# EFFECTS OF STEAM ADDITION AND/OR INJECTION ON THE COMBUSTION CHARACTERISTICS
## A Review

by

***Ashkan SEHAT[a], Fathollah OMMI[b*], and Zoheir SABOOHI[c]***

[a] Kish International Campus University of Tehran, Kish Island, Iran
[b] Tarbiat Modares University (TMU), Tehran, Iran
[c] Aerospace Research Institute, Ministry of Science, Research, and Technology, Tehran, Iran

Review paper
https://doi.org/10.2298/TSCITSCI191030452S

*Due to increasing global energy demand and the fact that a major source of the required energy is generated from fossil fuels, the combustion process has turned into a topic of interest in converting fossil fuels to energy. An ideal combustion system is one that can combine high engine efficiency with low fuel consumption and low emissions. Increasing humidity is a technique used by researchers for influencing the combustion process. The present study aims to review previously conducted researches in this regard. Based on viewpoints of these researches, the reviewed studies were categorized into four groups: the case studies used, the methodology applied, the design guidelines considered, and the performance parameters studied. It can be concluded from the reviewed articles that $NO_x$ reduction is the most significant advantage of increasing humidity in the combustion process, and has led to the widespread use of this method. The other studied emissions either remained constant or their respective increases were negligible.*

Key words: *combustion process, gas turbine, steam/water injection, performance study, design study*

## Introduction

Energy and power generation from the heat released during the combustion of different fuels is a topic frequently discussed and studied by researchers nowadays. In general, an ideal combustion process provides the highest efficiency and performance while releasing the least amount of hazardous materials into the environment (emissions). Depending on the type of the combustion system, these parameters can have different values. In a particular study on the combustion process, a researcher might examine an industrial gas turbine in the power generation cycle of a power plant. In another study, the turbojet engine of an airplane might be studied and in another study, a group of researchers might work on the combustion process of a Diesel engine. Today, experts pay specific attention the quality as well as the quantity of the combustion process parameters such as emissions. Governments, besides environmental researchers, are especially concerned about $NO_x$ emissions. The results obtained in many different studies have shown that adding water or steam would considerably improve the conditions of the combustion process [1, 2].

* Corresponding author, e-mail: fommi@modares.ac.ir

Accordingly, the present study aims to conduct a review study on this subject to guide future researchers in the field. Upon categorizing the relevant studies based on their viewpoints, the following sections and subsections presented in this article:

*Approach I*: Categorizing based on the apparatuses and place of the conducted study, whether laboratory or industrial facilities were used in the study. Also in this approach, it will be determined what kind of engine system has been studied on the combustion process. A gas turbine that used for power-generation, an aircraft engine or a Diesel engine.

*Approach II*: Classifying the studies by the methodology used (experimental or empirical, numerical, analytical, or a combination thereof).

*Approach III*: Reviewing the design studies and parametric studies in terms of the type and phase of the injected or added humidifier (water or vapor), addition of different diluents to the combustion process, comparing addition of humidifier to the fuel side or oxidizer (air) side, the point at where the humidifier is injected or added (combustion chamber, compressor, or gas turbine), type of flame or combustion (premixed, partially premixed, or non-premixed), and the type of fuel used in the combustion process.

*Approach IV*: Providing the significant design goals (performance parameters), even under undesirable conditions should be monitored [3]. Parameters such as maximum efficiency, lowest pressure loss, minimum emission, suitable outlet temperature distribution, combustion and flame stability, and reliability.

### *Search method*

This section discusses the methods used for extracting the content for the present article. First, the data bases search engine was used to look up the following key words or phrases (both individually and in context): $NO_x$; emission, steam or water injection, steam or water addition, combustion design, combustion performance, flame stability, and experimental, numerical and/or analytical analysis. The articles were mostly extracted from the following websites: springer.com, scientific.net, tandfonline.com, elsevier.com, imeche.org, nasa.gov, sciencedirect.com, and asme.org. The search period extended from March 15 to April 15, 2019, during which more than 190 references were extracted. Upon comparing the searched article titles with the subject matter, the irrelevant articles were duly disregarded. Subsequently, the abstracts of the remaining articles were examined and those with acceptable structure and content were selected based on the authors' point of view. Next, the conclusion and introduction sections of these articles were studied to further filter the less relevant articles. Finally, 130 articles were selected in this way for the preliminary study phase.

The next step involved studying each selected reference, taking the necessary notes, and summarizing them according to a specific format. Upon further examination, a number of selected articles were designated as suitable for use in the present article.

## Findings

This section explains what topics a researcher should consider in studying this field. The first step in this section was to identify the existing case studies. In other words, the case studies were examined based on researchers options in terms of access to equipped laboratories, industrial facilities or only the experimental results are available. Only upon completing such examination can a researcher decide the type of study (*i. e.* experimental, numerical, or analytical) that he or she plans to conduct. Next, the target points had to be set. Two types of studies are generally conducted in the field of gas turbine and combustion: design studies and performance studies. The efforts made in the design studies must aim at improving the performance or efficiency of the studied system. Accordingly, the selected articles were categorized into four groups based on their presented perspectives which are shown in fig. 1. References were prioritized based on the opinions and experiences of the authors of this study (according to subjects such as being state-of-the-art and referring to more details). Then, the essential articles were analyzed in more detail in each section.

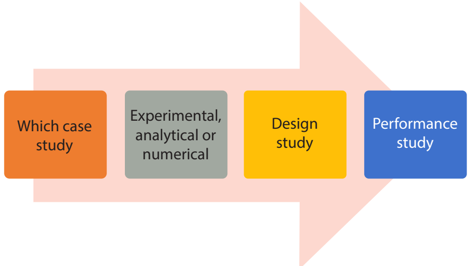


**Figure 1. Four approaches of this work**

### *Approaches: Case studies types*

Engineering studies are generally conducted on specific research subjects called *case studies*. Their results are discussed and evaluated based on the information obtained from one or more relevant case studies which may be experimental, numerical, or analytical. When searching for references, the researcher must take into account the characteristics of each case study. Accordingly, the case studies were categorized into different groups based on main keywords.

#### *Industrial or lab test stand case studies*

Case studies in the field of gas turbine and combustion are conducted on either (or sometimes both) industrial or laboratory equipment.

##### Industrial

In an industrial research study, Xue *et al.* [4] investigated the effects of adding steam to the gas turbine cycle in the conceptual design phase and examined the resulting performance of the studied turbine. To validate their model, they used annular combustors of two actual turbofan engine models, one of which was similar to the CFM56 [5] and the other was the NASA energy efficient engine E3 [6, 7]. The input parameters associated with the gas turbine engine performance required for combustor design were extracted from a home computer code developed by them that called turbomatch [8, 9], tab. 1. Adding steam via a computer code, they first formulated and subsequently modeled a preliminary detailed design procedure for single annular combustors, thus integrating gas turbine performance into the field of combustor design. The results obtained from their proposed model were in good agreement with the actual results, as shown in tab. 2.

Upon comparing their model with the actual combustors, they fixed the operating conditions to examine the effect of adding steam on the design parameters, and went on redesign the combustor. According to the results in fig. 2, the length and height of the different combustor components had to be increased.

##### Lab test stand case studies

In their series of laboratory studies, Novelo *et al.* [10] studied the effects of water injection on reducing NOx and increasing engine efficiency in compressors. The laboratory measurements in this study were taken using the equipment developed by the authors. Their work was comprised two parts. In the first part, they measured and analyzed the characteristics of the droplets that were to be injected into the compressor at different injection pressures and water temperatures. They then examined the effects of injecting these particles into the compressor and the combustion chamber. The first part of this experiment (*i. e.* measuring size of the droplets) was conducted by using a laser via the method described in references [11-13],

**Table 1. Operating values of combustor inlet at design condition [4]**

| Parameters | CFM56 model | E3 model |
|---|---|---|
| Inlet total pressure [atm] | 28.5 | 30.0 |
| Inlet total temperature [K] | 800.5 | 815.0 |
| Fuel flow rate [kgs$^{-1}$] | 1.3 | 1.35 |
| Air-flow rate [kgs-1] | 43.92 | 55.2 |

as shown in fig. 3. This method was consistent with the standard ASME method used for measuring droplet dimensions [14]. At this stage, an impact-pin nozzle was used.

In the second part of their experiment, they made use of the laser measurement equipment used in the first part and also an injector plate alongside a Rolls Royce Artouste gas turbine engine. Water-to-air ratios of 0.5%, 1%, and 2% were applied. The droplet dimensions at the compressor inlet were obtained via formulas validated from the measured droplet dimensions. Simultaneously, at the other end of this set-up towards the outlet, the emissions were instantaneously measured and logged. According to the results obtained from the first part of the experiment, the droplet dimensions decreased with increased injector pressure. In

**Table 2. Results of combustor preliminary design [4]**

| Overall dimensions | CFM56 model | | | E3 model | | |
|---|---|---|---|---|---|---|
| | Model | Data [5] | % Deviation | Model | Data [7] | % Deviation |
| Diffuser length [m] | 0.123 | 0.119 | 2.56 | 0.085 | 0.099 | –13.40 |
| Primary zone length [m] | 0.051 | 0.053 | –3.98 | 0.035 | 0.034 | 1.48 |
| Secondary zone length [m] | 0.059 | 0.060 | –0.85 | 0.041 | 0.040 | 2.56 |
| Dilution zone length [m] | 0.066 | 0.065 | 1.57 | 0.054 | 0.053 | 0.48 |
| Linear height [m] | 0.084 | 0.086 | –2.06 | 0.074 | 0.076 | –2.67 |
| Casing height [m] | 0.106 | 0.012 | –11.08 | 0.097 | 0.119 | –18.58 |
| Jet holes | | | | | | |
| Fuel nozzle number [–] | 20 | 20 | 0 | 19 | 20 | –5.00 |
| Secondary zone jet hole number [–] | 79 | 80 | –1.25 | 81 | 80 | 1.25 |
| Dilution zone jet hole number [–] | 120 | 120 | 0 | 120 | 120 | 0 |

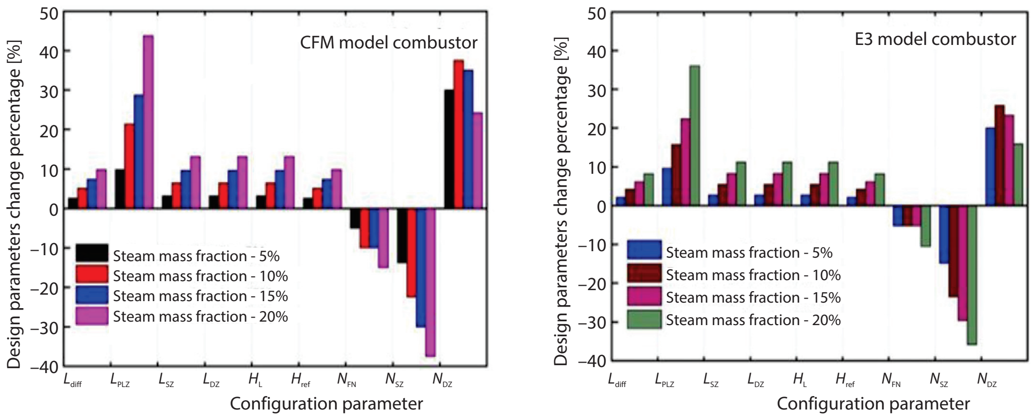


**Figure 2. Change in combustor design parameters showed in percent [4] (abbreviations are listed in tab. 2)**

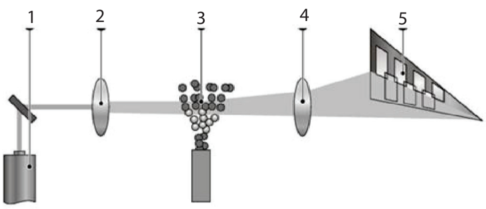


**Figure 3. Mechanism of laser scattering [10, 15];** *1 – laser, 2 – laser lens, 3 – water droplets, 4 – receiver lens, 5 – detectors on receiver*

addition, the droplets grew larger as their axial distance from the nozzle increased, fig. 4. The measurements showed a 2.2% increase in the fuel-to-air ratio, which corresponded to a 40% increase in CO emissions. However, it was the 25% reduction in $NO_x$ emissions that demonstrated the true worth of the applied method, see fig. 5.

