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ADDRESSING NEW REQUESTS FOR SINGLE-DIGIT NO_X

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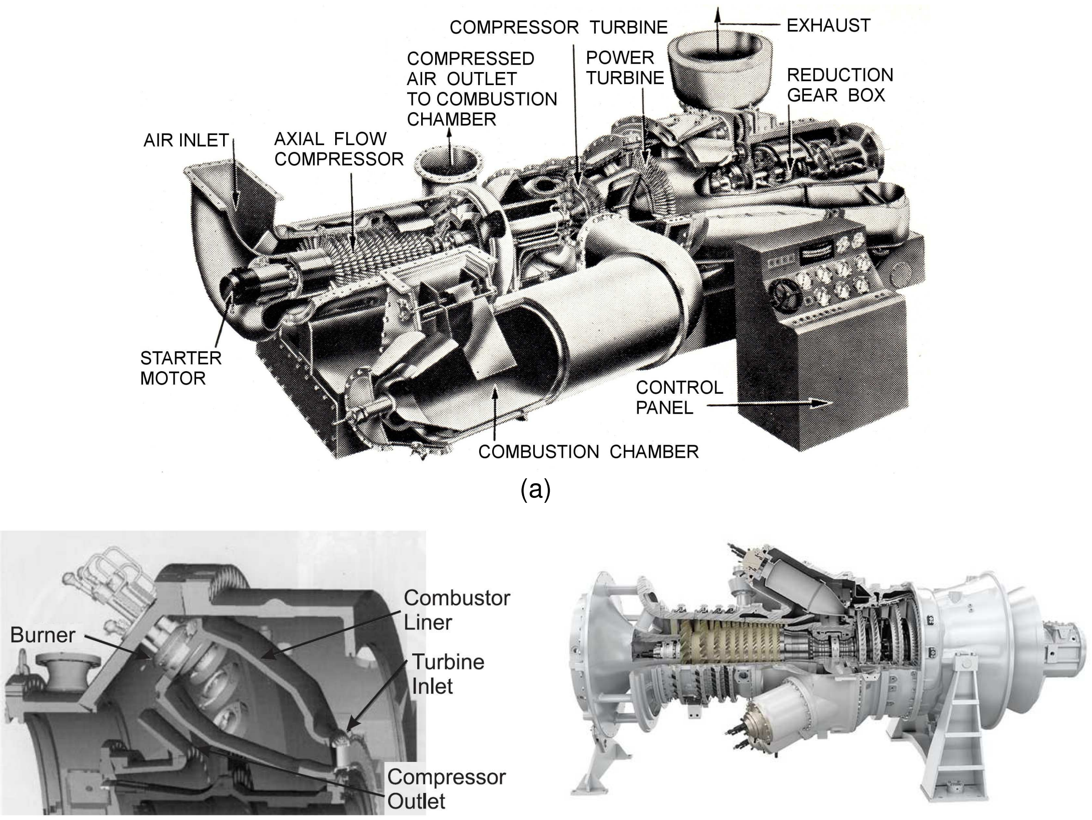
Emissions requirements for industrial gas turbines are becoming increasingly stringent. Moreover, many US states impose limits that are stricter than Federal Government requirements. There are several cases of customers specifying NO_x less than 10 ppm, together with increased life of component parts and increased efficiency. In response to such challenges OEMs have invested in the development of dry low emissions combustion systems, with the result that state-of-the-art combustion technology is capable of achieving single-digit NO_x. The current paper reviews the critical factors affecting NO_x including load profile, fuel quality, and control strategies for maintaining low emissions.

Introduction

Modern industrial gas turbines are expected to achieve low emissions whilst running reliably and efficiently on a wide range of fuels, often with calorific values considerably different from standard pipeline gas. Requests for Quotations specifying sub-10 ppm levels of NO_x are increasingly common in the US, due to a combination of federal, state, and local requirements, which may be expressed either as definitions of Best Available Control Technology or as simple limits on the NO_x emissions per station in tons/annum. Reducing the cost of power generation via efficiency gains and extended operating lives of component parts is also of paramount importance.

