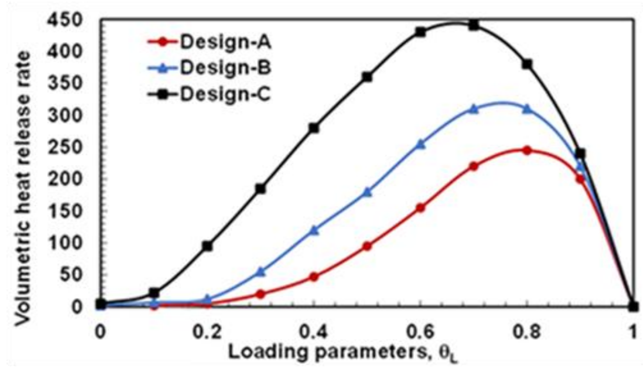


Figure 7. VHRS against the loading parameter (L) for different combustion chamber designs (A, B, and C).

The changes in engine height above the ground result in changes in temperature, pressure, and humidity (also known as loading factors), which in turn affect the volumetric heat rate inside the combustion chambers for different designs of combustion chambers (A, B, and C). Figure 7 shows how these changes impact the inputs to the gas turbine compressor. According to the design specifications for each model, the figure illustrates that the power generated inside the various combustion chambers varies depending on the design. When the loading parameter is increased to 0.7 with combustion chamber design C, the volumetric heat release rate rises until it reaches 0.8 with A shape.

With various combustion chamber designs, the rate drops off dramatically. For such combustion chambers, a highly intricate design process involving numerous calculations is necessary to optimize their performance and reduce emissions. In actuality, it is among the most frequent problems that design engineers encounter. As a result of the methods' reliance on empirical correlations obtained from prior design experiences.

The impact of intake temperature and fuel/air ratio (stoichiometric Phi, Φ) on the entropy gain is depicted in Figure 8 for both lean and rich mixtures. As Φ increases entropy, it is evident that increasing Φ also increases entropy. Due to higher overheating of initial conditions, previously burning charges at higher pressures and temperatures resulted in an increased heat flux within the combustion chamber. Figure 9 shows the decreases in Lewis number with increase of the fuel/air ratio Φ, intake temperature and the lean mixture give higher Lewis number than with the rich, while no significant effect on Lewis number with increasing Φ or inlet temperature.

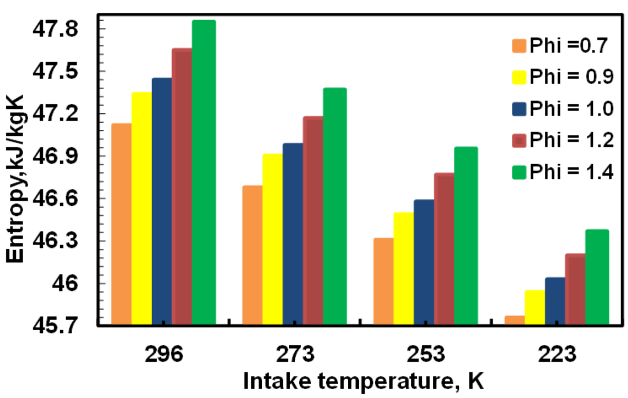


Figure 8. Effect of intake temperature and fuel/air ratio (stoichiometric- Phi) on entropy

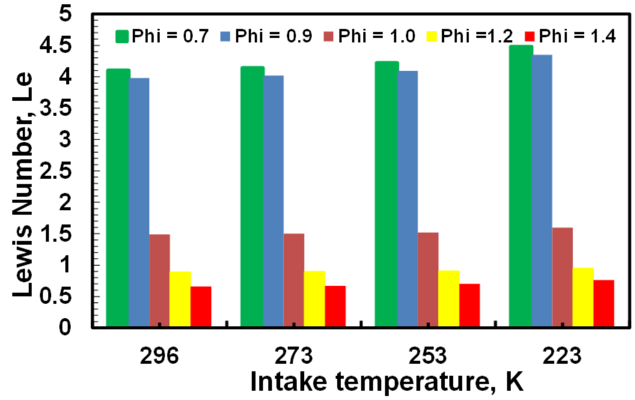


Figure 9. Effect of Phi and intake temperature on Lewis number

Figure 10 shows an increase in both internal energy and the amount of heat inside the combustion chambers with an increase in the fuel-to-air ratio Φ, and the effect on internal energy is greater. But Lewis number decreases sharply with increasing Φ, as shown in Figure 11.