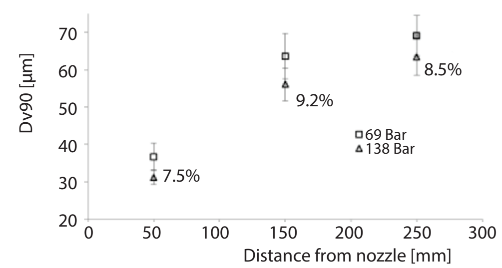


**Figure 4. Diameter of droplet-distance from nozzle [10] (69 bar, 138 bar)**

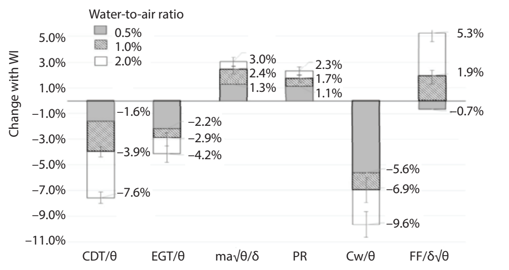


**Figure 5. Effects of water injection on engine parameters change [10]**

In another study, Mazas *et al.* [16] numerically and experimentally investigated the effects of the addition of water vapor on laminar burning velocity in oxygen-methane flames enriched with oxygen-steam-nitrogen at atmospheric pressure and a constant inlet temperature of 373 K. The experimental measurements were conducted on an oxycombustion-dedicated setup comprised of gas feedlines, a humidifier for generating water vapor, and an axisymmetric burner with steady conical laminar premixed $CH_4$-$O_2$-$N_2$-$H_2O_{(vapor)}$ flames. They determined the flame speed using a conical flame method with a Schlieren device. They applied the mixture equivalence ratio, molar oxygen enrichment, and water vapor molar fraction variations of 0.6-1.5, 0.21-0.5, and 0-0.45, respectively [17].

In their experimental-numerical study, Nicola Donohoe *et al.* [18] studied the effect of dilution through water vapor addition at high pressures on combustion chemistry when hydrogen, syngas, and natural gas were used as fuel. They conducted their experimental measurements on two separate systems. The first system was a rapid compression machine, which was part of the equipment at the National University of Ireland Galway [19, 20]. The second system was a shock-tube device (Texas A and M University); the detailed description of which is presented by Aul *et al.* [21].

### *Engine types*

Categorization can also be based on the type of engine used in the turbine. Depending on the studied turbine application, the engine might be used to generate electricity for a power plant or to provide thrust in a turbojet system. Classification can also be based on the water spray method used in Diesel engines. Whereas experimental studies are dependent on direct measurements and observations made on the studied engine, the numerical and analytical studies merely use the available engine data.

### Gas turbine (power plant) case studies

In their study on a power plant gas turbine, Zhang *et al.* [22] proposed an analytical model for the thermodynamic analysis of a partial oxidation steam-injected gas turbine cycle. They studied the respective effects of partial oxidation reaction temperatures, as well as other key variables, actually examining a new system that combined the partial oxidation gas turbine (POGT) and the steam injected gas turbine (STIG) systems. Due to the staged release of the

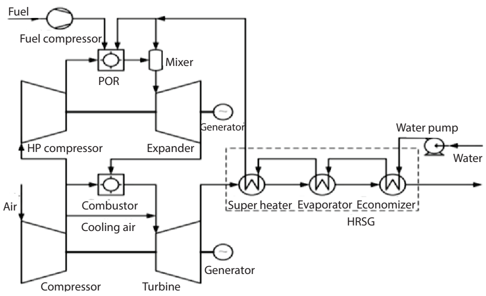


**Figure 6. Partial Oxidation STIG cycle [22]**

chemical energy of the fuel, the POGT system has great potential in improving the system efficiency. A STIG system is more efficient and less expensive, and also produces lower levels of emissions [23, 24]. They also conducted an energy analysis to compare their newly developed system with a system that operated based on the STIG cycle. Figure 6 shows a schematic of the POSTIG cycle.

They used the conservation of mass and energy equations to model their compressors, combustors, turbines, and pumps. Their superheater, evaporator, and heat exchanger models, however, were adopted from the relevant studies in the literature [25]. According to their results, the following key variables affected the efficiency and the specific work output of the POSTIG cycle:
– The bottoming gas turbine cycle temperature.
– The pressure ratio of the bottoming gas turbine cycle compressor.
– The partial oxidation temperature.

## Gas turbine (aircraft) case studies

In their numerical-experimental study, Benini *et al.* [26] studied the variations of CO and NO emissions in a turbojet combustor as a result of the direct injection of water (in the form of mist) and steam into the combustion chamber. The advantages and disadvantages of each case for a 200 Newton static thrust turbojet were evaluated. They introduced variations amounting to 200% in the steam-to-fuel and water-to-fuel ratios. To solve the thermofluid dynamic flow field within the combustor and study the emissions resulting from the combustion process, the ANSYS CFX computer package was used to generate a 3-D CFD model of the combustion process. To cool the combustion gases, in both the experimental and numerical models, a cooling (refrigerant) flow was injected directly into the combustor liner outlet. Their model included all the main paths for NO formation [27]. Their model was verified by comparing its results to the measurements conducted on the direct-flow annular-type combustor of the test turbojet engine at the Padova University laboratory. The exact specifications of the laboratory turbojet and combustion chamber are presented in references [28]. According to their report, figs. 7 and 8, NO emissions were reduced by 16% at an injected steam flow rate twice that of the injected fuel, whereas water injection reduced NO emissions by merely 8% (at constant fuel ratio). Due to its higher thermal capacity, water exhibits better cooling properties than steam. Their results showed that the CO levels were reduced due to steam injection, whereas water injection increased CO emissions. This was indicative of incomplete or partial combustion in the combustion chamber.

Lee *et al.* [29] examined the effect of dilution on the combustion performance by adding $N_2$, $CO_2$, and steam to an industrial gas turbine that used synthetic gas (comprised of CO, $H_2$, and $CH_4$ and *etc.*), in their experimental study. Upon establishing the desired $N_2$, $CO_2$, and steam dilution ratios, they logged their observations and measurements related to the following parameters: combustion instabilities, flame shapes, and $NO_x$ and CO emissions. Table 3 lists the measurement conditions applied in these tests. Also reduction in $NO_x$ emissions was reported at all the three dilution cases results.

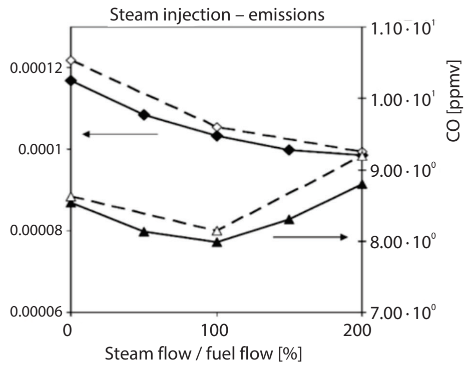


**Figure 7. Steam injection: measured (dash) *vs.* computed (solid) emissions [26]**

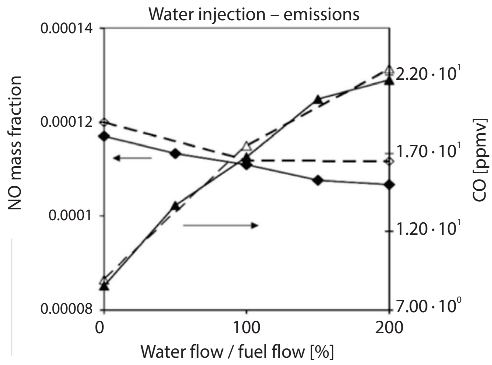


**Figure 8. Water injection: measured (dash) *vs.* computed (solid) emissions [26]**

**Table 3. Experimental conditions [29]**

| Heat input [kW] | Syngas-flow rate [$Nm^3h^{-1}$] | $H_2$ [$Nm^3h^{-1}$] | CO [$Nm^3h^{-1}$] | Overall equialence ratio | Dilution ratio [%] | | |
|---|---|---|---|---|---|---|---|
| | | | | | $N_2$ | $CO_2$ | Steam |
| 30 | 25.62 | 3.15 | 6.36 | 0.343 | 0-90 | 0-40 | 0-100 |
| 35 | 29.89 | 3.68 | 7.42 | 0.400 | 0-90 | 0-40 | 0-100 |
| 40 | 34.17 | 4.2 | 8.47 | 0.457 | 0-90 | 0-40 | 0-100 |
| 45 | 38.44 | 4.73 | 9.53 | 0.514 | 0-90 | 0-40 | 0-100 |
| 50 | 42.71 | 5.26 | 10.59 | 0.572 | 0-90 | 0-40 | 0-100 |
| 55 | 46.98 | 5.78 | 11.65 | 0.628 | 0-90 | 0-40 | 0-100 |

## Diesel engine case studies

The effect of adding humidity has also been studied in diesel engines. In their theoretical-experimental study on direct-injection diesel engines, Kokkulunk *et al.* [30] examined the effect of steam injection on the performance as well as emissions of these engines. Employing the electronic injection method for optimal injection, they subsequently reported improved engine efficiency and performance in addition reduced $NO_x$ emissions as compared with standard engines. Their experimental results showed that steam injection (at the ratio of 20%) improved the torque and effective power at 1200 rpm by at most 2.5%. In addition, the specific fuel consumption and effective efficiency increased by 6.1% at 2400 rpm. The NO and $CO_2$ emissions at 1200 rpm and 1800 rpm were reduced by 22.4% and 4.3%, respectively. However, smoke concentration at 2200 rpm increased from 44-46%.

In another experimental study, Tesfa *et al.* [31] studied the effect of water injection on the performance and emissions characteristics of an ignition-compression Diesel engine that burned biodiesel under steady-state conditions. According to their results, water injection caused $NO_x$ and CO emissions to decrease and increase by (at most) 50% and 40%, respectively. Thus, they concluded that water injection could be used to reduce $NO_x$ emissions without causing power reduction or negative effects on fuel consumption.

Other case studies have also been conducted on the effects of wet combustion in internal combustion engines (diesel engines included) during the previous period, including references [32-48].

### *Approaches: Type of investigations*

Categorizing engineering articles based on their methodology can facilitate their review. Accordingly, articles can be classified into three categories: experimental, numerical, and analytical. Also some articles combined these three methodologies. In this section, a number of articles are discussed based on the main present keywords, and their categories identified according to the aforementioned classification.

#### *Experimental articles*

The experimental-analytical study by Araki *et al.* [49] examined the operational characteristics of an advanced humid air turbine (AHAT) system. This study aimed to improve the operational conditions of the gas turbine power generation system that utilized the AHAT system. The authors also intended to study various operational characteristics of a 3 MW AHAT pilot plant. The characteristics were, effects of ambient temperature, characteristics of loading, characteristics of start-up, and variations of heat transfer characteristics of the recuperator. This pilot plant was constructed in 2006 in Hitachinaka, Japan, to conduct a feasibility study on the use of the AHAT system. Their secondary goal was to compute and compare the effects of ambient temperature and power variations in an AHAT and a combined-cycle (CC) system (based on the assumption that the two systems could be classified as mid-sized industrial gas turbine systems).

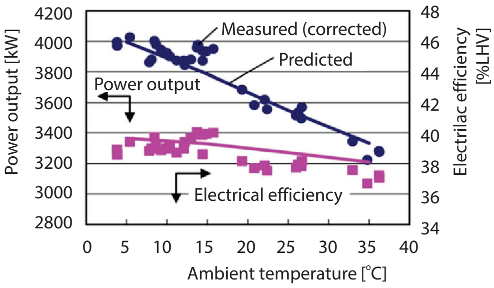


**Figure 9. Effects of ambient temperature on power output and electrical efficiency in the 3 MW pilot plant [49]**

According to their report, which is shown in fig. 9, the rated power and the electrical efficiency of the primary 3 MW plant were reduced with increasing ambient temperature. It was compatible with the computed results, and thus, validated these results.

The predicted results of the ambient temperature effects for the three plants are shown in fig. 10.