Over the past 25 years Original Equipment Manufacturers (OEMs) have developed low NO_x combustion systems, making significant advances in component design, intelligent control, and materials technology [1]. Nevertheless the basic configurations of combustion systems offered by each OEM reflect the legacy of designs that date back to the early 1950s. Figure 1 presents the three most common types: silo, annular, and can-annular. The silo configuration, as illustrated by the Ruston and Hornsby TA-series [2] (Figure 1(a)), has a single combustor mounted externally to the engine. In terms of power density, footprint, and weight the silo arrangement is less competitive than the other two types. Annular combustion systems (Figure 1(b)) are often used in aero-derivative industrial gas turbines which are characterised by light weight and the ability to carry out quick starts. On the other hand can-annular systems (Figure 1(c)) tend to be selected for their ease of serviceability and relatively short development times. Basic development of the combustion hardware in a can-annular layout can be carried out using a single-combustor test rig whereas full scale testing of an annular system is often prohibitively expensive. Hence the development of annular combustors usually relies on test results from a single-burner sector.



(a)

(b)

(c)

Figure 1: Common combustor configurations: (a) silo [2], (b) annular [3], (c) can-annular.

Modes of Combustion

The production of NO_x during combustion is due to the following main processes: the thermal (Zeldovich) mechanism, the prompt (Fenimore) mechanism, and conversion of fuel-bound nitrogen to NO [4]. Natural gas, which is the most commonly used fuel in low NO_x industrial gas turbine combustors, has no fuel-bound nitrogren. Thermal NO is produced in high temperature post flame regions, typically where the temperature exceeds 1850 K. The elimination of thermal NO by maintaining flame temperatures below this threshold is considered as a prerequisite for achieving ultra-low NO_x emissions [5]. Prompt NO has a linear temperature dependency and is sensitive to the reaction zone thickness.

Table 1: Typical NO_x emissions for an 8MW industrial gas turbine.

Combustor Type	**NO_x (ppmv)**	**NO_x (tonnes/year)**
Diffusion w/o steam injection	220	571
Diffusion w steam injection	60	172
Dry Low Emissions	9–15	10–20

Reduction of the firing temperature to avoid the generation of thermal NO is achieved either by water/steam injection in nonpremixed (diffusion) type combustors; or by lean premixing of the fuel and air as in Dry Low Emissions (DLE) combustors.

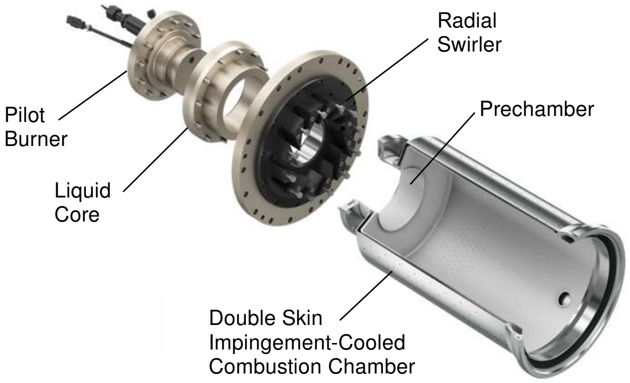
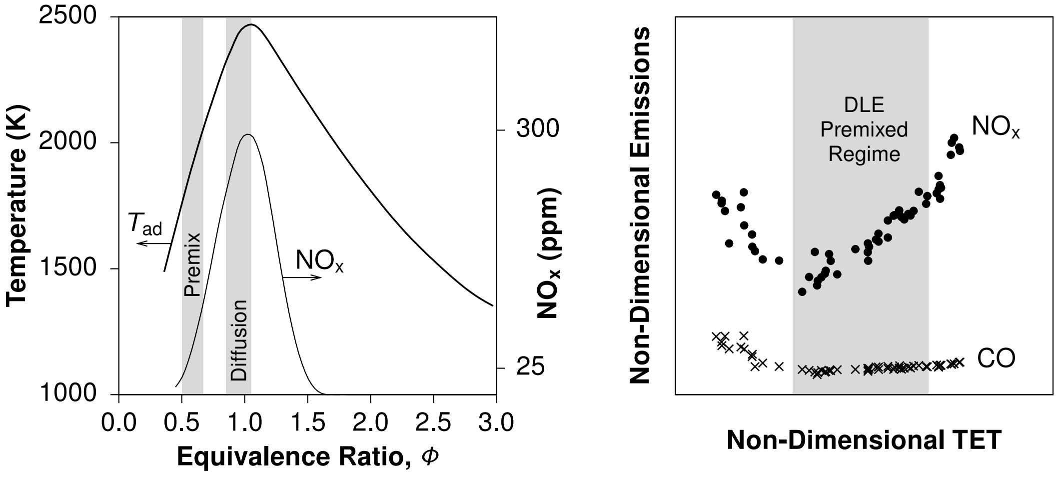


Figure 2: Siemens Dry Low Emissions (DLE) combustor.