Figure 12 shows strong decreases in the NO ratio by increasing the fuel to air ratio, while there is significant effect on CO or CO2 with increasing Φ. The current findings support the conclusion drawn by [38-40] that as combustion temperature, pressure, and fuel flow increase, so does the NOx emission index.

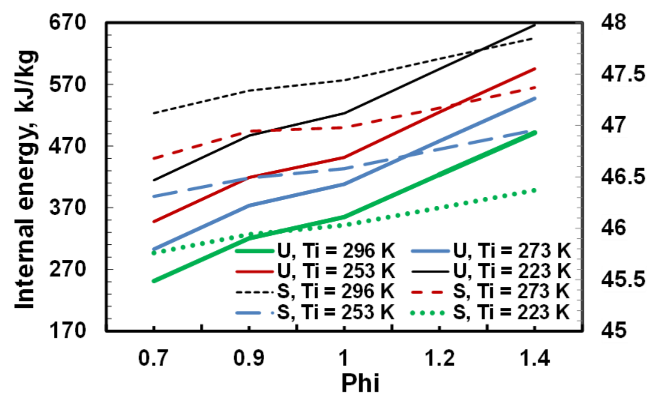


Figure 10. Effect of Phi. and inlet temperature on energy generated

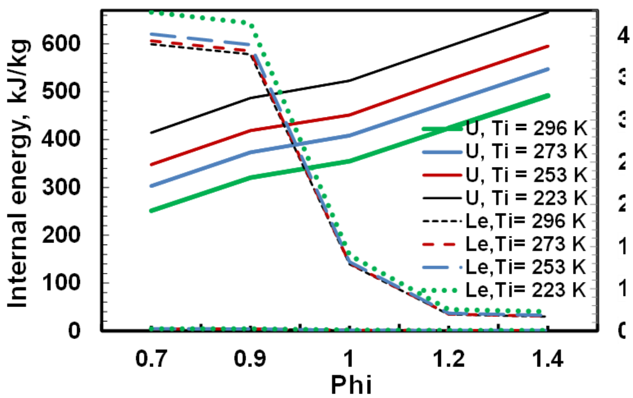


Figure 11. Effect of Phi and inlet temperature on internal energy, and Lewis number

