Spraying water at the compressor inlet improves the performance of a small gas turbine and lowers fouling rates

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Abstract

Since water contains hydrogen and hydrogen has the highest rating on the flammability scale because it is flammable when mixed even in small quantities with normal air, therefore, spraying water to the compressor inlet was tested to improve the efficiency of the compressor and reduce the emission rates of polluting gases to the environment. Despite their low efficiency, gas turbine engines are still used for power generation, aircraft engines, and rockets. It is therefore necessary to find ways of improving the efficiency of these cycles and the consistency of the compressor flow. This research aims to reduce compressor instability, increase the operating limit and improve gas turbine performance. One of these methods is to spray water into the air at the compressor inlet. The effect of inlet water sprayers on the stable flow operating range and gas turbine performance has been investigated. A numerical analysis model without water spray is described. Then the effect of water spray is added to this model and the surge onset with and without water spray and the wet pressure processes are predicted based on the average line calculations. These analyses were necessary for the gas turbine compressor to understand the effect of water spray on the stable flow region and its effect on the efficiency of the entire gas turbine. Amounts of water ranging from 1% to 20% of the air mass were injected into the compressor through a nozzle, a valve, and an injection pump. At different operating conditions, the surge was found and considered as the compressor limit of the flow stability of the gas turbine. The aerodynamic instability caused by the occurrence of stall in axial compressors was determined using a simple model. The result shows an improvement in the operating range and performance of gas turbine.

Submitted: 5-OCT-2024

Accepted: 12-DEC-2024

Published: 1-JUNE-2025

DOI: 10.5455/jeas.2025010601

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Keywords:

water spraying, axial flow compressor, gas turbine, rotating stall, surge initiation.

Highlights:

The effect of injecting or mixing water with the air entering the compressor on improving the production of energy generated by small gas turbines with high speeds, performance, exhaust gas emissions, and high ambient temperatures.

1. Introduction

Nowadays, there has been an increase in the demand for gas turbines as they are widely used for electricity and power generation. Therefore, researchers have made efforts to improve their thermal performance. In recent years [1-6] and in the past [7-9], many types of research have been conducted using various techniques to increase the performance of gas turbines and improve their efficiency, including the use of water injection with air, either in the combustion chamber or at the compressor inlet. The effects of injecting water and steam into the combustor of a gas turbine on fuel consumption [10], NOx reduction [11, 12], and power enhancement [13, 14]. Most of the theoretical papers published [15, 16] use simple thermodynamic models without considering the effects of water/steam injection on gas turbine performance and the range of stable operation due to stall initiation and surge limit. The effect of cooling the air entering the compressor after spraying with water on the performance of gas tubes in both open and combined cycles [17] has been studied and applied to existing engines. General Electric has combined inlet cooling and inter-compressor cooling by water injection in the LM6000 twin-disk engine [18]. Some previous studies presented analytical or numerical methods that showed that injecting water into the compressor inlet at a rate of 12% of the base air volume [19, 20] resulted in up to 50% reduction in nitrogen oxide emissions. Some previous studies [21, 22] presented analytical or numerical methods that showed that spraying the compressor inlet with water at a rate of 12% of the base air volume has reduced NOx emissions by about 50% [23-25]. Other researchers [26-29] showed that spraying water at 1% of the air has reduced compressor discharge temperature by 10%, and researchers [30-38] presented figures very similar to the previous one. Adding steam alters the combustion process inside the combustor, which should be considered during combustor design [39].

The application [40] model was used to study the effect of the Steam Injection Gas Turbine (STIG) cycle as well as the change in ambient temperature on the performance of the unit in terms of power and output efficiency and it was concluded that there is a significant improvement in performance using this specific technique.