Table 1 summarises the expected NO_x concentrations and the annual yield of NO_x for an 8 MW gas turbine. Note that the DLE system achieves significantly lower NO_x than the steam injection method. Considering that the provision of steam injection adds cost to diffusion type combustors and also affects component life, lean premixing is the preferred method of NO_x control. A number of OEMs have developed DLE combustion systems which have now recorded millions of hours operating on industrial gas turbines.

Figure 2 presents the main components of a DLE combustor from a small industrial gas turbine, consisting of: a pilot burner, a radial swirler where the main fuel is injected, and a double-skin combustion chamber. The premixed flame is stabilized in a turbulent shear layer that forms between the central recirculation zone due to the swirl and the outer recirculation caused by the dump expansion after the prechamber. Downstream from the combustion chamber a transition duct connects the circular exit of each combustor to a sector of the turbine entry annulus (cf. Figure 1(c)).



(a) (b)

Figure 3: Trends of emissions versus equivalence ratio: (a) predicted equilibrium NO_x and adiabatic flame temperature, (b) data from a DLE engine operating in the field.

Figure 3(a) presents the variation of NO_x and adiabatic flame temperature with respect to equivalence ratio for a natural gas/air mixture. This highlights the different levels of emissions that are possible for nonpremixed (diffusion) and lean premixed modes of combustion. In a diffusion type combustor (without steam injection) the flame burns in a near-stoichiometric mixture of fuel and air ($\Phi \simeq 1.0$), resulting in a high flame temperature and correspondingly high NO_x, i.e. via to the thermal route. On the other hand lean premixing of the fuel and air ($\Phi \simeq 0.6$) yields a significantly lower flame temperature and low NO_x emissions.

There is an optimal range of DLE operating conditions for which thermal NO is fully suppressed and CO also remains low (Figure 3(b)). At startup or very reduced load conditions it is necessary to increase the equivalence ratio in the near-burner zone either by bypassing air around the combustor or by increasing the percentage split of pilot fuel compared to main fuel, i.e. to avoid lean blowoff and combustion instability. Such control methods tend to increase the flame temperature. Similarly the onset of thermal NO occurs at high loads, e.g. if poor mixing causes fuel-rich pockets to arrive at the flame front and/or if the flame temperature exceeds 1850 K.

Post Combustion Control Methods

Post combustion control is used to chemically reduce NO_x to nitrogen, either with or without the use of a catalyst. While such methods are capable of yielding single-digit NO_x it should be noted that the additional costs associated with installation and maintenance are very significant. The control methods are categorized as:

- Selective Non-Catalytic Reduction (SNCR). These use either urea or ammonia and have removal efficiencies of between 40 and 60 percent. The effective temperature range is limited and hence unsuitable for applications with varying exhaust temperatures.
- Selective Catalytic Reduction (SCR). With a higher removal efficiencies between 70 and 95 percent, SCR systems are also less susceptible to temperature fluctuations. Recently the dual-function layout for both NO_x and CO oxidation has gained popularity for gas turbine applications (see Figure 4).

In some US states where NO_x limits are less than 10 tonnes/year a combination of DLE combustion systems and SCR post combustion control are used. Typical NO_x guarantees are 2–4 ppmv for the whole installation, and 9–15 ppmv for the the gas turbine itself.