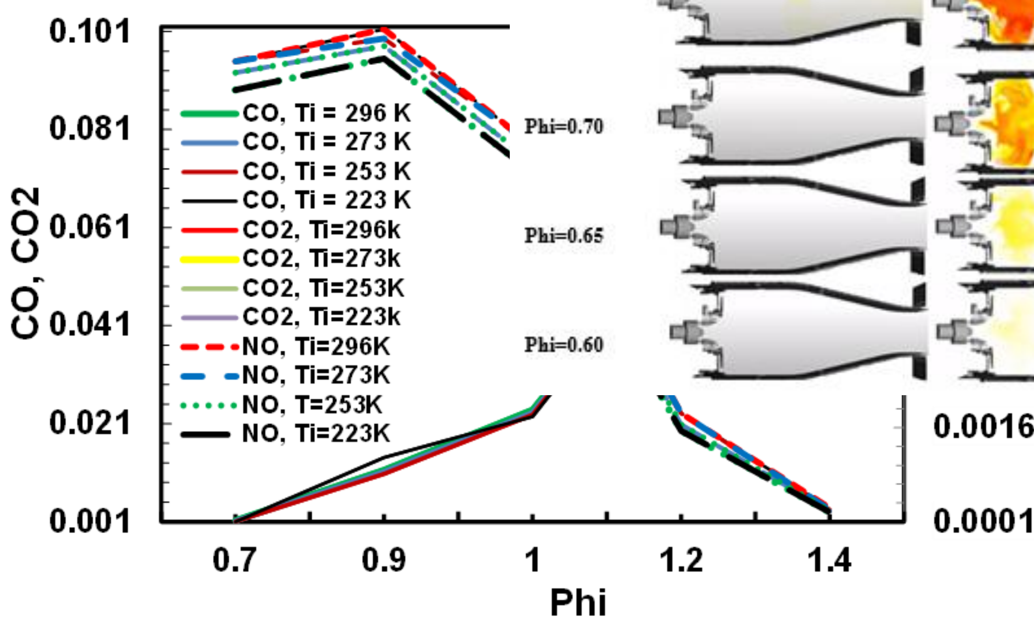
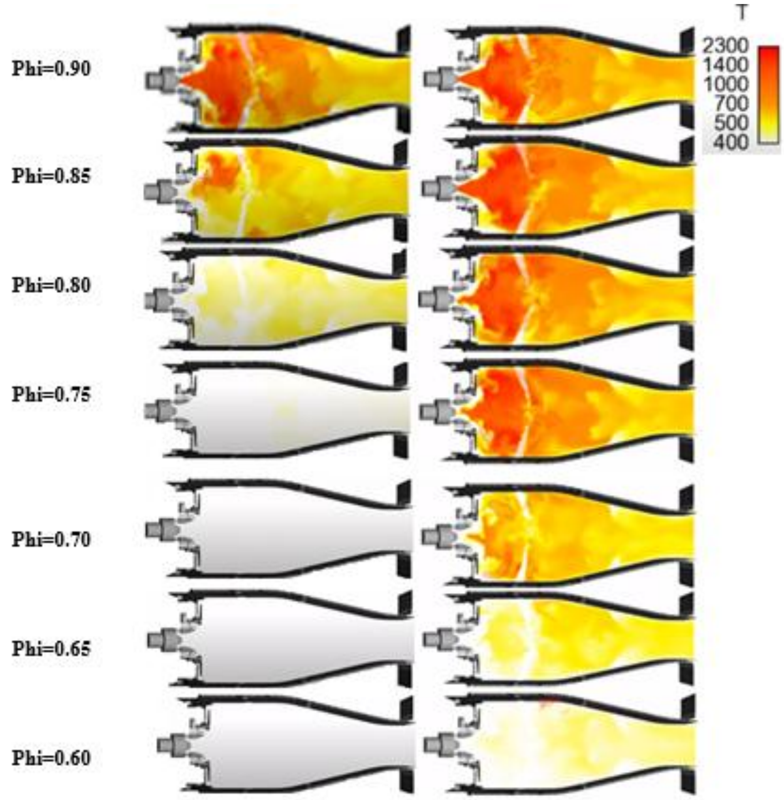


Figure 12. Effect of Phi, and inlet temperature on CO, CO2, and NO

compressor flow are predicted by this simulation.



7. Effect of humidity ratio

The inlet-to-compressor acceleration ratio during internal combustion gas turbine engine combustion is examined in this section. Utilizing ANSYS Fluent software, a computational fluid dynamics (CFD) simulation was conducted to simulate a gas turbine's combustion. Increasing humidity and decreasing flow rate determine the inlet and outlet boundaries of a chamber that represents the combustion field. The k-ω SST model of turbulence, which is renowned for accurately capturing turbulent interactions and boundary effects, is the model that is employed. The software ANSYS was used to numerically simulate the flow of mixture particles inside a gas turbine combustion chamber. As air humidity rises, flame propagation within the combustion chamber at various flow rates is depicted in Figure 13. The onset of vortex formation and fire stalling due to surge at low