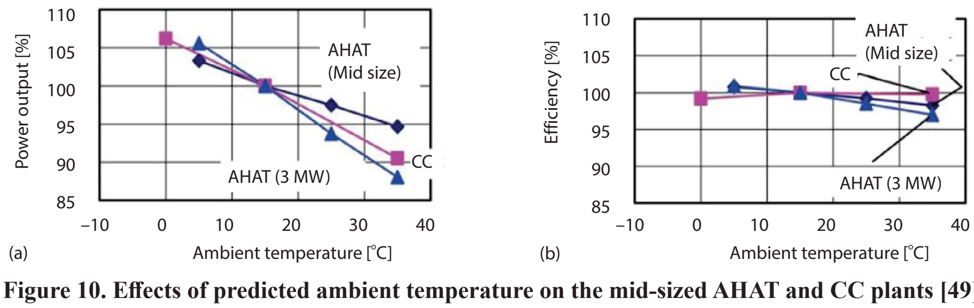


**Figure 10. Effects of predicted ambient temperature on the mid-sized AHAT and CC plants [49]**

Upon carrying out the necessary computations and measurements at partial load, they observed that, in spite of the power variations experienced by the 3 MW system, there was a good agreement between the calculated and the measured electrical efficiencies. They reported that by reducing the rotational velocity (power) to 60% of its maximum level, the reduction in electrical efficiency was reported to be 6.2% in the mid-sized AHAT system, which was less than the 8% obtained for the CC system (the maximum output power was assumed to be 100%, equal to 3990 kW). The system start-up time was reported to be a function of the recuperator thermal capacity. The measured start-up time for the cold engine of the 3MW AHAT plant was announced as 60 min.

## *Numerical articles*

In a NASA report, Daggett and Hendricks [50] numerically studied the effect of water atomization and injection via a new approach implemented in commercial aircraft aimed at reducing the $NO_x$ emissions of their engines. In older aircrafts (*e. g.*, Boing 707 and 747), water injection would be used for increasing engine thrust. However, the study used a new technique called *water misting* in which, in addition increasing thrust, other factors such as reducing fuel consumption, $NO_x$ emissions, and inlet temperature of the turbine were also considered. The author also believed that once the objectives of this numerical study had been realized, the proposed technique could reduce maintenance costs.

A conceptual design of the Boeing 777-200ER (with certain alterations applied to the size and material of the wings), equipped with a GE engine, was used in this study [51]. Two types of engines were studied. The first was an industrial 40 MW aeroderivative engine (Model GE LM6000), capable of injecting atomized water into the compressor and the second was a state-of-the-art aircraft engine NEPP with a large bypass ratio, which was used by NASA Glen and Boeing companies to examine the ultimate performance. The exact specifications of the latter, however, have not been disclosed, and the only reported fact is that it resembles Model PW4000 of the GE series. To validate the results obtained by NASA, Boeing used the information related to the GE90-85B and PW4084 engines.

It was reported in this study that using water misting before the low pressure compressor (LPC) was more useful than injecting water into the combustion chamber or adding water inside the high pressure compressor (HPC), as was done in the older method, fig. 11. This phenomenon is more pronounced on hot days. Although water injection into the high pressure compressor produces the same reduction of $NO_x$, it also reduces fuel efficiency by almost 1.7%. Direct injection into the combustion chamber would lead to greater $NO_x$ reduction (roughly 70%) as compared to other methods while reducing the fuel efficiency by about 2%. The optimal temperature was achieved at the turbine due to water injection into the LPC.

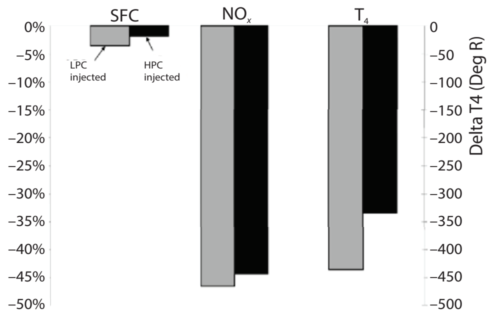


**Figure 11. Comparison between LPC and HPC injection by SFC, $NO_x$ and $T_4$ changes [50]**

The $T_4$ stands for temperature at the inlet to the high pressure turbine, turbine inlet temperature (TIT).

As reflected in their NASA report, Balepin *et al.* [52] conducted a numerical study on $NO_x$ reduction due to water injection in a commercial jet engine during the takeoff and climbout flight phases. In addition $NO_x$ reduction during these two flight phases, they also reported a perceptible decrease in the turbine inlet temperature (which would result in prolonged engine life as well as increased safety). Water injection was studied in five different locations of the turbofan engines, the LPC, HPC, and combustor. Figure 12 shows water fraction of the core air-flow [%] against the $NO_x$ drop [%] for observed cases. Most economical case ($NO_x$ reduction with regard to the required amount of water) is injection in the LPC with reduced cooling air bleed. Regardless of the amount of water needed, injection in the combustor (Case 5) resulted in the highest $NO_x$ reduction.

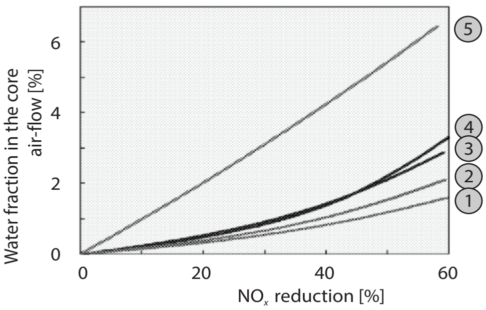


**Figure 12. The NO$_x$ reduction against water fraction for water injection [50]**

The aforementioned results are plotted for water injection at the inlet of:
- the LPC, reduced cooling air bleed,
- the HPC, reduced cooling air bleed,
- the LPC, normal cooling air bleed,
- the HPC, normal cooling air bleed, and
- combustor.

Their calculations also showed that the water required for NO$_x$ reduction was only 0.42% of the total fuel mass consumed. They also reported that the saved fuel mass amounted to approximately 0.1 of the total mass of the water used.

In their experimental-numerical study, Paepe *et al.* [53] examined the effect of dilution via steam injection on $CH_4$ combustion in a humidified micro gas turbine. In general, using steam injection in a gas turbine would positively affect its performance. However, due to the greater sensitivity exhibited by a micro gas turbine, humidification, if applied without conducting the necessary preliminary studies, might lead to incomplete and unstable combustion. Thus, reducing the overall efficiency, and at times, even causing the engine to stall. Another unfavorable occurrence that might occur is an increase in CO. They conducted the experimental observations at atmospheric pressure on a premixed variable-swirl combustion chamber. They also studied the simulations carried out on the subject by other researchers using the information provided in these studies to extract their results. Adiabatic flame temperature (equilibrium calculations) as well as CO emissions level (equilibrium and chemical kinetics) were simulated. The GASEQ [54] was used for the equilibrium calculations, while OpenSMOKE [55] and GRI-Mech 3.0 [56] were used for the chemical kinetics calculations (using a perfectly-stirred reactor or PSR). For their study, they used a modified version of the combustion chamber introduced by Sayad *et al.* [57] who had conducted an experimental study on the conditions that influenced the lean blowout (LBO) limit. They argued that there was a linear relation between the steam fraction and the LBO equivalence ratio, *i. e.*, increasing steam fraction would increase the equivalence ratio that led to LBO. The results showed that steam injection would produce negligible CO emissions in the presence of a perfect stable combustion. As the equivalence ratio decreased due to the reduction in fuel rate, the CO levels began to rise as a result of reduced combustion temperature (due to incomplete combustion and in combination with a low residence time the LBO limit approaches to complete blowout).

In Lim's [58] experimental-numerical study conducted at Purdue University, the effects of adding steam and preheating air on the flame structure and formation of NO$_x$ during combustion with laminar counterflow flames were studied. The sampling technique was implemented to conduct the experimental studies, carry out the NO$_x$ measurements, and measure the other combustion species. The numerical calculations were conducted via a code developed based on the GRI-Mech 2.11 software. An experimental combustion chamber test stand was used for the studies.

### *Analytical articles*

Mathioudakis [59] used explicit analytical relations to study the effects of water or steam injection on gas turbine performance. Drawing on the information obtained regarding the performance parameters, they used this model to examine the fuel variation, the output power, and the efficiency of the studied turbine in the absence of water or steam injection. According to the results, it was possible to predict the behavior as well as the performance of the system by using the proposed model and a minimum amount of design data rather than making use of more detailed models. The proposed analytical relations were verified by comparing their outcome to the results obtained from more accurate computer models that had been previously validated. The design data of many commercial gas turbines were used to demonstrate the engine parameter deviations. Thus, a comprehensive guidebook was provided to evaluate the expected parameter deviations when water or steam was injected between the compressor outlet and gas turbine inlet. The obtained relations were used to predict the differences between the gas turbine behavior or performance in the presence and absence of water or steam injection. Even the changes in fuel characteristics were duly predicted.

An important result obtained from the collected information was that water and steam injection would both increase the turbine output power, fig. 13. However, steam injection would increase the turbine efficiency, whereas water injection would decrease it, as shown in fig. 14.

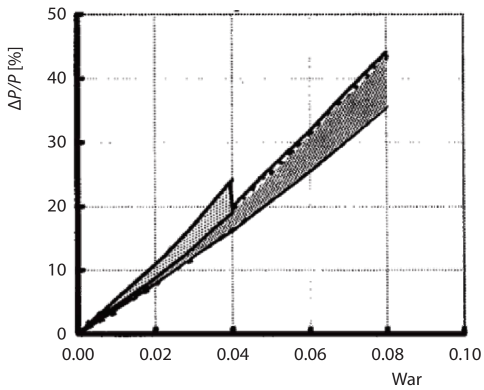


**Figure 13. Power deviation variation against war (single shaft, constant geometry) [59]**

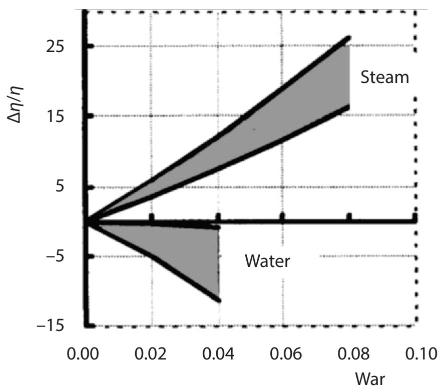


**Figure 14. Efficiency deviation variation against war (single shaft, constant geometry) [59]**

In recent figures war stands for water flow rate to air-flow rate ratio. Their model could also be used to accurately examine the variations of operational conditions in the compressor (*e. g.*, pressure ratio and mass-flow rate) due to steam or water injection.

The combined use of steam-injection gas turbines with other plants has been investigated in many studies. Examples include the numerical-analytical study by Esfahani *et al.* [60]. They conducted a feasibility study on the performance of a steam-injected gas turbine operated alongside a multi-effect thermal vapor compression (METVC) desalination system.

Bouam *et al.* [61] injected steam into the combustion chamber of a gas turbine in the Sahara Dessert, Algeria, in order to improve its performance, ultimately proposing a numerical model by conducting a thermodynamic analysis. The reason for this study was the reduced thermal efficiency experienced by the turbine due to the harsh operating conditions imposed on it by the regional climate. They proposed that suitable quantities of steam be injected at the upstream of the combustion chamber.

Conducting a thermodynamic analysis, Kim [62] investigated the effects of water and steam injection on the thermodynamic performance of gas turbines. In their parametric analysis, they studied the performance of three power-generating gas turbine systems: the regenerative after-fogging gas turbine system, the steam injection gas turbine system, and the regenerative steam-injection system. With due attention the pressure ratio and water-to-steam ratio variations, they used an analytical model to evaluate the important system parameters including the thermal efficiency, fuel consumption, specific power, and $CO_2$ emission in the environment.

### *Approaches: Design or parameter study*

Researchers pay special attention the design cases related to the parameters that influence the quality as well as the quantity of combustion parameters. In this section, the studied articles conducted on these design parameters are classified based on their major keywords.

#### *Type of injected or added humidifier*

The phase of the added water (steam or liquid water) was observed to be the focal point of some of the reviewed case studies. Other studies examined the effect of the diluents used (*e. g.*, exhaust gas re-circulation).

Touchton [63] conducted one of the first comprehensive studies in this respect. In their experimental study, they examined the effect of combustion chamber design as well as operational parameters on $NO_x$ emissions control via water or steam injection. The study aimed to examine the combustion system of gas turbine models GE MS7001E and MS9001E generally operated in CC power plants. The results related to the standard combustion systems, the modifications applied to their spraying method and location, and the combustion chamber design modifications were also included in the study. Both the studied gas turbine models were uniaxial and rotated at constant speed. The second model (with 14 combustion chambers) was developed from the first model (with 10 combustion chambers). The results obtained from the injection of water were then compared to those from steam injection in the same combustor. The influence of the fuel type on the effectiveness of water and steam injection in the same combustor was also studied. The author then compared their findings with those presented in the previous studies. According to their report, steam or water injection would reduce the peak flame temperature, thus preventing NO formation. He believed water injection was highly preferable to steam injection (due to the latent heat associated with water evaporation). The study also reported that, in jet-stirred combustion chambers burning methane as fuel, no significant differences were observed between the results in the following: Case 1 – adding steam to the air-flow and Case 2 – adding steam to the fuel flow in the primary zone of the combustion chamber. In addition, the role of important parameters such as inlet temperature, overall equivalence ratio, and swirl in NO formation was found to be insignificant.