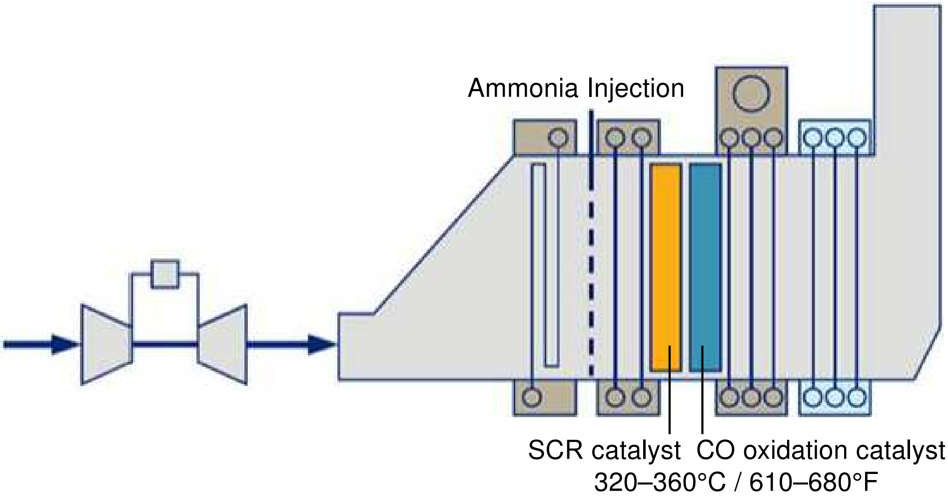


Figure 4: SCR and CO oxidation catalysts for an industrial gas turbine.

Control Strategies

The control logic of a DLE combustion system has a large impact on the total emissions and may also affect the permitting limits for plant operation. It is common to switch between diffusion and lean premixed modes of combustion at a fixed operating condition which is defined in terms of either load or firing temperature (see Figure 5). Other control methods use a variety of fuel nozzles which are brought in or taken out in a sequence, called staging. Alternatively lean premixing is applied across the entire load and operating range. The latter method is applied by Siemens in its light industrial gas turbine range.

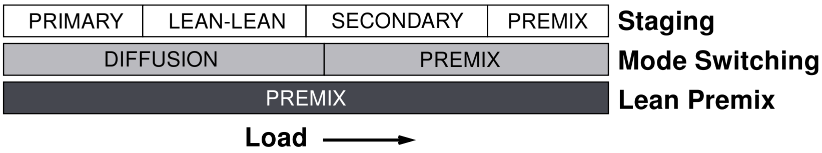
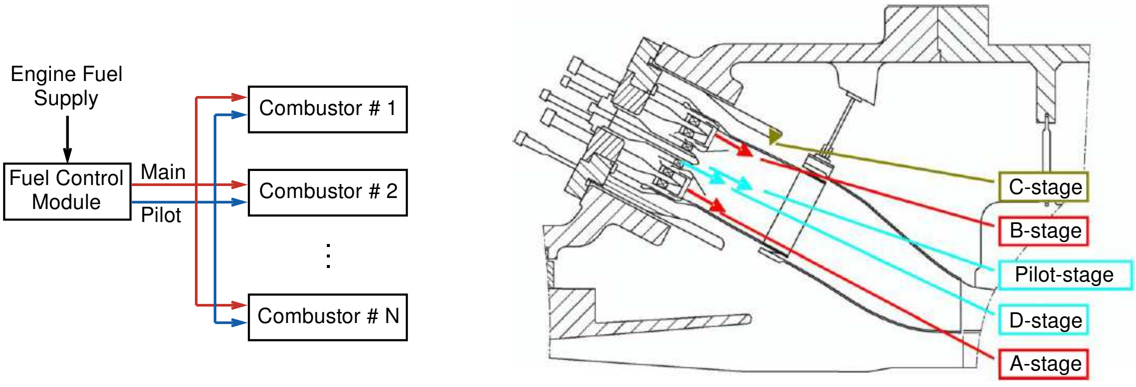


Figure 5: Control methods for low emission gas turbine operation.

Fuel placement also affects on the operability and emissions of a gas turbine combustion system. For this reason, some designs have between two and five separate fuel streams as shown in Figures 6(a) and 6(b). Adding fuel lines has an obvious impact on the complexity and cost of the design. Nevertheless with closed loop intelligent control algorithms and robust actuator control valves such systems are suitable for applications where fuel, load, and ambient conditions change frequently.



(a) (b)

Figure 6: Fuel streams for low emissions combustion systems: (a) in a small gas turbine [6], (b) in a large gas turbine [7].

Improvements in control methodology developed on one combustion system are routinely applied to the other type to maximize reliability and availability of the entire fleet. Closed loop control methods as presented in figure 7, based on actual flame response to operational requests of the combustor are now part of the standard offer by some OEMs. In addition, the NO_x emissions were found to be significantly reduced if intelligent controls methods are used, as presented in figure 8. The intelligent controls such as presented in figure 7 will identify and operate the engine with the lowest pilot split and as a result the NO_x are significantly reduced.