2. Pilot working test device

Figure 1 shows micro-gas turbine apparatus, biaxial with a gas generator, power turbine, loading unit, and measuring instruments. In each experiment the pressure and temperature at the inlet and outlet of the compressor and turbine and at outlet of the system, turbine power output, and mass flow rate for fuel, air, and water injection are measured. Pollution levels were detected and recorded using a gas analyser (Fig.2) at a gas turbine system exhaust. The technology of injecting water mist into the air drawn by the compressor is shown in Fig. 3, in addition to the flow rate measuring device. Figure 4 shows influences of injecting water mist at different rates into the air required for small gas turbines. The different percentages of water injection gave different results of compressor performance, and the values of 15% water to air gave the highest results. Figure 5 shows increasing of injecting water spray into the air required for micro-gas turbines decreases the exhaust temperature. Figure 6 shows decreases in pollution with increased quantity of water injection. The previous figures concluded that increasing the water injection to the compressor decreases the exhaust gas temperature and increases the proportions of water added to the air. The decrease in nitrogen reached 20% and in both carbon dioxide and nitrogen monoxide up to 3% and the improvement in gas turbine overall efficiency reached11%. The result emphasizes the importance of adding water to compressor inlet to improve pollution rates and system efficiency.

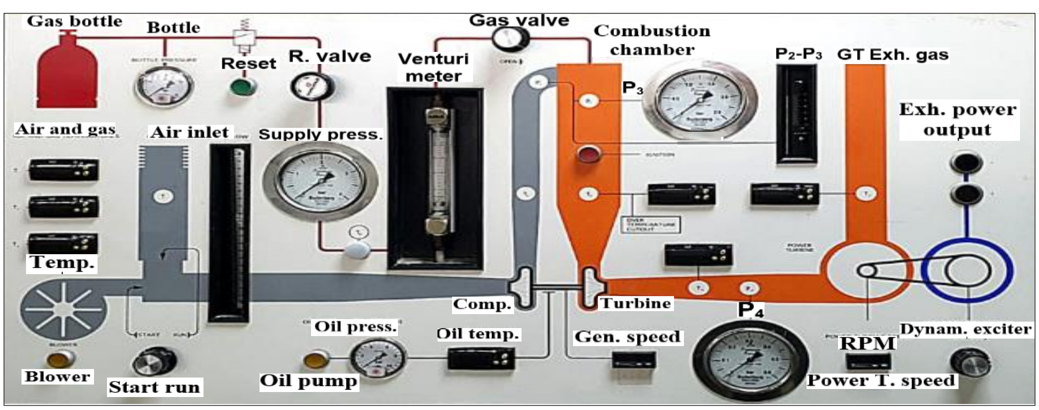

Fig.1. Micro-gas turbine apparatus

Fig.2. Emission ratio measuring device

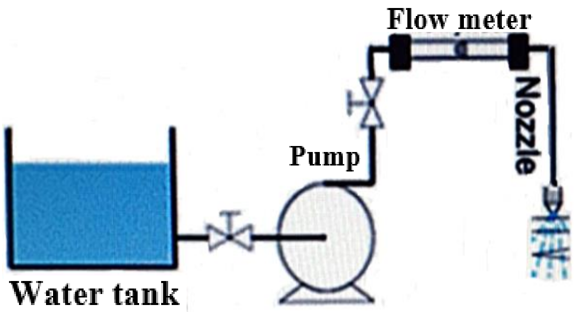

Fig.3. Method of water injection and measurement

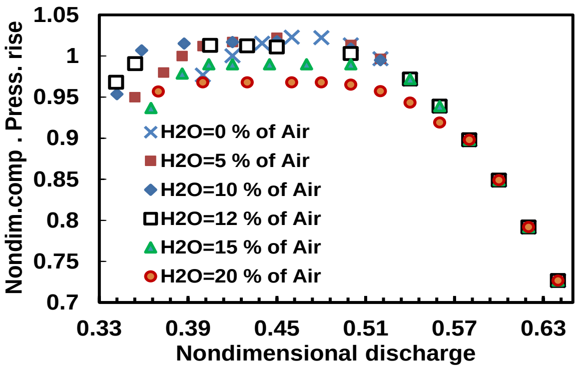

Fig.4. Influence of injecting water spray into the air required for micro-gas turbines

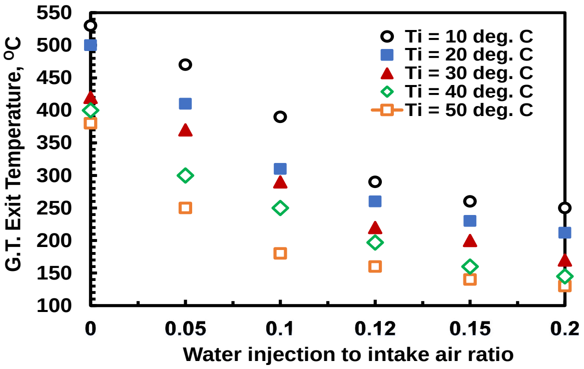

Fig. 5. decreasing of exit temperature with increasing of amount of water injection