Since the compressor runs far from the surge line and suppresses the surge, the right portion of the graph illustrates how increasing air humidity affects the combustion process' ability to continue successfully without stalling. It is noted that surge has a significant impact on flame and explosion within the combustion chamber and on gas turbine stability. As the humidity of the air entering the gas turbine compressor increases, the compressor surge is suppressed, allowing complete combustion to continue until the flow rate reaches a low level, increasing by 27% within the compressor's stable operating range. A satisfactory agreement was found between the simulation results and the experimental data and the ANSYS Fluent model, confirming the validity of the findings regarding the impact of water injection in gas turbine engines.

Figure 13. **Effect of increasing humidity ratio on combustion stability**

8. Conclusions

The main findings of this study summarize the effects of combustion parameters and its characteristics which lead to Blowoff conditions in aero gas turbine engine- like conditions. It is quite clear that loading parameters play tremendous effects on allocating ignition and no ignition zones. The design criteria are another important issue in optimizing thermal efficiency and flames stabilities in combustion chambers for such engines. It can be concluding with effects of intake temperature on loading parameters which shows remarkable decrease as temperature increase.

Increasing the air intake temperature or fuel/air ratio (Phi), from lean to rich mixture increases the entropy due to increased heat flux within the combustion chamber. Decreases in Lewis number with an increase of the fuel/air ratio. The lean mixture gives a higher Lewis number than the rich mixture. Increase in internal energy and the heat inside the combustion chambers with an increase in the fuel-to-air ratio. But Lewis's number decreases sharply with increasing air/fuel ratio. Decreases in the NO by increasing the fuel/air ratio. Continuous combustion can be achieved up until a low flow rate with high humidity levels in the air entering the gas turbine compressor. Water injection at 12% of compressor airflow decreased compressor power requirements by 36%, decreased discharge temperature by 37%, and increased the pressure surge margin by 32%.

Laboratory tests revealed that by spraying water into the engine at a rate of 20% relative to the air, nitrogen oxide emissions from the gas turbine's exhaust gases into the atmosphere could be reduced by up to 25%, and the temperature could be lowered by more than 30%. These results have been validated by theoretical investigations. Over-injection of water beyond the specified percentage can result in stress concentration, fatigue cracking, reduced aerodynamic efficiency, and long-term blade wear. Turbulence, mixture formation, and residence time are all regulated by variations in combustion chamber geometry, which affects emissions and flame stability. The results of the simulation regarding the effect of water injection in gas turbine engines were found to be in satisfactory agreement with the experimental data and the ANSYS Fluent model.

References

[1] Y. Ning-Ning, C. Yi-Feng, W. Li-Ming, X. Qi-Yu, and P. Wei-Guo, "Progress in CFD simulation for ammonia-fueled internal combustion engines and gas turbines", Journal of the Energy Institute, 119, 101951. https://doi.org/10.1016/j.joei.2024.101951, 2025.

[2] A. Medhat, M. El-Adawy, A. Abdelhalim, H. Mohamed, and A. Abdelhafez, "On the effects of flow/mixture stratification on combustion/stability behaviors of dual-swirl oxy-methane flames: Experimental and numerical study", Process Safety and Environmental Protection, 196, 106912. https://doi.org/10.1016/j.psep.2025.106912, 2025.

[3] A. Joon, "Large Eddy Simulation Approaches for Trailing-Edge Heat Transfer in Gas Turbine Blades: A Review". Energies, 18 (6), 1386. https://doi.org/10.3390/en18061386, 2025.

[4] S. Ting, L. Yi, J. Shiqi, S. Yuang, G. Zihao, G. Bing, and D. Dongxia, "Effects of swirl intensity on the instability of hydrogen micro-mixing diffusion combustion. International Journal of Hydrogen Energy", 36 https://doi.org/10.1016/j.ijhydene.2025.03.064, 2025.