Other studies that simultaneously examined the effects of water and steam injection include Benini *et al.* [26] and Mathioudakis [59], *Gas turbine (aircraft) case studies* and *Analytical articles*, respectively. Some studies including Lee *et al.* [29] *Gas turbine (aircraft) case studies* and Kruger *et al.* [64] *Performance study: Emission* also investigated the effect of inert or neutral diluents.

#### *Location of humidity addition and injection in study apparatuses*

Humidity injection location is another matter that is of interest to the researchers in the field. Most recent studies have examined the direct injection into the combustion chamber. However, injection into the compressor or even the turbine has also been investigated. Injection into the turbine is generally aimed at reducing blade temperature.

Farokhipour *et al.* [65] recently studied water spray injection into the gas turbine combustion chamber to decrease the $NO_x$ emissions. They used an Euler-Lagrangian model in their numerical study. They also studied the effects of such an injection on the performance parameters of the turbine. They found in the course of their study that few accurate numerical studies had been conducted on spraying water into combustion chambers. They studied the parameters of the water spray injection design such as mass-flow rate, injection location, and injection direction, and examined their respective effects on performance as well as on $NO_x$ reduction. They also paid particular attention the swirl number.

For numerical discretization of the Eulerian part of the governing equations, they applied the finite volume method, using the PISO algorithm [66], to decouple the pressure velocity term from the Navier-Stokes equations. The detailed numerical solution of the Lagrangian equations is discussed in the other studies conducted by the same team of researchers [67, 68]. Considering the previous literature, they decided to use the 4-equation transition $k$-$\omega$ SST model [69], since it was a suitable tool for simulating the intermittent swirl-stabilized flames and was considered to be the best available RANS model [70]. They also used a special 30-species, 184-reaction CNG-air mechanism in the flamelet calculations to model the combustion chemistry [71]. To predict the amount of $NO_x$ emissions, they added eight reactions in this mechanism. Three of these reactions were related to the Zeldovich mechanism where thermal $NO_x$ was produced [72], two of the reactions were due to the $N_2O$-intermediate mechanism [73], and the remaining three reactions were associated with the $NO_x$ reburning mechanism [74]. To further investigate the subject, they introduced a number of performance/design parameters and relations: a swirl number formula, two different relations for combustion efficiency, highest temperature of the combustor outlet gas, $T_{\mathrm{max,out}}$, pattern factor relations, and temperature uniformity index, $\gamma_t$, and temperature standard deviation (parameters related to the temperature profile of the outlet flow), a relation (merit function) to calculate $NO_x$ values and evaluate the total $NO_x$ and CO emissions, water evaporator efficiency, and entropy generation rate [75].

Other studies on the simultaneous injection into the combustor and compressor include articles by Dagget [50] and Balepin [52], both of which are *Nimerical articles*. Also, Elwekeel and Abdala [76] researched the injection in the combustion chamber and turbine, which will be referred to in *Approaches: Performance stady*.

### *Type of flame: Premixed, non-premixed, and partially premixed*

Another categorization observed and based on the main subject of the studied articles was combustion type or flame type (the latter is a more specialized expression). A flame can be premixed, non-premixed (diffusion flame), or partially premixed.

### Premixed flame

In their experimental study, which led to the extraction of a numerical model, Stathopoulos *et al.* [77] studied the emissions of a wet premixed flame at high pressure. The fuel was comprised of natural gas and a mixture of hydrogen-enriched natural gas. Their purpose was to examine the advantages of adding steam to a premixed flame as well as the effects of pressure variations and hydrogen content of the fuel on the flame shape and the emissions. The goal of this study was to continue and develop the results of previous research by Kuhn *et al.* [78] on combustion system performance at high pressure. To conduct their measurements, they used a swirl-stabilized combustor which was comprised of a radial swirl generator and a mixing tube located before a cylindrical combustion chamber, as shown in fig. 15.

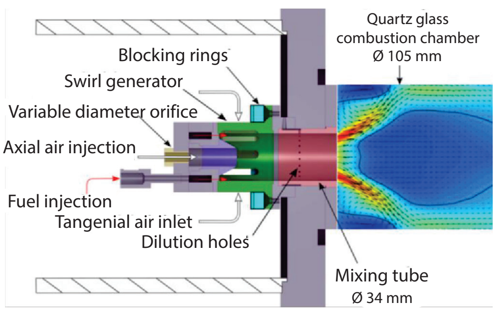


**Figure 15. Main section of used test apparatus [77]**

Air would enter through an orifice (on the main axis of the combustor) and pass through the radial swirl generator before entering the mixing tube. Using this system could alleviate existing concerns regarding flame flashback. The overall amount of air passing through the system was kept constant during the experiment, and the value of this parameter was obtained from the velocity field measurements conducted in previous studies [79].

The tests in this study were conducted using a high pressure test rig in a high pressure combustor in Stuttgart, Germany. A detailed description of this test stand (HBK-S) can be found in references [80].

Measurements were taken for two different fuel types at different pressures (maximum 9 bar) and four different steam dilution ratios (maximum 25% of steam-to-air mass-flow rate ratio). Natural gas (enriched by hydrogen up to 10% by mass) was selected as the basic fuel. Using a reactor network model generated via the CANTERA computer package [81], they obtained the required emissions results based on their adjusted conditions. They subsequently compared these results with their experimental results. To simulate the desired process, they combined a single perfectly stirred reactor (PSR) to model the flame with a plug flow reactor (PFR) to model the post-flame zone (PFZ) since, in CANTERA, a PFR must be modelled by joining several PSR [82, 83].

In general, there was an acceptable agreement between the simulation results obtained for the two mixtures and the experimental results. They attributed the slight discrepancies between the numerical and experimental results to the heat transfer model and the existing uncertainty associated with the measurements and the chemical reaction mechanisms. According to their results, increasing pressure and hydrogen enrichment during the measurements led to increased flame burning velocities, thus introducing variations in the flame shape and position. In view of the previous studies, they expected $NO_x$ emissions to increase with increasing combustion pressure (due to the strengthened thermal pathway). They also knew, based on the same studies, that steam injection into the combustion chamber would reduce $NO_x$ at high pressures without having a negative effect on CO emissions. Through their measurements and observations, they learned that the combustion of hydrogen-enriched fuel at a high pressure required intensive steam addition in a gas turbine to reduce $NO_x$ emissions down to the threshold recommended by environmental standards. They added steam in sufficient amounts within the standard limits by taking into account the performance conditions of the studied gas turbine [84].

The next study by Goke *et al.* [85] examined the effects of pressure variations and dilution (via steam) on the $NO_x$ and CO emissions in a premixed flame which used natural gas as fuel. In this experimental-numerical study, a natural gas injector with satisfactory operation at high steam rates was designed, thus guaranteeing a stable flame. Their injector involved a radial swirl generator followed by a mixing tube with a diffuser which led into the combustion chamber via an area expansion. They reported that steam would significantly reduce $NO_x$ concentration, and that such reduction was intensified with increasing pressure. The flame stability was observed favorable and recorded as an almost perfect combustion at a 25% steam injection. At all pressure levels, a 20% steam injection led to $NO_x$ reductions below 10 ppm. The CO emissions were also very low at the same time.

## Non-premixed flame

Taking advantage of CFD numerical simulation, Lancua *et al.* [86] studied the effects of using fuel gas and adding steam on $NO_x$ reduction in industrial burners with non-premixed flames. The simulationol ANSYS FLUENT (ANSYS tutorial, 2015) was used to conduct a CFD analysis on a 300 kW swirl-stabilized combustion chamber. The required input data for the simulation (*e. g.*, temperature, velocity, and boundary conditions) were obtained from the experimental data provided by Sayre *et al.* [87]. They used the $k$-$\varepsilon$ turbulence and P-1 radiation models to simulate the flow. They also selected the non-premixed model in FLUENT due to the separate fuel and air inlets. Two fuel groups were tested to examine the effect of fuel composition: a typical methane composition, Union Gas [88], and a biomethane composition, Rasi [89]. According to the simulation results increasing the amount of added steam decreased the temperature of the system. The presence of the steam slightly decreased the peak temperature of the flame (about 40 K), but its effect on the reaction mechanism was so considerable that the $NO_x$ emissions at the maximum amount of steam were reduced by half as compared with dry conditions. Upon adding steam with this ratio, the reduction of $NO_x$ emissions was halved and independent of fuel composition and burner geometry. According to their calculations, the addition of steam to the fuel or air for subsequent injection into the combustion chamber was an inexpensive method for reducing $NO_x$ emissions. However, adding steam to fuel (rather than to air) was reported to be more effective. To determine the $NO_x$ quantity from the information obtained after the CFD simulation, they used the RGibbs reactor via the ASPEN Plus computer package. They also studied the swirl effect. The NOx reduction percentage is shown in fig. 16.

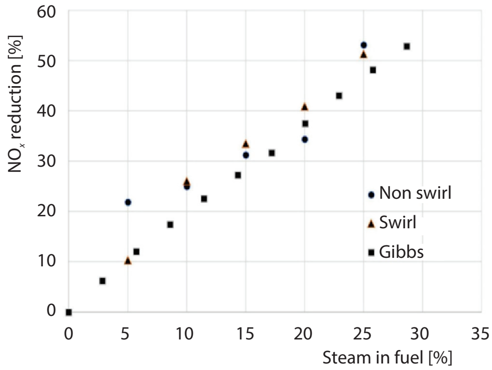


**Figure 16. Percent of $NO_x$ drop under steam injection in fuel condition [86]**

A later experimental-numerical study by Wang and Chiou [90] involved certain modifications in the structure of a conventional gas turbine owned by the Tai Power Company. This turbine had a heat recovery steam generator and used the non-premixed combustion method. Upon selecting the simple working cycle of this turbine as the main unit, the STIG and IAC units were added to the system in the same order. In addition, the advantages of using these units separately, as well as the effect of using them simultaneously, were enumerated. It was recommended that the steam injection and inlet air cooling technologies be used in the studied system to increase its power generation capacity and its efficiency. Under local summer conditions, they reported a 70% increase (from 52.14-88.2 MW) in the power output in the presence of both the STIG and IAC systems. In addition, the efficiency increased from 29.3-37.24%, and the thermal rate was improved by 20.4%.

In another numerical study, Hwang and Choi [91] studied the effect of dilution with $H_2O$ on the counterflow diffusion flame structure. They also examined NO emissions when $CH_4$-$O_2$-$N_2$ was used as the fuel.

## Partially premixed flame

In their experimental study, Chen *et al.* [92] examined the effect of adding humid air to a partially premixed combustion process that used two types of liquid diesel fuel. They also studied the impact of this addition on the generated $NO_x$ emissions. During their research in previous studies, they examined the effects of adding pre-combustor humidity in the presence of natural gas as fuel [93-96]. They concluded that since liquid fuel generally produced more $NO_x$ than lean premixed natural gas, studying the $NO_x$ generation behavior in such systems would be beneficial due to the associated negative environmental effects. According to their results, at a constant flame temperature, adding 10% humidity to the compressed air before entering the combustor would reduce $NO_x$ concentration by 90% (as compared with the dry conditions). They also presented information on the CO measurements. They attributed such a significant reduction in NO emissions to the reduced number of O atoms along with the increase of OH radicals due to the humid air combustion process.

### *Fuel type study*

The fuel type is an important parameter in engine design since it directly affects the efficiency and geometric characteristics of the engine. The fuel type also influences the quality and quantity of the generated emissions.

Kayadelen and Ust [97] presented an accurate and practical analytical model to recognize the exhaust species characteristics and the thermodynamic properties of the working or operating gases in combustion chambers equipped with water or steam injection systems. The effects of injecting the diluents (water or steam) on each exhaust species were studied for different fuel types as well as for different diluents and equivalence ratios. They were then compared with the experimental results obtained via precise measurement instruments. Using the model proposed for mole fractions, they calculated the specific heat of the exhaust mixtures as well as the adiabatic flame temperature. They also presented the same calculation results for four fuels at different water-to-steam injection ratios. In their analytical model, all gases were assumed to be ideal gases, *i. e.*, their enthalpy and specific heat were dependent only on temperature variations. The following numerical tools were employed to compare their simulation results: CHEMKIN [98] that uses the Gibbs energy perspective minimization and GASEQ [54] where the element potential method is used. According to recorded data, a good agreement was observed between their simulation results and the results obtained from these computer packages, which showed the reliability of the proposed model by the authors. Their model was also applicable for other diluent and fuel types and was capable of carrying out parametrical analysis due to its high accuracy.