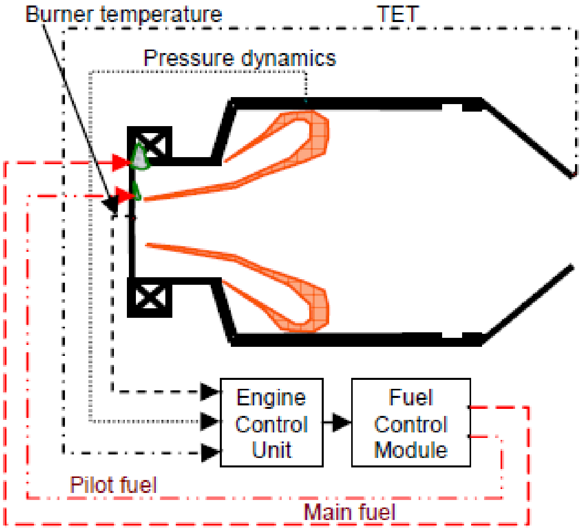


Figure 7: Control methods of low emissions combustion operation of a gas turbine

Figure 8 presents the results of intelligent control methods as applied to an 8 MW gas turbine having two fuel streams, cf. Figure 6(a). Here the percentage split of pilot fuel is automatically reduced to a minimum while avoiding the possibility of combustion dynamics at lean conditions [8]. According to figure 8, most of the time the engine was operational with a single digit NO_x. However the data presented here are the total measurements obtained over the whole month with a 1 second sampling interval of a gas turbine of 8 MW rating operating in USA. As a result, the transient values were included into the sample and thus higher values than 9 ppmv of NO_x are being measured. On average, the NO_x was reduced from 12 ppmv to 7 ppmv via intelligent control which corresponds to a net reduction from 20.2 tonnes/year to 11.8 tonnes/year.

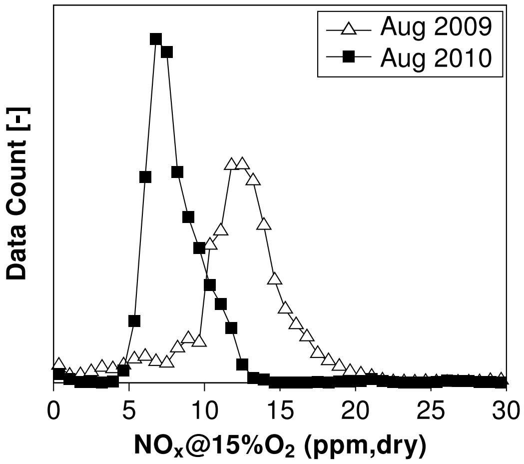


Figure 8: Distribution of NO_x emissions for PLG fuel before and after implementation of intelligent control software [8] .

On figure 9, the NO_x improvements at part load is highlighted, where again a single digit NO_x capability is achieved on a 7 MW engine without compromising the engine reliability or operability. In figure 9, the intelligent controls was only applied between 60 and 80 percent load, not throughout the whole load range.

Transient emissions measurements are also of interest, specifically when fuel changeovers are required. The continuous operation of an industrial gas turbine with tri-fuel flexibility: diesel, natural gas and processed landfill gas (PLG) over a period of 16 hrs is presented in [9]. NO_x emissions are again under 10 ppmv for gaseous fuel at full power for both natural gas and landfill gas. According to [9], for liquid fuel, NO_x emissions are below 50 ppmv. Data presented in [9] also provides a snapshot of the slow and fast transient responses from acception and rejection of load during changes in fuel composition. The results showed transient operation is smooth and stable during fuel change over for a range of gaseous fuels (Wobbe index from 32 to 49 MJ/m^3).

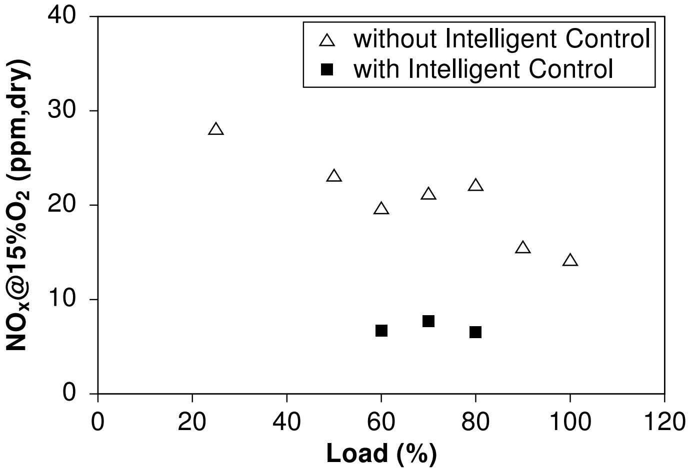


Figure 9: NO_x emissions with and without intelligent control of fuel splits [6].