[5] Z. Runfan, W. Wubin, L. Siyu, W. Wenyu, H. Yong, W. Zhihua, "Flame stability and NOx emission characteristics of a high H2-content CH4/H2 fueled micro-mixing burner", Fuel, 375, 132506. https://doi.org/10.1016/j.fuel.2024.132506, 2024.

[6] L. Suhui, Q. Wenkai. L. Haoyang, and L. Guijun, "Autoignition and flame lift-off behavior of a fuel jet mixing with turbulent hot air coflow, Proceedings of the Combustion Institute 38(4), doi:10.1016/j.proci.2020.06.230. 2020.

[7] C. Mark, and A. Priyant, "Design and Analysis of Annular Combustion of a Low by Pass Turbofan Engine in a Jet Trainer Aircraft", Elsevier, Propulsion and Power Research 5(2), 97-107, doi: 10.1016/j.jppr.2016.04.001, 2016.

[8] S. Fawzi, D. Raheem, and H. Khaldoon", Review of Gas Turbine Combustion Chamber Designs to Reduce Emissions", International Journal of Advanced Engineering, Management and Science (IJAEMS), 9(6), 421-431, doi: 10.22161/ijaems.69.2, 2020.

[9] F. Mochammad, B. Madiah, I. Rosdiazli, and A Bahaswan, "Dry-Low Emission Gas Turbine Technology: Recent Trends and Challenges", Applied Sciences, 12(21), 10922, doi.org/10.3390/app122110922, 2022.

[10] X. Zhi, L. Ivan, and S. Nedunchezhian, "The Role of CFD in Modern Jet Engine Combustor Design, Environmental Impact of Aviation and Sustainable Solutions", Int. J. of Combustion and Flame. 232(3), 111532, doi: 10.5772/intechopen.88267, 2021.

[11] C. Xinyi, B. Hannes, S. Arne, H. Christian, and C. Zheng", Effects of stretch-chemistry interaction on chemical pathways for strained and curved hydrogen/air premixed flames. doi.org/10.1016/j.combustflame.2021.111532, 2021.

[12] A. Hassan, "Spraying water at the compressor inlet improves the performance of a small gas turbine and lowers fouling rates", Journal of Engineering and Applied Sciences JE&AS, Vol. 12, Issue (1) June (2025).

[13] D. Santanu, K. Avinash C. Swetaprovo, and S. Swarnendu", Modeling and Simulation of Turbulent Combustion", Springer Singapore ISBN: 978-981-10-7409-7, doi:10.1007/978-981-10-7410-3, 2017.

[14] C. Andrea, R. Mirko, B. Birute, P. John, and F. Gerhard, "Superior fuel and operational flexibility of sequential combustion in Ansaldo Energia gas turbines", Journal Glob. Power Propuls. Soc. 2019;3:630-638, doi.org/10.33737/jgpps/110717, 2019.

[15] D. Thong, K. Iman, H. Tatang, and F. Osamu, "Investigation of combustion of the gas turbine engine from kerosene and Biokerosene and their soot characteristics in diffusion flames', ACS Omega2022,7, 37085-37094, doi.org/10.1021/acsomega. 2c02703, 2022.

[16] B. Cuenot, "Gas Turbines and Engine Simulations", Advances in Chemical Engineering, 49, 273-385. https://doi.org/10.1016/bs.ache.2016.09.004, 2016.

[17] M. Enache, C. Petcu, R. Carlanescu, and F. Gabriel, "The Design of an Annular Combustion Chamber. 6th CEAS Air & Space Conference Aerospace Europe, Bucharest, Paper No. 810, SBN of the proceedings 978-973-0-25597-3, 2017.

[18] P. Chiesa, G. Lozza, and L. Mazzocchi, "Using Hydrogen as Gas Turbine Fuel", ASME Journal of Engineering and Gas Turbines and Power; (127), 73-80, doi.org/10.1115/1.1787513, 2005.