Goke *et al.* [99] studied the effect of steam dilution on premixed and rich-quench-lean (RQL) combustors with hydrogen and natural gas used separately as fuel. According to their report, a stable flame was observed in the premixed combustor at an inlet temperature of about 650 K (when natural gas was used) until a steam ratio of 30% was reached. In the RQL combustor, however, flame stability was maintained only until a 20% steam ratio was reached. Their results indicated that if hydrogen were used as fuel, further steam additions would be possible. In addition, the flame flashback risk was observed to be reduced in the presence of steam for fuel compositions that contained hydrogen. As such, pure hydrogen could be burned in the premixed combustor even at the minimum steam-to-air ratio (10%) until the stoichiometric conditions were established.

### *Effect of humidity addition and/or injection air (oxidizer) side or fuel side*

An oxidizer and fuel are necessary for the combustion process to occur. In the studies conducted on gas turbines, air is generally used as the oxidizer. Depending on the flame type, the importance of the humidity injection or addition side is determined. Generally, steam is injected into the combustion chamber in a premixed flame. Therefore, the air and fuel are humidified simultaneously. However, in a non-premixed flame, the humidity might be injected to the air side first before being added to the fuel side.

Upon proposing an analytical model and conducting the required numerical calculations, Zhao *et al.* [100] used the detailed chemical kinetics in GRI-Mech to study the effect of adding steam to a counterflow diffusion flame on the $NO_x$ emissions generated by the OH radical in the presence of methane-air fuel composition. They found that if the steam were added to the air side, adding steam would have a greater effect on the flame characteristics. This was attributed to the probability of steam entering the reaction zone [101]. To generate their numerical-analytical model, they first applied the conservation of mass and energy as well as the state equations. In addition determining the thermodynamic properties of each species, the CHEMKIN database was used [102]. A simplified transport model was used to calculate the transport properties [103]. They introduced relations for effective thermal conductivity, effective mass diffusivity of species, and effective viscosity of mixtures. As for the required numerical calculations, a code previously written for counterflow diffusion flames was run [104]. Their results showed that at a fixed initial temperature for the fuel and oxidizer, increasing the amount of steam would reduce the flame temperature as well as the OH concentration. However, at a constant steam rate, the flame temperature and OH concentration increased by increasing the initial temperature. According to their report, at a specified maximum flame temperature, increasing the steam would increase the OH concentration, as shown in fig. 17. The reason was attributed to the increased steam concentration in the combustion zone, which would trigger a steam decomposition reaction, thus preventing the OH radicals from being consumed.

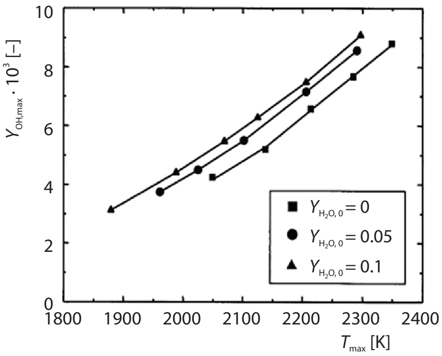


**Figure 17. Maximum flame temperature against maximum mass fraction of OH ($Y_{OH,max}$) [100]**

Another result indicated that the increased OH concentration due to steam addition negatively affected the $NO_x$ reduction process. However, as the CH concentration was also reduced during this process, the rate of HCN and N generation dramatically slowed down, and the overall NO emissions were also reduced because of the greater effectivity of the reduced N radical concentration.

### *Approaches: Performance study*

Another categorization that can be applied to the articles in the field of gas turbine and combustion can be based on a performance study of the relevant systems. Subjects such as emissions rate, power output, efficiency, fuel consumption, flame characteristics, and flame stability can be included in this classification. These are the most common subjects currently pursued by the researchers in the field. In this section, a number of performance studies are reviewed which address the mentioned topics.

In their performance study, Elwekeel and Abdala [76] studied the effect of the mist cooling technique on exergy and energy analysis in a steam-injected gas turbine cycle. In their considered system, the steam generated by the exhaust gas re-circulation was injected into the combustion chamber and simultaneously used for cooling the turbine blades through a closed loop. They used different values for mist fraction, steam coolant temperature, mist temperature, pressure ratio, turbine inlet temperature, and blade temperature, $T_b$, and observed their respective effects on the following: fuel conversion ratio, energy ratio, plant efficiency, net work, and exergy efficiency. According to their reported results, at higher saturated steam coolant temperatures, a higher net work and plant efficiency were obtained. In addition, they concluded that increasing mist mass fraction would reduce the turbine blade temperature, reduce aerodynamic losses, and increase blade life. At the same time, slight reductions were observed in the net work and plant efficiency. For low saturated steam coolant temperature with a mist fraction between 2-26%, the efficiency of the system varied between 47.6% and 47.2%.

Delattin *et al.* [105] examined the effects of steam injection on the efficiency and performance of a micro-turbine in their analytical-numerical study. By performing a process analysis on a dry micro-turbine, they simulated its dry process via ASPEN software. According to their results, if the CHP mode were deactivated, the steam-to-air ratio could be increased to 3.3 through a simple steam heat exchanger. The excess heat would be fully directed into the exchanger to increase the electrical efficiency by 5%, thus reducing the total annual working hours by 1500 hours as compared with the dry condition.

In another study that included experimental measurements along with numerical calculations, Boushaki *et al.* [106] examined the effects of hydrogen and steam addition on the laminar burning velocity in premixed methane-air flames. Their results showed a linear increase in the laminar burning velocity upon increasing the hydrogen fraction. By increasing the hydrogen-to-methane volumetric ratio by 25%, the laminar burning velocity increased by about 25% from 37-46 cm/s. It was reported that adding steam to the system and increasing the air humidity from 0-100% could reduce the burning velocity by 50%. According to the results, increasing the hydrogen increased the adiabatic flame temperature, whereas increasing the steam fraction reduced this temperature. In addition, it was observed that increasing pressure under isentropic conditions would raise the gas temperature, which would in turn increase flame velocity. In such a case, the linear relationship between the increase in hydrogen fraction and laminar burning velocity at higher pressures would be lost, leading to a further increase in this velocity.

In a following performance study by Alaefour and Reddy, the effect of steam injection into the combustion chamber of a gas turbine on the performance of a CC power plant operating on natural gas (containing methane as its major component) was examined based on the first law of thermodynamics, as well as energy analysis [107]. According to their results, steam injection affected the work output and efficiency of the gas turbine, the steam turbine, and the main power generation unit of the combined cycle. The results showed that the work output of the gas turbine increased and reached its peak as maximum steam addition (5%) was applied in spite of the fact that steam addition had demonstrated a negative effect on the total work output of the steam turbine, decreasing it to a minimum at the maximum steam ratio. A similar trend was also reported for the performance efficiency of the components. According to the results, increasing steam injection would, in general, raise both the performance efficiency and the total work output of the gas turbine and the combined cycle assembly.

### *Performance study: Emissions*

Due to the particular significance of emissions, their adverse environmental impact, and their role in global warming, a number of studies that have addressed engine emissions (in addition the general keywords) are also -cited in this section.

In their analytical performance study, Nadir and Ghenaiet studied the thermodynamic performance of a steam turbine injection generator with due regard to blade cooling and $NO_x$ emissions. Steam was sprayed into the combustion chamber in this study [108]. Due to the higher heat transfer occurring in the gas-steam mixture (as compared with a pure gas), blade cooling might be unsuccessful, and the blade material might be damaged as a result [109]. In their joint study, they proposed two solutions for the problem to prevent its undesirable consequences by maintaining blade temperature around 800 °C, the desirable range [23]. The first solution involved maintaining the discharge combustor temperature at its initial temperature and substantially increasing the coolant fraction. The second solution (which was subsequently proposed) was to maintain the coolant fraction at its initial value and induce a substantial decrease in the discharge combustor temperature. The analytical model and the two solutions were proposed for the Siemens gas turbine Model V94.3A. Their model was originally designed without steam injection equipment, and this study aimed to provide steam injection possibilities for this turbine. Based on their results and analyses, they reported that both solutions had led to improvements in the performance of the system. They also reported that the first solution had produced better results with regard to specific work, efficiency, and steam quantity. According to their results, neglecting the problem of cooling the blades, steam injection significantly improved the gas turbine performance and particularly its power output. Finally they mentioned that utilizing the STIG cycle would lead to reduced $NO_x$ emissions. The $NO_x$ reductions resulting from the first and second solutions were below 10 ppm and 14 ppm, respectively.

In their experimental-numerical study, Belokon *et al.* [110] collected sufficient experimental data to study the performance of a compressor that was injected with highly humidified air. The experimental results were instrumental in generating a diffusion flame combustor model with $CH_4$ as fuel and a maximum steam-to-air ratio of 20%, which could be used for the estimation of combustion efficiency and the quantity of $NO_x$ emissions. This diffusion flame combustor was used to achieve the most efficient combustion process possible because of its higher flame temperature (close to stoichiometric temperature) as compared to premixed combustors. The operating pressure was equal to the atmospheric pressure, and the inlet temperature was 700 K.

They subsequently measured the combustion efficiency and the $NO_x$ level of the studied turbine. The well-known Theta, $\theta_2$, parameter [111] is an effective operational parameter in the design of combustors, which expresses the exponential dependence of the thermal efficiency of the combustor on the reaction temperature within the combustor. In the calculations of dry combustors (no steam added), the inlet temperature, $T_{in}/e^{300}$, is used instead of the reaction temperature. Based on previous studies, Belokon *et al.* [112] argued that in diffusion flame combustors with water injection, if the inlet temperature is substituted by stoichiometric temperature, $T_s$, a modified $\theta_s$ ($e^{Ts/300}$) can be obtained to achieve more realistic results. They reported that the combustion efficiency and the $NO_x$ levels obtained from the flamelet model and from the modified Theta formula were in very good agreement with the experimental results. They proposed two solutions if the case in which a specific amount of steam used in the calculations produced an undesirable combustor performance:

– modifying the combustor dimensions to obtain the desired performance and
– modifying the amount of injected steam.

In another experimental-numerical performance study, Hermann *et al.* [113] investigated the flame stability and formation of emissions particles in premixed combustion at different water vapor fractions in the fuel composition. They found during calculations that increasing the water would substantially reduce the $NO_x$ emissions. However, the measurements showed this reduction in $NO_x$ concentration had diminished since richer combustion was required for providing an acceptable normal efficiency as well as better combustion (*i. e.*, acceptable CO concentration).

In their performance study, Kruger *et al.* [64] conducted large eddy simulations related to the oxidization of hydrogen under ultra-wet conditions in a premixed combustor model of a gas turbine. Their study was aimed at examining the flame properties and emissions by applying detailed chemistry. In this experimental-numerical research, the use of an ultra-wet gas turbine was recommended. The major modifications introduced in this turbine included a new design for the combustion chamber so that it could accommodate a large quantity of steam without the loss of combustion stability.

Their experimental data were obtained from measurements via a test rig under atmospheric conditions. The preheated air was mixed with the overheated steam before entering the combustion chamber. Further details on this experiment are given in references [114]. Due to lack of sufficient studies on hydrogen flame dilution with large steam quantities, the information provided in Koroll and Mulpuru's [115] study was adhered to for comparison purposes. Their calculations showed that, unlike steam, inert diluents consistently reduced the burning velocity. Substituting the inert diluents with steam increased this velocity. They reported that the addition of steam to the combustion process would not only increase the efficiency but also reduce the $NO_x$ emissions due to the increased heat capacity and the reduced peak temperature of the combustion chamber. The significant reduction in $NO_x$ formation can be attributed to the shifting of the preheat zone to higher temperatures. According to the calculations, adding steam caused the heat release to spread. Thus, the flame front thickened and the flame often developed slowly to the downstream of the flow.

In Kobayashi *et al.* [116] experimental study, the effects of dilution with oversaturated water vapor on the fundamental characteristics of premixed methane-air turbulent flames under the high pressures and temperatures produced in an internal combustion engine were investigated. To this end, they applied high temperature air combustion (HiTAC) to high load combustors and clarified the effects of exhaust gas re-circulation in the IC engine. They also compared the parameters related to the flame structure such as turbulent burning velocity, mean volume, and the structure of the turbulent flame region with the corresponding parameters in the case where $CO_2$ dilution was applied. The results of previous studies were used for this comparison [117].