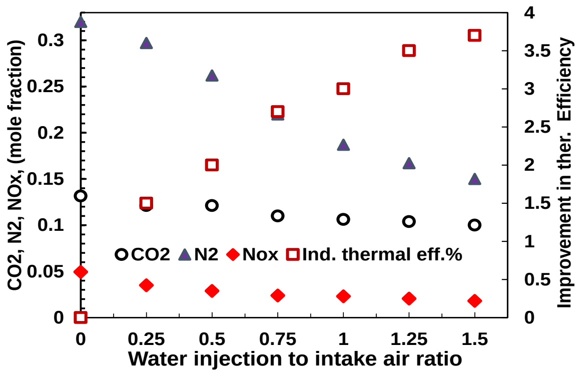

Fig. 6. decreasing of pollution with increasing amount of water injection

3. Analytical study of the effect of water injection into the compressor inlet

To study the effect of injecting or adding water spray process with the air drawn by the compressor to complete the combustion process inside the gas turbine requires full knowledge of the phenomenon of turbulence and the ability to predict the beginning of the cessation of combustion. This requires integrating the compressor, turbine, and combustion chamber models into one model (Fig. 7) to ensure knowledge of the effect of adding water on the performance of the engine as a whole.

We conducted these analyses similar to what was done by both researchers [19, 27- 42] and with the development carried out by Gretzer [29]. This captures the behavior of the limit cycle after stalling in pressure regimes and can be predicted to cause a rotary surge or stall at the height line shown in Fig. 1. The model corresponds to the maximum characteristic of total pressure rise versus static pressure, and this model has been confirmed by many researchers and has been used on this system and written in a nondimensional form as follows:

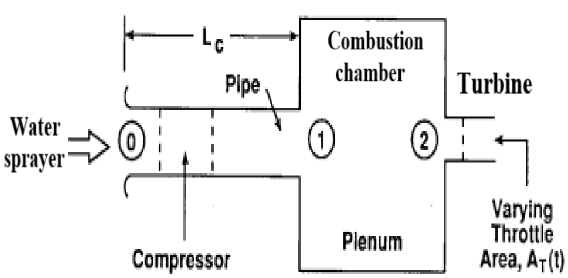

Fig. 7. Micro gas turbine mode

$$d\Phi_c/d\tau = B\left[\Psi_c(\Phi_c) - \Psi_p\right] - C_1\phi_w\left[\Phi_c - \Psi_c(\Phi_c)\right] \quad (1\text{-a})$$

$$d\Psi_p/d\tau = (\Phi_c - \Phi_T)/B - C_2\phi_w\Psi_p d\Psi_p/d\tau \quad (1\text{-b})$$

$$d\Phi_T/d\tau = B\left[\Psi_p - \Psi_T(\Phi_c)\right] - C_3\phi_w\Psi_c(\Phi_c) \quad (1\text{-c})$$

$$d\Psi_c(\Phi_c)/d\tau = [\Psi_0 - \Psi_c(\Phi_c)] - C_4\phi_w\Psi_p/\tau \quad (1\text{-d})$$

Where C_1, C_2, C_3, C_4 are constants. If we assumed h, is aptitude of the regulator $\Phi_T(\Psi_T) = (h\Psi_p)^{0.5}-1$, the chamber room is exhibited as Ψ_p. The compressor operation curve is polynomial cubic curvature [36]:

$$\Psi_c(\Phi_c) = 12.117\Phi_c^2 - 2.423\Phi_c + 0.221;\ \Phi_c \le 0.1$$
$$-49.62\Phi_c^3 + 39.509\Phi_c^2 - 6.413\Phi_c + 0.395;\ 0.1 < \Phi_c \le 0.4$$
$$-10.0695\Phi_c^2 + 9.43\Phi_c - 1.184;\ <0.4 \quad (2)$$