Meeting emissions requirements is only one aspect of gas turbine combustion design. It has also to meet operational criteria, including: component life; flexible fuel operation; reliable starting; reliable switching between fuels; reliable transient response; and all without excessive cost. However the drive towards smaller emission values combined with higher efficiencies has resulted into more complex design systems than those used in early gas turbine design. Nowadays, the control panel of an early gas turbine as per figure 1 is being superceded with totally integrated automation engine control software supporting up to 16 million of high speed I/O with a multi-platform interface ability.

Measurement and Prediction of NO_x

Continuous Emissions Monitoring Systems (CEMS) are often used to demonstrate the emissions compliance of installed gas turbines. These typically draw a sample of gas from the exhaust stack which is fed to the CEMS unit. The maintenance and calibration of the measurement equipment represents a significant cost to the process owner since measurement accuracy often relies on skilled technical support from the CEMS vendor. Furthermore, for industrial applications such as compressor stations where discontinuous operation is typical, the requirement to periodically carry out testing to demonstrate emissions compliance can be time-consuming and expensive in terms of fuel usage.

Figure 10 presents CEMS data from a 13 MW rating industrial gas turbine which has DLE combustors. This engine is installed at a Combined Heat and Power plant in Europe and is operated continuously at or near full power for long periods. The emissions measurements at the start of the time series on the 6th of June agree with the results of a Works Acceptance Test

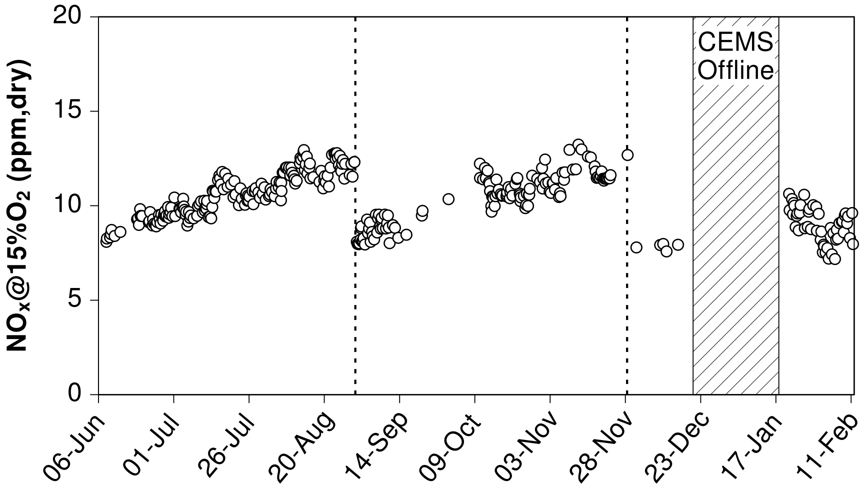


Figure 10: CEMS measurements from an engine during operation at site, filtered by Load.

that was carried out prior to the engine being shipped to site. However, significant upwards drift of NO$_x$ is observed between the bi-monthly calibrations of the CEMS unit which are denoted by dashed vertical lines in Figure 10. Immediately after each calibration the NO$_x$ returns to the expected value. Such behavior highlights the high maintenance burden and associated costs of CEMS and could also justify the reluctance of some gas turbine OEMs to set the same emissions guarantees when CEMS are used for monitoring purposes.

As an alternative to CEMS, it is possible to predict emissions via a 1D-network model of the combustion process, with inputs taken from the monitoring of selected engine operating parameters. Such models are referred to as Predictive Emissions Monitoring Systems (PEMS) and they offer a potential means of demonstrating compliance with emissions regulations at relatively low cost [10]. The algorithm for a PEMS model is straightforward to implement in an Engine Control Unit. Legislation already exists in the US for PEMS [11], and a similar legislative framework is also being considered in Europe.