Syed [118] in his Ph. D. dissertation at the University of Louisiana, successfully used a new detection device to monitor and model emissions in gas turbines equipped with water injection systems. A continuous emissions monitoring system (CEMS) was installed on the exhaust to measure the $NO_x$, $O_2$, and CO concentrations. The data reconciliation and gross error detection technique were used to verify the validity of his data sampling performance. The emissions measurement data was utilized to validate the kinetic emissions model that was developed (based on GRI-Mech 3.0) for estimating the $NO_x$, CO, and $O_2$ quantities. The kinetic model was applied inside a network of equivalent reactors (ERN) that included perfectly stirred and plug flow reactors. This network accurately modeled the primary and dilution zones. He combined his model with the emissions measurement instrument that was installed in the exhaust, thus managing to predict any problems that might occur based on the variations of $NO_x$ and other emissions. For example, when variation of $NO_x$ concentration from 35-44 ppm was observed, they correctly determined that the studied system had six or seven damaged nozzle, fig. 18. None of the available maintenance manuals could detect any problem in the system.

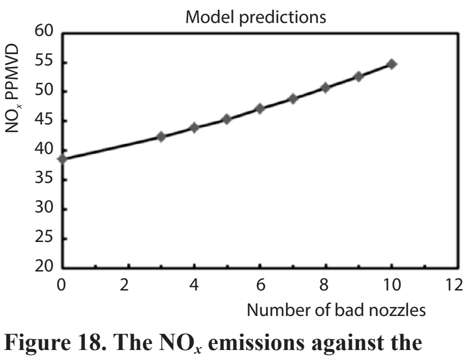


**Figure 18. The $NO_x$ emissions against the quantity of bad fuel nozzles for normal operating conditions [118]**

Cardu *et al.* [119] showed a thermodynamic analysis on water injection into the combustion chamber of a gas turbine assembly. They suggested total water injection into the combustion chamber, instead of partial water injection. As a result, the desired temperature could be established in the chamber via the direct injection of water and the inlet air quantity would be considered as the optimum for the combustion.

The thermal efficiency of the gas turbine with higher total water injection was reported to be greater than that obtained in other cases. Higher thermal efficiency means that perfect combustion can be achieved at lower combustion chamber temperatures. Thus, there would be less concern with regard to the thermal resistance of materials used in gas turbine components.

Their results showed that the $NO_x$ quantities produced in the studied gas turbine were lower than those in the conventional gas turbines, which could be due to excess air reduction in the system. In addition, the compressor dimensions would be smaller as a result of this reduction. Thus, the overall size of the system would be reduced. Based on their results, the thermal efficiency of the conventional water injected gas turbines (GTIWI) was observed to be less than that of the studied gas turbine (GTITWI), but more than that of the gas turbines without water injection:

$$\eta_{t,\mathrm{GTI}} < \eta_{t,\mathrm{GTIWI}} < \eta_{t,\mathrm{GTITWI}}$$

## Conclusions

The previous studies on combustion process humidification as well as a number of other studies on the subject were used in the present study to review the effects of adding humidity to the combustion process. Due to the inevitable conflicting requirements that exist in any method, the most favorable method would be the one in which the overall advantages outweigh the disadvantages. The articles were initially selected based on their keywords and later chosen based on the search method. A more detailed review of the selected articles was then carried out. In view of the studied statistical population, the laboratory case studies outnumbered the industrial ones. Moreover, the number of articles on power plant gas turbines was far more than those on aircraft gas turbines (which was reasonable due to the widespread use of gas turbines in power plants). State-of-the-art studies have also been carried out on aircraft gas turbines. The statistical dispersion between the experimental and numerical case studies was almost equal. The analytical studies, however, were fewer in number. In most cases, humidity was added in the combustion chamber and also it injected in gas phase (steam). In the majority of case studies, humidification was applied to the oxidizer side (air). A greater number of studies were conducted on non-premixed flames.

It was argued in almost all of the studied articles that the positive effects of humidification were far more than the negative effects. The performance and efficiency of the studied engines (with humidification) were improved by providing suitable operating conditions. Fuel consumption was also reduced or kept constant through suitable engine designs. Nevertheless, increased fuel consumption was reported in some studies. In all the studied cases, the most significant result of steam injection into the combustion process was the reduction of $NO_x$ emissions, which is why this method is being considered by researchers. The other emissions, including CO, either remained unaffected by the humidification process or experienced negligible increases.

### *Table of approaches*

Each article consists of different parts and details. In order to allow researchers to access references more quickly in the future, the main articles used in this paper are presented in tab. 4 and grouped by main keywords.

**Table 4. References categorization based on presented subjects**

| | | |
|---|---|---|
| Approach I: the case study | Industrial case | [4, 29, 49, 50, 52, 59, 61, 63, 90, 105, 108, 119] |
| | Lab test stand case | [10, 16, 18, 26, 31, 53, 58, 64, 65, 77, 85, 86, 92, 99, 100, 106, 110, 113, 116, 118] |
| | Gas turbine (power plant) | [22, 29, 49, 50, 59-63, 65, 76, 90, 105, 107, 108, 113] |
| | Gas turbine (aircraft) | [4, 10, 26, 50, 52, 65] |
| | Diesel engine | [30-48] |
| Approach II: study type | Experimental | [10, 16, 18, 26, 29, 31, 33, 49, 53, 58, 63, 64, 77, 85, 90, 92, 99, 106, 110, 113, 116, 118] |
| | Numerical | [4, 16, 18, 26, 30, 32, 50, 52, 53, 58, 60-62, 64, 65, 77, 85, 86, 90, 91, 99, 100, 105, 106, 110, 113, 118] |
| | Analytical | [22, 49, 59-62, 76, 97, 100, 105, 107, 108, 119] |
| Approach III: design study | Type of injected or added humidifier: steam | [4, 18, 22, 30, 53, 59, 60, 63, 64, 76, 77, 85, 86, 97, 99, 108] |
| | Type of injected or added humidifier: water | [10, 26, 31, 50, 59, 63, 65, 91, 118] |
| | Location of humidity addition and injection in facility study: combustor | [16, 18, 22, 26, 32, 50, 52, 53, 58, 59, 63, 65, 76, 77, 85, 86, 92, 100, 107, 108, 110, 113, 116, 119] |
| | Location of humidity addition and injection in facility study: compressor | [10, 50, 52, 76] |
| | Type of flame: premixed | [16, 22, 53, 64, 77, 85, 99, 113, 116] |
| | Type of flame: non-premixed or diffusion | [10, 26, 31, 32, 49, 61, 65, 86, 90, 91, 100, 105, 106, 108, 110] |
| | Type of flame: partially premixed | [58, 92] |
| | Humidity addition and or injection air (oxidizer) side | [16, 22, 26, 31, 49, 50, 53, 58, 63, 64, 76, 86, 92, 99, 100, 105, 106, 108, 110, 116, 119] |
| | Humidity addition and or injection fuel side | [22, 50, 58, 63, 86, 100, 106] |
| | Fuel type study | [18, 32, 77, 86, 92, 97, 99, 106] |
| Approach IV: performance study | Performance study (Emissions study) | [4, 10, 26, 29, 31, 32, 41, 50, 52, 53, 58, 60, 62-65, 77, 85, 86, 91, 92, 97, 100, 108, 110, 116, 118, 119] |

## Nomenclature

$C_p$ – specific heat at constant pressure, [29]
D32 or SMD – sauter mean diameter, [10]
Dv90 – droplet diameter: 90% of the volume, [10]
$f$ – merit function, in order to evaluate the total (CO and $NO_x$) emission, [65]
$H_L$ – linear height, [m] [4]
$H_{\mathrm{reff}}$ – casing height, [m] [4]
$L_{\mathrm{diff}}$ – diffuser length, [4]
$L_{\mathrm{DZ}}$ – dilution zone length, [m] [4]
$L_{\mathrm{PZ}}$ – primary zone length, [4]
$L_{\mathrm{SZ}}$ – secondary zone length, [m] [4]
$\dot{m}$ – mass-flow rate, [kgs$^{-1}$] [29]
$M_{\mathrm{a}}$ – air mass-flow, [10]
$N_{\mathrm{DZ}}$ – number of dilution holes for the dilution zone, [4]
$N_{\mathrm{FN}}$ – fuel nozzle number, [4]
$N_{SZ}$ – number of dilution holes for the secondary zone, [4]
$S$ – swirl number, [53]
$S_{\mathrm{gen}}$ – Entropy generation rate in the combustor, [JK$^{-1}$s$^{-1}$] [65]
$T_{\mathrm{b}}$ – blade temperature, [76]
$T_{\mathrm{s}}$ – stoichiometric temperature, [108]
$T_{\mathrm{SD}}$ – temperature standard deviation, can be used to measure the non-uniformity of temperature profile, [65]
$T_{\mathrm{u}}$ – temperature of unburned gases, [64]
$W_c$ *or* $C_w$ – specific compressor work, [10]
$W_s$ – specific work, [108]

*Greek symbols*

$\gamma_t$ – temperature uniformity index, [65]
$\delta$ – correction factor distance, [10]
$\eta_c$ – combustion efficiency, [65]
$\eta_p$ – plant efficiency, [76]
$\eta_{\mathrm{vap}}$ – water evaporation efficiency, [65]
$\theta_1$ – temperature correction factor, $T\,T_{\mathrm{isa}}^{-1}$ [10]
$\theta_2$ – loading parameter, [108]
$\theta_s$ – modified loading parameter, [108]
$\varphi$ – equivalence ratio, [97]
$\omega$ – steam fraction, [%] [108]

*Acronyms*

AHAT – advanced humid air turbine system, [49]
CC – combined-cycle, [49]
CDT – compressor discharge temperature, [10]
CEMS – continuous emissions monitoring system, [118]
EGT – exit gas temperature, [10]
ERN – equivalent reactor network, [118]
FF – fuel flow, [10]
GTITWI – gas turbine installationtal water injection, [119]
HPC – high pressure compressor, [50]
HRSC – heat recovery steam generator, [90]
IAC – inlet air cooling, [90]
LBO – lean blowout, [53]
LES – large eddy simulation, [64]
LPC – low pressure compressor, [50]
METVC – multi-effect thermal vapor compression, [60]
PF – pattern factor, [65]
PFR – plug flow reactor, [77]
PFZ – post-flame zone, [77]
POGT – partial oxidation gas turbine, [22]
POSTIG – partial oxidation steam-injected gas turbine, [22]
PR – pressure ratio, [10]
PSR – perfectly stirred reactor, [77]
RAF – regenerative after-fogging, [62]
RCM – rapid compression machine, [16]
RQL – rich burn – quick mix – lean burn (combustor), [99]
RSTIG – regenerative steam-injection, [62]
SFC – specific fuel consumption, [50]
STIG – steam injected gas turbine, [22]
WAC – water atomization cooling, [49]
WAR – water flow rate / Air-flow rate, [59]

## References

[1] Lefebvre, A. H., Ballal, D. R., *Gas Turbine Combustion*: *Alternative Fuels and Emissions*, CRC Press, Boca Raton, Fla., USA, 2010
[2] Ommi, F., Investigation of the Eefects of Steam Addition on the Conceptual Design and Pollutants Emission of the Gas Turbine Combustor, *Modares Mechanical Engineering*, *18* (2018), 6, pp. 85-96
[3] Saboohi, Z., *et al*., Multi-Objective Optimization Approach Toward Conceptual Design of Gas Turbine Combustor, *Applied Thermal Engineering*, *148* (2019), Feb., pp. 1210-1223
[4] Xue, R., *et al*., Effect of Steam Addition on Gas Turbine Combustor Design and Performance, *Applied Thermal Engineering*, *104* (2016), July, pp. 249-257
[5] Dodds, W., Engine and Aircraft Technologies to Reduce Emissions, *Proceedings*, UC Technology Transfer Symposium, San Diego, Cal., USA, 2002
[6] Burrus, D., *et al.*, Energy Efficient Engine Component Development and Integration: Single-Annular Combustor Technology Report, NASA Lewis Research Center, Cleveland, O., USA, 1980, p. 118