Using Equs. (1 & 2), with Euler's equation, the system pressure rise is:

$$P_2 = P_1 + 0.5\rho U^2[1 - \phi^2(1 - \tan\beta_2^2) - C_i\phi^2 - C_{fw}\phi^2 - C_f(1-\phi^2) - C_{sh}(\phi - \phi_0)] \quad (3)$$

where β is the exit impeller outlet vane angle, ϕ perturbation in flow, C_i incidence angle loss contingent, C_f damage factor, C_{sh} is nondimensional stall injury flow, and C_{fw} partition defeat. Suppose, C_f=0.075, C_{sh}=3 and C_{fw}=0.25, the steadiness is:

$$dP_2 = \rho\omega^2(1 - \phi\tan\beta)^2 r dr \quad (4)$$

Reckonings (1-4) give the system curve shown in Fig.2, while, the derivative $dP_2/d\phi$ vanishes for, $\phi = (C_x/U) = \phi_s$. Participating the equation imitative from Equs. (4 and 3) by eliminating P_2 gives the outward scattering of the local flow ϕ. The whole flow coefficient of the compressor can be designated as follows:

$$\Phi = 2\int_{r_h}^{r_t}\phi r^2 dr/[r_t(r_t^2 - r_h^2)] \quad (5)$$

To detect the initiation of rotating stall above inviscid flow, the stagnation temperature and pressure relative to inlet as a function of Mach number can be written similar to [30, 31] as:

$$T_{O2W}/T_1 = [1 + 0.5(K-1)M_{r1}^2(T_{2W}/T_1 - 1)(k-1)\, M_{r1}^2 \sin\beta_2(W_2 - w_2)/U_2 \quad (6)$$

$$\frac{P_{O2w}}{P_1} = \left\{\frac{[1 + 0.5(K-1)M_{r1}^2]\left[1 + \frac{w}{U_2} - 2\frac{w}{U_2}\sin\beta_2\right]}{\left(\frac{T_{O2w}}{T_1}\right) + 0.5(K-1)M_{r1}^2\frac{T_{2wr}}{T_1}\left(\frac{W_2}{U_2}\right)^2}\right\}^{(k-1)/k} \quad (7)$$

Equations (5-7) show that the beginning of the formation of rotating vortices is the result of the weakening of the energy carried by the fluid at the rotor exit, and this leads to the rotation of the air or the cessation of flow in some parts of the diffuser passages, which leads to oscillation or a sudden rise in pressure and thus the compressor. The purpose of spraying water into the compressor is to control aerodynamic instability so that the increase in mixture density is proportional to the instability disturbances. Therefore, the characteristic of the pressure supplied by water inoculation, Ψci(Φc), is as follows:

$$\Psi_{ci}(\Phi_c) = \Psi_c(\Phi_c) + FR(f_o + f_1\Phi_c) \quad (8)$$

Where f_o, and f_1 are coefficient, will be used to exchange the steady operating points to the slope of the bifurcation curve which can be written as:

$$\Phi_T = (F\Phi_T + h)\Psi_T \quad (9\text{-a})$$

$$[dS]_{h=hc} = \Psi_p^{0.5}/\{[\Phi\partial\Psi_{ca}/\partial\Psi\Phi_c \quad (9\text{-b})$$

$$\partial\Psi_{ci}(\Phi_c)/\partial\Phi_c = -0.327S\partial^3[\Psi_{ci}(\Phi_c)]/\partial\Phi_c^3 \quad (9\text{-c})$$

Using Equ.9, the branching at the vital effective theme (h_c) is:

$$[dS]_{h=hc} = \Phi_p^{0.5}/\{[(\frac{\Phi\partial\Psi_{ca}}{\partial\Phi_c} + \frac{0.327\partial^3\Psi_c}{\partial^3\Phi_c})/\frac{\partial^2\Psi_c}{\partial^2\Phi_c}] - (\frac{\Phi_c}{2\Psi_c})(F\Psi_{ca} - 0.125)(\frac{\partial^2\Psi_c}{\partial^2\Phi_c})\} \quad (10)$$

turbulences ϕ_c, ψ_c, ϕ_T, and ψ_c are used in Equs. (8-9) to matrix [32], transferred to equation from 4^{th} deg. as):