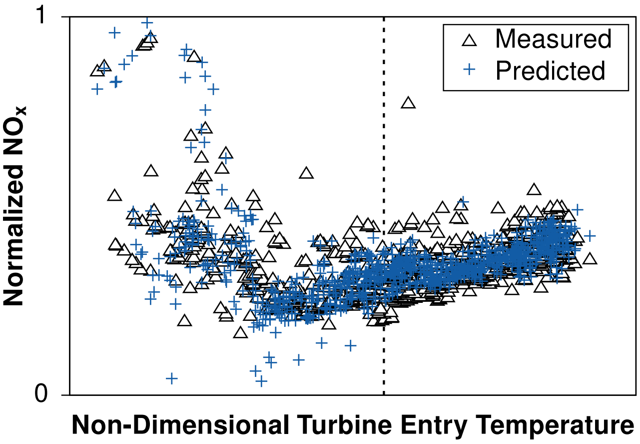


Figure 11: Engine test data compared to PEMS predictions [12]. The dashed vertical line denotes a typical Oil & Gas pipeline compressor duty point.

Figure 11 presents a comparison of measured and predicted NO_x for a sample of 90 different engines between 2012 and 2015. These include both Work Acceptance Tests and development tests for a wide range of operating conditions [12]. For the majority of test points the predictions are within ±5 ppmv of the measured NO_x. Overall, the agreement with the measured emissions is satisfactory and indicates that the 1D-network model is a good basis for PEMS. It is anticipated that the accuracy of the PEMS could be improved for individual engines by tuning the calibration factors to match a specific load point. The simplicity of the PEMS algorithm allows it to be easily incorporated in the Engine Control Unit.

Oil and Gas applications typically operate with some margin on power output and therefore at lower Turbine Entry Temperature than an Industrial Power Generation unit at maximum load. The impact of this for NO_x generation is indicated in Figure 11 where the dashed vertical line denotes a typical Oil & Gas pipeline compressor duty point. As the engine population data from 90 engines include both power generation and mechanical drive aplications, each engine is factory tested for it's full temperature rating, not necessarily for specific cutomer operation. This margin between the gas turbine capacity and the actual user requirement makes single-digit NO_x easier to achieve, particularly for Oil & Gas applications. This will favourably impact the annual NO_x production, permitting and cost of any post-combustion treatment equipment. Consequently, the selection of the gas turbine and compressor/pump equipment should be carefully considered and discussed between the end-user and the OEM/EPC prior to permitting application, taking into account the expected operating profiles.

Summary

This paper covers a brief summary of the gas turbine combustion technologies and main factors affecting NO_x production. Combustion types, control strategies and post-combustion control methods have been briefly discussed and associated NO_x production was highlighted. Temperature dependency, the relationship to CO, fuel placement and the loading profiles all have an impact on the formation and total annual emissions signature of a gas turbine. The single-digit levels of NO_x required by customers in many US states can be achieved using available technology but this requires careful management of factors such as the likely load profile of the engine and fuel quality. Following conclusions could be summarised:

- Operation of DLE combustors in a lean premixed combustion mode throughout the load range of the engine yields significantly lower NO_x compared to mode-switching design options. A 30 times annual reduction of NO_x compared to difussion systems is achieved. Some OEMS offer only DLE premixed systems across the entire load range as standard design option of latest gas turbine units.
- Single digit NO_x capability of gas turbines was proved consistently since 2007 on a range of gas turbine units of different power output. The single-digit levels of NO_x required by customers in many US states can be achieved using available technology but this requires careful management of factors such as the likely load profile of the engine and fuel quality.
- Expected or actual load profiles for the gas turbine units should be used to provide better estimates of the cumulative NO_x production and take advantage for the lower emissions expected at typical operating conditions, particularly in the Oil and Gas segment.
- Continuous measurement of NO_x is strongly dependant on the calibration and maintenance of CEMS system and adds additional cost to end-user. The measurement errors and drifts associated with CEMS should be included into permitted values.

- PEMS technology is now being accepted by legislators and end users as an alternative to CEMS and provides good accuracy at relatively low cost.

All above highlight the need for a continuous engagement and discussion between the end-user and the OEM/EPC during the planning and selection process of rotating equipment. A headline grab of a single digit NO_x capability or guarantee value is not usually sufficient to prove the best available technology.

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