[7] Burrus, D., *et al*., Energy Efficient Engine (E3) Combustion System Component Technology Performance Report, https://ntrs.nasa.gov/search.jsp?R=19900019239, 1984
[8] Palmer, J., The TURBOMATCH Scheme for Gas Turbine, Cranfield University: Unpublished TURBO-MATCH Manual, 2011
[9] Vassilios, A. P., Gas Turbine Performance Simulation, Lecture Notes, September, 2011 (Unpublished), https://www.cranfield.ac.uk/people/professor-vassilios-pachidis-335215
[10] Novelo, D. A. B., *et al*., Experimental Investigation of Gas Turbine Compressor Water Injection for $NO_x$ Emission Reductions, *Energy*, *176* (2019), June, pp. 235-248
[11] Bhargava, R., *et al*., Gas Turbine Fogging Technology: A State-of-the-Art Review – Part II: Overspray Fogging – Analytical and Experimental Aspects, *Journal of Engineering for Gas Turbines and Power*, *129* (2007), 2, pp. 454-460
[12] Chaker, M., Mee, T. R. Design Consideration of Fogging and Wet Compression Systems as Function of Gas Turbine Inlet Duct Configurations, *Proceedings*, ASME Turbo Expo 2015: Turbine Technical Conference and Exposition, Montreal, Canada, 2015
[13] Savic, S., *et al*., Spray Interaction and Droplet Coalescence in Turbulent Air-Flow, An Experimental Study with Application Gas Turbine High Fogging, *Zaragoza*, *9* (2002), Sept., pp. 1-6
[14] ***, ASME, Gas Turbine Inlet Air-Conditioning Equipment – Appendix a Method of Testing Atomizing Nozzles PTC 51, 2011, p. 132
[15] ***, Malvern Instruments, Spraytec, Ltd., Malvern, man0368 Issue 3.0, Worcestershire, UK Ltd., 2007
[16] Mazas, A., *et al*., Effects of Water Vapor Addition on the Laminar Burning Velocity of Methane Oxygen-Enhanced Flames at Atmospheric Pressure, *Combustion and Flame*, *158* (2011), 12, pp. 2428-2440
[17] Mazas, A., *et al*., Effects of Water Vapor Addition on the Laminar Burning Velocity of Oxygen-Enriched Methane Flames, *Combustion and Flame*, *158* (2011), 12, pp. 2428-2440
[18] Donohoe, N., *et al*., Influence of Steam Dilution on the Ignition of Hydrogen, Syngas and Natural Gas Blends at Elevated Pressures, *Combustion and Flame*, *162* (2015), 4, pp. 1126-1135
[19] Brett, L., *et al*., Simulation of Methane Autoignition in a Rapid Compression Machine with Creviced Pistons, *Combustion and Flame*, *124* (2001), 1-2, pp. 326-329
[20] Gallagher, S., *et al*., A Rapid Compression Machine Study of the Oxidation of Propane in the Negative Temperature Coefficient Regime, *Combustion and Flame*, *153* (2008), 1-2, pp. 316-333
[21] Aul, C. J., *et al*., Ignition and Kinetic Modelling of Methane and Ethane Fuel Blends with Oxygen: A Design of Experiments Approach, *Combustion and Flame*, *160* (2013), 7, pp. 1153-1167
[22] Zhang, S.-J., *et al*., Performance Analysis of a Partial Oxidation Steam Injected Gas Turbine Cycle, *Applied Thermal Engineering*, *91* (2015), Dec., pp. 622-629
[23] Horlock, J. H., *Advanced Gas Turbine Cycles: A Brief Review of Power Generation Thermodynamics*, Elsevier, Amsterdam, Netherlands, 2013
[24] Smith, L., *et al*., The Gas Turbine Handbook, The NETL, Morgantown, W. Va., USA, 2006
[25] Kays, W. M., London, A. L., Compact Heat Exchangers, Krieger Publishing Company, Malabar, Fla., USA, 1984
[26] Benini, E., *et al*., Reduction of NO Emissions in a Turbojet Combustor by Direct Water/Steam Injection: Numerical and Experimental Assessment, *Applied Thermal Engineering*, *29* (2009), 17-18, pp. 3506-3510
[27] Raithby, G., Equations of Motion for Reacting, Particle-Laden Flows, Progress Report, *Thermal Science Ltd*., 1991
[28] Benini, E., Giacometti, S., Design, Manufacturing and Operation of a Small Turbojet-Engine for Research Purposes, *Applied Energy*, *84* (2007), 11, pp. 1102-1116
[29] Lee, M. C., *et al.*, Experimental Study on the Effect of $N_2$, $CO_2$, and Steam Dilution on the Combustion Performance of $H_2$ and CO Synthetic Gas in an Industrial Gas Turbine, *Fuel*, *102* (2012), Dec., pp. 431-438
[30] Kokkulunk, G., *et al*., Theoretical and Experimental Investigation of Diesel Engine with Steam Injection System on Performance and Emission Parameters, *Applied Thermal Engineering*, *54* (2013), 1, pp. 161-170
[31] Tesfa, B., *et al*., Water Injection Effects on the Performance and Emission Characteristics of a CI Engine Operating with Biodiesel, *Renewable Energy*, *37* (2012), 1, pp. 333-344
[32] Mello, J., Mellor, A., The $NO_x$ Emissions from Direct Injection Diesel Engines with Water/Steam Dilution, SAE Transactions, Technical paper, 1999-01-0836, 1999
[33] Gonca, G., Investigation of the Influences of Steam Injection on the Equilibrium Combustion Products and Thermodynamic Properties of Bio Fuels (biodiesels and alcohols), *Fuel*, *144* (2015), Mar., pp. 244-258

[34] Parlak, A., *et al*., New Method to Reduce $NO_x$ Emissions of Diesel Engines: Electronically Controlled Steam Injection System, *Journal of the Energy Institute*, *85* (2012), 3, pp. 135-139
[35] Gonca, G., *et al*., The Effects of Steam Injection on the Performance and Emission Parameters of a Miller Cycle Diesel Engine, *Energy*, *78* (2014), Dec., pp. 266-275
[36] Gonca, G., *et al*., Theoretical and Experimental Investigation of the Miller Cycle Diesel Engine in Terms of Performance and Emission Parameters, *Applied Energy*, *138* (2015), Jan., pp. 11-20
[37] Mohapatra, D., *et al*., Effect of Steam Injection and $FeCl_3$ as Fuel Additive on Performance of Thermal Barrier Coated Diesel Engine, *Sustainable Environment Research*, *28* (2018), 5, pp. 247-255
[38] Zhao, R., *et al*., Comparative Study on Different Water/Steam Injection Lay-Outs for Fuel RReduction in a Turbocompound Diesel Engine, *Energy Conversion and Management*, *171* (2018), Sept., pp. 1487-1501
[39] Boretti, A., Water Injection in Directly Injected Turbocharged Spark Ignition Engines, *Applied Thermal Engineering*, *52* (2013), 1, pp. 62-68
[40] Bozza, F., *et al.*, Potentials of Cooled EGR and Water Injection for Knock Resistance and Fuel Consumption Improvements of Gasoline Engines, *Applied Energy*, *169* (2016), May, pp. 112-125
[41] Adnan, R., *et al*., Performance and Emission Analysis of Hydrogen Fueled Compression Ignition Engine with Variable Water Injection Timing, *Energy*, *43* (2012), 1, pp. 416-426
[42] Wu, Z.-J., *et al*., A High Efficiency Oxyfuel Internal Combustion Engine Cycle with Water Direct Injection for Waste Heat Recovery, *Energy*, *70* (2014), June, pp. 110-120
[43] Wu, Z.-J., *et al*., Experimental Study of the Effect of Water Injection on the Cycle Performance of an Internal-Combustion Rankine Cycle Engine, Proceedings of the Institution of Mechanical Engineers – Part D: *Journal of Automobile Engineering*, *228* (2014), 5, pp. 580-588
[44] Hoppe, F., *et al*., Water Injection for Gasoline Engines: Potentials, Challenges, and Solutions, *International Journal of Engine Research*, *17* (2016), 1, pp. 86-96
[45] Zhu, S., *et al*., Thermodynamic and Experimental Researches on Matching Strategies of the pre-Turbine Steam Injection and the Miller Cycle Applied on a Turbocharged Diesel Engine, *Energy*, *140* (2017), Part 1, pp. 488-505
[46] Zhu, S., *et al*., Thermodynamic Analysis of an in-Cylinder Waste Heat Recovery System for Internal Combustion Engines, *Energy*, *67* (2014), Apr., pp. 548-556
[47] Zhao, R., *et al*., Numerical Study on Steam Injection in a Turbocompound Eiesel engine for Waste Heat Recovery, *Applied Energy*, *185* (2017), Part 1, pp. 506-518
[48] Gonca, G., Investigation of the Effects of Steam Injection on Performance and NO Emissions of a Diesel Engine Running with Ethanol – Diesel Blend, Energy Conversion and Management, *77* (2014), Jan., pp. 450-457
[49] Araki, H., *et al*., Experimental and Analytical Study on the Operation Characteristics of the AHAT System, *Journal of Engineering for Gas Turbines and Power*, *134* (2012), 5, 051701
[50] Daggett, D. L., Hendricks, R. C., Water Misting and Injection of Commercial Aircraft Engines to Reduce Airport $NO_x$, NASA Report CR-2004-212957, 2004
[51] Geiselhart, K. A., *et al*., Blended Wing Body Systems Studies: Boundary-Layer Ingestion Inlets with Active Flow Control, NASA Report CR-2003-212670, 2003
[52] Balepin, V., *et al*., The $NO_x$ Emission Reduction in Commercial Jets through Water Injection, *Proceedings*, 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Indianapolis, Ind., USA, 2002, p. 3623
[53] De Paepe, W., *et al*., Experimental Investigation of the Effect of Steam Dilution on the Combustion of Methane for Humidified Micro Gas Turbine Applications, *Combustion Tcience and Technology*, *188* (2016), 8, pp. 1199-1219
[54] Morley, C., Gaseq: A Chemical Equilibrium Program for Windows, Ver. 0.79, 2005
[55] Cuoci, A., *et al*., OpenSMOKE++: An Object-Oriented Framework for the Numerical Modelling of Reactive Systems with Detailed Kinetic Mechanisms, *Computer Physics Communications*, *192* (2015), July, pp. 237-264
[56] Smith, G., *et al*., GRI Mech 3.0 [Online], University of California, Berkeley, Berkeley, Cal., USA, 2000
[57] Sayad, P., *et al*., Experimental Investigations of the Lean Blowout Limit of Different Syngas Mixtures in an Atmospheric, Premixed, Variable-Swirl Burner, *Energy and Fuels*, *27* (2013), 5, pp. 2783-2793
[58] Lim, J., A Study of the Effects of Preheat and Steam Addition on the Flame Structure and NO Formation in Laminar Counterflow Flames, Ph D. thesis, Purdue University, West Lafayette, Ind., USA, 2000
[59] Mathioudakis, K., Evaluation of Steam and Water Injection Effects on Gas Turbine Operation Using Explicit Analytical Relations, Proceedings of the Institution of Mechanical Engineers – Part A: *Journal of Power and Energy*, *216* (2002), 6, pp. 419-431