$$S^4 + a_3S^3 + a_2S^2 + a_1S + a_0 \quad (11)$$

According to Gysling and Greitzer [38], Mansoux [41] and Behnken [42], the coefficients can be determined, which are used to solve Equation (11). On the other hand, effect of spraying water to the system intake on the hotness gratified (ds_e) is:

$$Tds_e = dh_a + \omega dh_w + dh_m - vdp \quad (12)$$

where, s, h and v are combination amounts, and ds is the entropy rise owing the balance among the vapour and watery can be is:

$$dh_m = h_{wg}\,d\omega + (\omega C_{pw} + C_p)dt + C_{pw}dT \qquad (13)$$

If the rise in moisture is dω, and and15), the perfect steamy density effort is:

$$W_{COmp} = \omega_2(C_{pg}T_2 + h_{wg}) - \omega_1(C_{pw}T_1 + C_p)dt + (\omega C_{pw} + h_{wg}) + C_2C_{pw}T_2 - C_1C_{pa}T_1 \qquad (14)$$

The influence of the gas turbine with the presence of water spraying is:

$$\omega C_{pw}\,dT_{s/}dt = A(q_s - q_L) = A(q_s - Iq_{wg}) \qquad (15)$$

Where I is the amount of steam volatility gone meanwhile the spewing, q_L the buried hotness flux owing to spraying desertion, and q_s the delicate warmth fluidity due to convection. Similar to Kollrack et al. [43], Kyoungjin et al. [44], Chuang et al. [45] and Pourhedayat et al. [46], the warmth is:

$$q_s = 2k(T - T_s)/D \qquad (16\text{-a})$$
$$I = (2kD_v/DR_v)\,(P_s/T_s - P_v/T) \qquad (16\text{-b})$$

Where D_v is the steam dispersion aspect, R_v air constant, P_s statured pressure, and k air thermal conductivity. By means of Equs. (15 and 16), the air humidity growth is:

$$d\omega = [\ln\pi_c/\ln T_r] + (R_a/R_{wg})[(\eta_c - k)/(\eta_c - 1)][(T_2 - T_1)/(k-1)] - [k/(k-1)] \qquad (17)$$

Figure 8 shows the result of injecting some water with the air drawn into the compressor on the temperature of the gases leaving the tested micro-gas turbine engine at different atmospheric temperatures. It is observed that at a certain temperature of the environment surrounding the system, the exhaust temperature decreases by a maximum of 50% at a water injection ratio of 20% of air.

To evaluate the wet pressure based on the increase in air density as a result of injecting water into the compressor inlet, the angular momentum can be written as follows:

$$d\omega^2/\omega^2 = 2(W_T - W_C - W_G - W_{loss})/I \qquad (18)$$

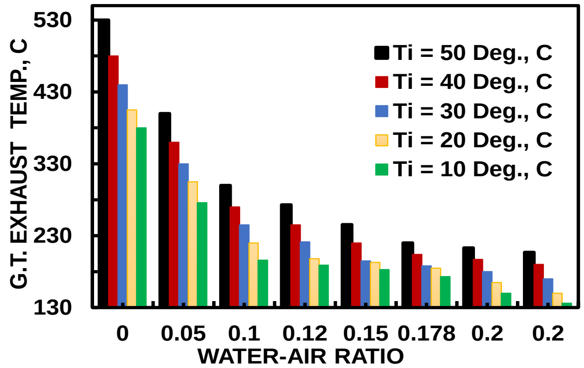

Fig.8. Effect of water injection on system exhaust temperature

The thermal efficiency of a micro-gas turbine system can be calculated as follows:

$$\eta_T = W_T/(h_{o,Ti} - h_{o,Te}) \qquad (19)$$

$$W_{net=W_T-W_C} = m_{ThT}C_{pga}(T_{o,Ti} - T_{o,Te}) - (m_a + m_w)C_{paw}(T_2 - T_1)/\eta_c \qquad (20)$$