[19] A. Valera-Medina, N. Syred, and A. Griffiths", Visualisation of isothermal large coherent structures in a swirl", International Journal of Combustion and Flame, 156(9), 1723-1734, doi.org/10.1016/j.combustflame.2009.06.014, 2009.

[20] S. Heng, H. Xiao, S. Tong, X. Xin, Z. Chi , and S. Chih-Jen, " Parametric study of the slope confinement for passive control in a centrally-staged swirl burner", Int. Journal of Combustion Flame 2009;156(9),1723-1734, doi.org/10.1016/j.energy.2021.121188,, 2021.

[21] N. Shelil, A. Bagdanavicius, N. Syred, A. Griffiths, and P. Bowen, "Premixed Swirl Combustion and Flash Back Analysis with Hydrogen/Methane Mixture", Conference: 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, doi: 10.2514/6.2010-1169, 2010.

[22] R. Sujitha, and I. Vishnu, "Vishnu Dynamical systems and complex systems theory to study unsteady combustion, " Proceedings of the Combustion Institute, 38(3), 3445-3462, https://doi.org/10.1016/j.proci.2020.07.081, 2020.

[23] M. AL-Hashimi, "Flashback and Blow off Characteristics of Gas Turbine Swirl Combustor", Ph.D. Thesis, Institute of Energy Cardiff, School of Engineering, Cardiff University, Cardiff / UK, 2011.

[24] S. Nick, A. Giles, L. Jonathan, and J. Griffiths, "Effect of inlet and outlet configurations on blow-off and flashback with premixed combustion for methane and a high hydrogen content fuel in a generic swirl burner", Journal of Applied Energy 116:288-296, doi:10.1016/j.apenergy.2013.11.071, 2014.

[25] L. Jonathan, M. Richard, V. Agustin, M. Steven, and B. Hesham, "The Use of CO2 to Improve Stability and Emissions of an IGCC Combustor", Proceedings of the ASME Expo 2014: Turbine Technical Conference and Exposition,16-20, Dusseldorf, Germany, GT2014-25446, doi:10.1115/GT2014-25446, 2014.

[26] Y. Mori, T. Kawada, S. Fukuda, and H. Gotoda, "Nonlinear dynamics of attenuation behavior in combustion oscillations in a swirl-stabilized combustor", Proceedings of the Combustion Institute, 39(4), 4671-4679, doi.org/10.1016/j.proci.2022.08.038, 2023.

[27] B. Shi, Q. Cao, D. Xie, W. Peng, and N. Wang, "A novel combustion system for liquid fuel evaporating and burning. Proceedings of the Combustion Institute, 37(4), 4329-4336, doi.org/10.1016/j.proci.2018.07.022, 2019.

[28] G. Yu, K. Larry, J. Hyunwook, and T. Kyu, "Effect of flame response asymmetries on the modal patterns and collective states of a can-annular lean-premixed combustion system. Proceeding of the Combustion Institute, 39(4), 4731-4739, doi.org/10.1016/j.proci.2022.08.095, 2023.

[29] T. Tom, S. Sebastian, P. Christian, and S. Panagiotis, "Combustion efficiency measurements and burner characterization in a hydrogen-oxyfuel combustor", Int. Journal of Hydrogen Energy, 44(56), doi: 10.1016/j.ijhydene.2019.05.055, 2019.

[30] B. Barnali, and V. Prabu, "Prospects and issues of integration of co-combustion of solid fuels (coal

and biomass) in chemical looping technology", Journal of Environmental Management, 231(1), 241-1256, /doi.org/10.1016/j. jenvman.2018.10.092, 2019.

[31] L. Haihang, Y. Wei, L. Pan, Z. Zhihui, and W. Jian, "The Influence of High Altitude on Combustion Efficiency and Radiation Fraction of Hydrocarbon Fires", Follow journal of Heat Transfer Research, 48(10), doi:10.1615/HeatTransRes.2016010282, 2016.