[60] Esfahani, I .J., Yoo, C., Feasibility Study and Performance Assessment for the Integration of a Steam-Injected Gas Turbine and Thermal Desalination System, *Desalination*, *332* (2014), 1, pp. 18-32
[61] Bouam, A., *et al*., Gas Turbine Performances Improvement Using Steam Injection in the Combustion Chamber under Sahara Conditions, *Oil and Gas Science and Technology – Revue de l'IFP, 63* (2008), 2, pp. 251-261
[62] Kim, K. H., Effects of Water and Steam Injection on Thermodynamic Performance of Gas-Turbine Systems, *Applied Mechanics and Materials*, *110* (2012), Oct., pp. 2109-2116
[63] Touchton, G., Influence of Gas Turbine Combustor Design and Operating Parameters on Effectiveness of $NO_x$ Suppression by Injected Steam or Water, *Proceedings*, Joint Power Generation Conference, GT Papers, Toronto, Canada, 1984, pp. V001T02A003-V001T02A003
[64] Kruger, O., *et al*., Large Eddy Simulations of Hydrogen Oxidation at Ultra-Wet Conditions in a Model Gas Turbine Combustor Applying Detailed Chemistry, *Journal of Engineering for Gas Turbines and Power*, *135* (2013), 2, 021501
[65] Farokhipour, A., *et al*., A Numerical Study of $NO_x$ Reduction by Water Spray Injection in Gas Turbine Combustion Chambers, *Fuel*, *212* (2018), Jan., pp. 173-186
[66] Hirsch, C., *Numerical Computation of Internal and External Flows: The Fundamentals of Computational Fluid Dynamics*, Elsevier, Amsterdam, The Netherlands, 2007
[67] Amani, E., Nobari, M., A Calibrated Evaporation Model for the Numerical Study of Evaporation Delay in Liquid Fuel Sprays, *International Journal of Heat and Mass Transfer*, *56* (2013), 1-2, pp. 45-58
[68] Amani, E., Nobari, M., Systematic Tuning of Dispersion Models for Simulation of Evaporating Sprays, *International Journal of Multi-Phase Flow*, *48* (2013), Jan., pp. 11-31
[69] Menter, F. R., *et al*., A Correlation-Based Transition Model Using Local Variables – Part I: Model Formulation, *Journal of Turbomachinery*, *128* (2006), 3, pp. 413-422
[70] Torkzadeh, M., *et al*., An Investigation of Air-Swirl Design Criteria for Gas Turbine Combustors through a Multi-Objective CFD Optimization, *Fuel*, *186* (2016), Dec., pp. 734-749
[71] Lu, T., Law, C. K., A Criterion Based on Computational Singular Perturbation for the Identification of Quasi Steady-State Species: A Reduced Mechanism for Methane Oxidation with NO Chemistry, *Combustion and Flame*, *154* (2008), 4, pp. 761-774
[72] WC Jr, G., *Gas-Phase Combustion Chemistry*, Springer Science and Business Media, New York, USA, 1999
[73] Malte, P., Pratt, D., Measurement of Atomic Oxygen and Nitrogen Oxides in Jet-Stirred Combustion, *Symposium (International) on Combustion*, *15* (1975), 1, pp. 1061-1070
[74] Bowman, C., *Chemistry of Gaseous Pollutant Formation and Destruction*, John Wiley and Sons, New York, USA, 1991
[75] Arjmandi, H., Amani, E., A Numerical Investigation of the Entropy Generation in and Thermodynamic Optimization of a Combustion Chamber, *Energy*, *81* (2015), Mar., pp. 706-718
[76] Elwekeel, F. N., Abdala, A. M., Effect of Mist Cooling Technique on Exergy and Energy Analysis of Steam Injected Gas Turbine Cycle, *Applied Thermal Engineering*, *98* (2016), Dec., pp. 298-309
[77] Stathopoulos, P., *et al.*, Emissions of a Wet Premixed Flame of Natural Gas and a Mixture With Hydrogen at High Pressure, *Journal of Engineering for Gas Turbines and Power*, *139* (2017), 4, 041507
[78] Kuhn, P., *et al*. Design and Assessment of a Fuel-Flexible Low Emission Combustor for Dry and Steam-Diluted Conditions, *Proceedings*, ASME Turbo Expo 2015: Turbine Technical Conference and Exposition, Montreal, Canada, 2015, pp. V04BT04A024-V04BT04A024
[79] Reichel, T. G., *et al*., Investigation of Lean Premixed Swirl-Stabilized Hydrogen Burner with Axial Air Injection Using OH-Plif Imaging, *Proceedings*, ASME Turbo Expo 2015: Turbine Technical Conference and Exposition, Montreal, Canada, 2015, pp. V04AT04A036-V04AT04A036
[80] Fleck, J. M., *et al*., Experimental Investigation of a Generic, Fuel Flexible Reheat Combustor at Gas Turbine Relevant Operating Conditions, *Proceedings*, ASME Turbo Expo 2010: Power for Land, Sea, and Air, Glasgow, UK, 2010, pp. 583-592
[81] Goodwin, D., CANTERA, An Open-Source, Extensible Software Suite for CVD Process Simulation, *Chemical Vapor Deposition XVI and EUROCVD*, *14* (2003), 40, pp. 2003-08
[82] Beer, J., Lee, K., The Effect of the Residence Time Distribution on the Performance and Efficiency of Combustors, *Symposium (International) on Combustion*, *10* (1965), 1, pp. 1187-1202
[83] Michaud, M. G., *et al*., Chemical Mechanisms of $NO_x$ Formation for Gas Turbine Conditions, *Symposium (International) on Combustion*, *24* (1992), 1, pp. 879-887
[84] Stathopoulos, P., *et al*., The Ultra-Wet Cycle for High Efficiency, Low Emission Gas Turbines, *Proceedings*, 7$^{th}$ International Gas Turbine Conference (ETN: IGTC-14), Brussels, Belgium, 2014, pp. 14-15

[85] Goke, S., *et al*., Influence of Pressure and Steam Dilution on $NO_x$ and CO Emissions in a Premixed Natural Gas Flame, *Journal of Engineering for Gas Turbines and Power*, *136* (2014), 9, 091508
[86] Iancu, P., *et al*., Computational Fluid Dynamics (CFD) Simulation of Fuel Gas and Steam Mixtures to Decrease $NO_x$ Emissions of Industrial Burners, in: *Computer Aided Chemical Engineering*, Elsevier, Amsterdam, Netherlands, 2017, pp. 565-570
[87] Sayre, A., *et al*., Scaling Characteristics of Aerodynamics and Low-$NO_x$ Properties of Industrial Natural Gas Burners, The Scaling 400 Study – Part IV: The 300 kW BERL Test Results, *GRI Topical Report*, *94* (1994), 0186
[88] ***, Union Gas, Natural-Gas (Information about Industrial Methane Composition), https://www.uniongas.com/about-us/about-natural-gas/Chemical-Compositionof, 2016
[89] Rasi, S., *Biogas Composition and Upgrading to Biomethane*, University of Jyvaskyla, Jyvaskyla, Finland, 2009
[90] Wang, F., Chiou, J.-S., Integration of Steam Injection and Inlet Air Cooling for a Gas Turbine Generation System, *Energy Conversion and Management*, *45* (2004), 1, pp. 15-26
[91] Hwang, D. J., *et al*., Numerical Study on Flame Structure and NO Formation in $CH_4$-$O_2$-$N_2$ Counterflow Diffusion Flame Diluted with $H_2O$, *International Journal of Energy Research*, *28* (2004), 14, pp. 1255-1267
[92] Chen, A. G., *et al*., Humid Air $NO_x$ Reduction Effect on Liquid Fuel Combustion, *Proceedings*, ASME Turbo Expo 2002: Power for Land, Sea, and Air, Amsterdam, The Netherlands, 2002, pp. 917-925
[93] Bhargava, A., *et al.*, An Experimental and Modelling Study of Humid Air Premixed Flames, *Proceedings*, ASME 1999 International Gas Turbine and Aeroengine Congress and Exhibition, Orlando, Fla., USA, 1999, pp. V002T02A002-V002T02A002
[94] Meyer, J.-L.,G. Grienche. An experimental study of steam injection in an aeroderivative gas turbine, *Proceedings*, ASME 1997 International Gas Turbine and Aeroengine Congress and Exhibition, Orlando, Fla., USA, 1997, pp. V003T10A013-V003T10A013
[95] Bhargava, A., *et al*. Pressure Effect on $NO_x$ and CO Emissions in Industrial Gas Turbines, *Proceedings*, ASME Turbo Expo 2000: Power for Land, Sea, and Air, Amsterdam, The Netherlands, 2000, pp. V002T02A017-V002T02A017
[96] Mansour, A., *et al*., Application of Macrolamination Technology to Lean, Premix Combustion, *Proceedings*, ASME Turbo Expo 2000: Power for Land, Sea, and Air, Amsterdam, The Netherlands, 2000, pp. V002T02A035-V002T02A035
[97] Kayadelen, H. K., Ust, Y., Prediction of Equilibrium Products and Thermodynamic Properties in $H_2O$ Injected Combustion for $C_\alpha H_\beta O_\gamma N_\delta$ Type Fuels, *Fuel*, *113* (2013), Nov., pp. 389-401
[98] Design, R., *Chemkin-Pro 15092*, Reaction Design: San Diego, Cal., USA, 2009
[99] Goke, S., *et al*., Influence of Steam Dilution on the Combustion of Natural Gas and Hydrogen in Premixed and Rich-Quench-Lean Combustors, *Fuel Processing Technology*, *107* (2013), Mar., pp. 14-22
[100] Zhao, D., *et a*l., Behavior and Effect on $NO_x$ Formation of OH Radical in Methane-Air Diffusion Flame with Steam Addition, *Combustion and Flame*, *130* (2002), 4, pp. 352-360
[101] Yamashita, H., *et al*., The $NO_x$ Formation by Steam Injection Using Detailed Chemical Kinetics, *International Journal of Global Energy Issues*, *15* (2001), 3, pp. 310-22
[102] Kee, R. J., *et al*., The Chemkin Thermodynamic Data Base, Technical Report, Sandia National Labs., Livermore, Cal., USA, 1990
[103] Smooke, M. D., *Reduced Kinetic Mechanisms and Asymptotic Approximations for Methane-Air Flames:* A Topical Volume, Springer, Amsterdam, The Netherlands, 1991
[104] Yamashita, H., Numerical Study on $NO_x$ Production of Transitional Fuel Jet Diffusion Flame, *JSME International Journal Series B Fluids and Thermal Engineering*, *43* (2000), 1, pp. 97-103
[105] Delattin, F., *et al.*, Effects of Steam Injection on Microturbine Efficiency and Performance, *Energy*, *33* (2008), 2, pp. 241-247
[106] Boushaki, T., *et al*., Effects of Hydrogen and Steam Addition on Laminar Burning Velocity of Methane–air Premixed Flame: Experimental and Numerical Analysis, *International Journal of Hydrogen Energy*, *37* (2012), 11, pp. 9412-9422
[107] Alaefour, I., Reddy, B.V., Effect of Steam Injection in Gas Turbine Combustion Chamber on the Performance of a Natural Gas Fired Combined Cycle Power Generation Unit, *Applied Mechanics and Materi*als, *110-116* (2012), Oct., pp. 4574-4577
[108] Nadir, M., Ghenaiet, A., Steam Turbine Injection Generator Performance Estimation Considering Turbine Blade Cooling, *Energy*, *132* (2017), Aug., pp. 248-256

[109] Chiesa, P., *et al*., Using Hydrogen as Gas Turbine Fuel, Transactions of the ASME-A-Engineering for Gas, *Turbines and Power*, *127* (2005), 1, pp. 73-80
[110] Belokon, A. A., *et al.*, Prediction of Combustion Efficiency and $NO_x$ Levels for Diffusion Flame Combustors in HAT Cycles, *Proceedings*, ASME Turbo Expo 2002: Power for Land, Sea, and Air, Amsterdam, The Netherlands, 2002, pp. 791-797
[111] Lefebvre, A. H., *Gas Turbine Combustion*, Hemisphere Pub, Corp., Washington, USA, 1983
[112] Kuznetsov, V., Sabelnikov, V., *Turbulence and Combustion*, Hemisphere Pub, Corp., New York, USA, 1990
[113] Hermann, F., *et al*., Computational and Experimental Investigation of Emissions in a Highly Humidified Premixed Flame, *Proceedings*, ASME Turbo Expo 2003, Collocated with the 2003 International Joint Power Generation Conference, Atlanta, Geo., USA, 2003, pp. 819-827
[114] Terhaar, S., *et al*., Non-Reacting and Reacting Flow in a Swirl-Stabilized Burner for Ultra-Wet Combustion, *Proceedings*, 41st AIAA Fluid Dynamics Conference and Exhibit, Honolulu, Hi., USA, 2011, p. 3584
[115] Koroll, G., Mulpuru, S., The Effect of Dilution with Steam on the Burning Velocity and Structure of Premixed Hydrogen Flames, *Symposium (International) on Combustion*, *21* (1988), 1, pp. 1811-1819
[116] Kobayashi, H., *et al.*, Dilution Effects of Superheated Water Vapor on Turbulent Premixed Flames at High Pressure and High Temperature, *Proceedings of the Combustion Institute*, *32* (2009), 2, pp. 2607-2614
[117] Kobayashi, H., *et al*., Effects of $CO_2$ Dilution on Turbulent Premixed Flames at High Pressure and High Temperature, *Proceedings of the Combustion Institute*, *31* (2007), 1, pp. 1451-1458
[118] Syed, M. S., A New Diagnostics Tool for Water Injected Gas Turbines, Emissions Monitoring and Modelling, Ph. D. thesis, Universuty of Lousiana, Lafayette, La., USA, 2013
[119] Cardu, M., Baica, M., Gas Turbine Installation with Total Water Injection in the Combustion Chamber, *Energy Conversion and Management*, *43* (2002), 17, pp. 2395-2404

Paper submitted: October 30, 2019
Paper revised: November 9, 2019
Paper accepted: November 14, 2019