Figure 7 shows the compression work against water spraying ratio for various ambient temperatures. Spraying water into the compressor inlet increases the system efficiency by 3% and the energy by 6%. It is clear in the figure that the compression work decreases with increasing water sprays ratio or decreasing ambient temperature due to increasing the air density. Relative compression work is plotted against water injection ratio in Fig. 8 for various ambient temperatures. The relative compression work decreases with increasing water injection ratio or decreasing ambient temperature, too. Figures 7 and 8 represent the relative power and capacity of the compressor versus the ratio of spraying water to the air entering the engine. Both figures show no values for the compressor capacity at a low flow, which is related to decrease pressure and ambient temperature, so the droplets can't evaporate inside compressor. At any specified pressure ratio, the compressor work increases with the increase of the ambient temperature. Note, the compressor relative work was defined as the ratio of the compressor work under the wet state to the dray. Using Equs (19, 20), the stage efficiency can be written as:

$$\eta_{GT} = [(\pi_t^{\frac{n-1}{n}} - 1)(m_a T_3 + m_w T_w)]/[m_a(T_3 - T_1) + m_w(T_3 - T_o)] \quad (21)$$

Figure 9 shows the increase in overall efficiency and decrease in the gas turbine-specific fuel consumption rate and overall efficiency with increasing water inoculation ratios to the compressor inlet and increased pressure. This is because increasing the amount of water injected turns into steam in the combustion chamber with increasing pressure, which leads to increases in the specific heat and thus increases the energy generated from the evaporation of water droplets. That there is an improvement of approximately 15% in the overall gas turbine efficiency at 20% water injection compared to the air volume flow rate. The specific fuel consumption of gas turbines decreases with increasing water injection and gives maximum boost enhancement of about 8% of total specific fuel consumption.

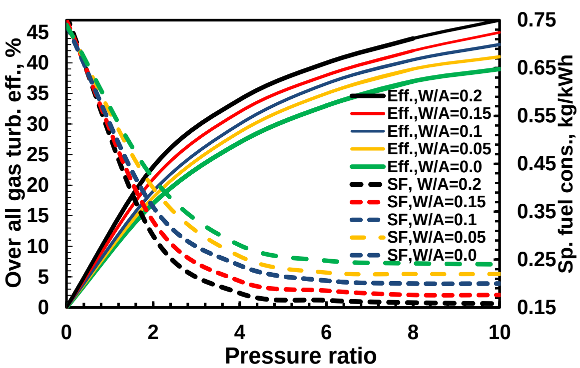

Fig. 9. Effect of water injection on overall gas turbine efficiency and specific fuel consumption

4. Conclusions

As a result of the change in fuel prices, the increase in carbon emission devices, and the increase in environmental pollution resulting from gas turbines, especially those used in power generation plants, the temperature of the gas coming out of them reaches about 400 degrees Celsius. It was necessary to think about finding solutions to reduce exhaust gas temperatures, prevent pollution, and reduce fuel consumption. One of these methods is to inject a quantity of water into the inlets of gas turbines. This research dealt with an attempt to improve the performance of a micro-gas turbine at high speeds by adding spraying or injecting an appropriate amount of water into the compressor inlet. This idea addresses carbon in order to reduce fuel consumption in addition to generators, as well as the pressure of emitting aluminum oxide and carbon dioxide with engine exhaust gas. Practical experiments and experimental analyses can be carried out to achieve effective results by adjusting the pressure ratio to the air-fuel ratio in a turbocharged engine.

Laboratory experiments have shown that increasing the fuel-to-air injection ratio leads to improving the efficiency of the tested gas turbine. When about 20% of water was injected relative to the air, the system increased efficiency by about 11%, reduced specific fuel consumption by about 15%, and reduced pollution rates by 11%. The theoretical analyses and outcomes were in good agreement with the laboratory results.

List of used Mathematical notations

ρ	*sound speed, m/s*
B	*non-dimensional parameter*
C_x	*axial fluid velocity, m/s*
H	*Helmholtz frequency, Hertz*
Lc	*compressor length, m*
M_r	*Mach number relative to the rotor*
m_s	*surge flow rate with water spray, kg/s*
P	*pressure rise, kPa*
m_{so}	*surge flow rate without water spray, kg/s*
r	*rotor radius, m*
T	*absolute temperature, K*
U	*impeller tip speed, m/s*
V_p	*chamber volume, m^3*
W/A	*water to air ratio*
Φ	*nondimensional flow,* $=\dot{m}_c/\rho A_c U^2$
Ψ	*nondimensional pressure,* $= \Delta P_c / 0.5\rho u^2$

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