[32] O. Tosin, K. Athanasios, P. Kumar, W. Stuart, F. Beatriz, and J. Nelia, H. Dawid, M. Vasilije, P. Alison, M. Ewan, W. Leon, T ,Stean, C Elise. An experimental investigation of the combustion performance of human faeces. International Journal of Fuel, 184, 780-791, doi.org/10.1016/j.fuel.2016.07.077, 2016.

[33] S. Ramazan, Y. Murat, and G. Mehmet, "Effects of injection strategy and combustion chamber modification on a single-cylinder diesel engine", International Journal of Fuel, 266 (3), 117122, doi.org/10.1016/j.fuel.2020.117122, 2020.

[34] S. Serhiy, F. Kateryna, and C. Daifen, "Investigation of the Characteristics of a Gas Turbine Combustion Chamber with Steam Injection Operating on Hydrogen-Containing Mixtures and Hydrogen. International Journal of Chemical Engineering", doi.org/10.1155/2022/9123639, 2022.

[35] W. Zhonghao, and B. Hu, Z. Qingjun, "Predicting lean blow-off limit of gas turbine combustors based on Damköhler number and detailed atomization information. Proceedings of the Institution of Mechanical Engineers", Part A: Journal of Power and Energy, Volume 235, Issue 2, https://doi.org/10.1177/0957650920920038, 2020.

[36] P. Malbois, E. Salaün, B. Rossow, G. Cabot, L. Bouheraoua, S. Richard, B. Renou, and F. Grisch, "Quantitative measurements of fuel distribution and flame structure in a lean-premixed aero-engine injection system by kerosene/OH-PLIF measurements under high-pressure conditions", HAL, Id: hal-02011677, https://hal.science/hal-02011677v1 https://hal.science/hal-02011677v1/file/S1540748918301779.pdf, 2021.

[37] H. Tira, and F. Fathonah, "Evaluating the Thermodynamic Performance of 2 Spool Gas Turboshaft Engines", International Journal of Progressive Sciences and Technologies (IJPSAT), ISSN: 2509-0119, Vol. 44, No. 2, pp. 446-453, May 2024.

[38] T. Harlass, R. Dischl, S. Kaufmann, R. Märkl, D. Sauer, M. Scheibe, P. Stock, T. Bräuer, A. Dörnbrack, A. Roiger, H. Schlager, U. Schumann, T. Schripp, T. Grein, L. Bondorf, C. Renard, M. Gauthier, M. Johnson, D. Luff, P. Madden, P. Swann, D. Ahrens, R. Sallinen, and C. Voigt, "Measurement report: In-flight and ground-based measurements of nitrogen oxide emissions from latest generation jet engines and 100% sustainable aviation fuel", https://doi.org/10.5194/egusphere-2024-454, Feb., 2024.

[39] E. Büyükkabakci, and A. Yönetken, "The Effect of Gas Turbine Inlet Air Temperature On Electricity Production Effiency in Trigeneration Power Plants", OKU Journal of the Institute of Science and Technology, 7(4): 1579-1599, DOI:10.47495/okufbed.1336600, 2024.

[40] L. Yi-Guang, and L. Yang, "Off-design performance control and simulation for gas turbine engines with sequential combustors. Proceeding IMechE Part A: J Power and Energy 2025, Vol. 0(0) 1-19, DOI: 10.1177/09576509251327695, 2025.

Nomenclature

Symbols	Description
A	Cross section area (m^2)
D	Diameter (m)
$\dot{m}$	Mass flow arte (kg/s)
P	Pressure (Pa)
T_b	Burned Temperature (K)
T_u	Unburned Temperature (K)
VHRR (q)	Volumetric Heat Release Rate (kJ/s)
ρ	Density (kg/m^3)
θ_b	Loading parameter at blow off condition
θ_L	Loading parameter at flying condition
θ_r	Loading parameter at re–ignition condition