Parametric Modeling of Exhaust Gas Emission From Natural Gas Fired Gas Turbines

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Increased focus on air pollution from gas turbines in the Norwegian sector of the North Sea has resulted in taxes on CO_2. Statements made by the Norwegian authorities imply regulations and/or taxes on NO_x emissions in the near future. The existing CO_2 tax of NOK 0.82/Sm^3 (US Dollars 0.12/Sm^3) and possible future tax on NO_x are analyzed mainly with respect to operating and maintenance costs for the gas turbine. Depending on actual tax levels, the machine should be operated on full load/optimum thermal efficiency or part load to reduce specific exhaust emissions. Based on field measurements, exhaust emissions (CO_2, CO, NO_x, N_2O, UHC, etc.) are established with respect to load and gas turbine performance, including performance degradation. Different NO_x emission correlations are analyzed based on test results, and a proposed prediction model presented. The impact of machinery performance degradation on emission levels is particularly analyzed. Good agreement is achieved between measured and predicted NO_x emissions from the proposed correlation. To achieve continuous exhaust emission control, the proposed NO_x model is implemented to the on-line condition monitoring system on the Sleipner A platform, rather than introducing sensitive emission sensors in the exhaust gas stack. The on-line condition monitoring system forms an important tool in detecting machinery condition/degradation and air pollution, and achieving optimum energy conservation.

Introduction

Proposed national and international guidelines normally include language that is biased toward continuous in-stack emission monitoring. The capital cost of an in-stack system is high, and in addition frequent calibration and maintenance are required. Especially for offshore installations, this places a financial burden on the operators.

Effective in 1991, Norway has introduced a CO_2 tax on natural gas and distillates used in petroleum production facilities and transport. On average, the CO_2 tax per platform is NOK 120 million/year. In total this represents approximately NOK 2.2 billion/year for Statoil as a North Sea operator. The introduction of CO_2 tax on natural gas and distillates has, however, led to a continuous effort to optimize energy conservation on offshore turbomachinery.

Further environmental restrictions are expected, especially in terms of emissions to air. The Norwegian Petroleum Directorate is at present preparing a national act for offshore emissions, which specifically includes guidelines for NO_x reduction. The conflict introducing both CO_2 and NO_x taxes is highlighted.

Introducing emission control on NO_x, whether in the form of a maximum absolute emission level or tax, requires that NO_x pollutants to the atmosphere have to be detected. Continuous detection is at present normally performed by in-stack emission monitoring. Alternatively, NO_x emissions might be established by parametric monitoring alternatives. The challenge of the latter approach lies in testing and modeling emissions to a given level of confidence.

This paper describes the field measurement results, emission scaling, and model implementation to perform on-line NO_x emission control. The major challenges include:

- field measurements of emissions and machinery condition (degradation)
- evaluation of important scaling parameters and parametric models
- development of a proposed parametric emission model to reflect machinery degradation
- implementation of the proposed NO_x model to the on-line condition monitoring system to perform continuous emission control.

In addition, gas turbine operating and maintenance costs, including emission taxes, are evaluated with respect to optimum energy conservation.

Gas Turbine Operating and Maintenance Costs

Pollutant emissions from combustion have become of great concern due to their impact on human health and nature. Restrictions in specific pollution components are introduced in several countries. Emission taxes are also introduced to curb air pollution.

At present, offshore gas turbines are operated, encouraging high thermal efficiency and low power consumption. High thermal efficiency normally demands operation close to full load, which may increase the emission of specific components. However, due to the introduction of taxes on certain emitted components, this philosophy might have to be revised.

The present emission tax on CO_2 has a substantial impact on gas turbine operating costs. Efficient operation of offshore gas turbines is most important, as optimum energy conservation on oil and gas facilities is highly influenced by gas turbine load and operating conditions. Increased tax level on CO_2, combined with a new tax or upper limit on NO_x, may change the existing operating philosophy.

Statoil has at present more than 60 gas turbines in operation. Approximately two-thirds of these are of the General Electric LM2500 type. Emission data, operation, and maintenance costs are in most cases related to operational experience from the LM2500.

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Table 1 Engine operating costs due to component degradation (P = 20 MW)

Costs (NOK/hr)	New engine	Increased air filter loss	Reduction in η_C	Reduction in η_{HPT}	Combined degradation
CO_2-tax	4 046	4 074	4 179	4 214	4 375
Fuel costs	2 527	2 548	2 611	2 632	2 737
Maint. costs	270	270	270	270	270
Total costs	6 843	6 892	7 060	7 116	7 382

Operating and Maintenance Costs. The introduction of a CO_2 tax on fuel gas increases the operating costs of a gas turbine system dramatically. At present it is of great importance to include the influence of CO_2 taxation by focusing on optimum energy operation and maintenance.

The influence of machinery degradation on operating costs is high. Performance deterioration over 20,000 running hours represents a drop in power of up to 10 percent, at constant firing temperature. This is mainly due to inlet filter, compressor, and high-pressure turbine degradation. In-service experience shows that the main problem has become compressor fouling and erosion due to a combination of dry salt, hydrocarbons, drilling cement, and shotblast residues. However, during a hot section life cycle there will be a nonrecoverable degradation of the gas turbine due to thermal effects and mechanical wear.

To maintain high component efficiency, compressor cleaning is usually done every 750 hours, using an off-line crank washing procedure. Recently, several turbine units have been retrofitted with an on-line washing system to reduce compressor fouling effects. In addition, inlet filters are retrofitted when the pressure drop across the filter system increases by more than 100 mm H_2O. However, both filter and compressor fouling are very dependent on other platform activities.

Gas turbine *operating costs* are mainly affected by fuel costs, CO_2 tax, and maintenance costs. Almost all gas turbines are run on gaseous fuel. Fuel costs are dependent on natural gas quality at the specific installation, and in most cases in the range of NOK 0.50–0.70/Sm^3. At present the CO_2 tax is NOK 0.82/Sm^3 fuel gas. Operational experience indicates total average maintenance costs of NOK 270 per running hour.

The effect of gas turbine component degradation on performance, emissions, and operating costs is analyzed by using gas turbine simulation models (V-deck [1] and Tusipro [2]). The Tusipro model has been tuned to vendor reference performance and field test data at actual site operating conditions. The model is an important tool in investigating and establishing deterioration effects.

To highlight the influence of component deterioration on gas turbine operating costs, a case study has been performed, based on operational experience and field test performance data. The following conditions have been analyzed:

- new engine with clean air filter system
- air inlet filter loss of 150 mm H_2O
- a reduction in compressor efficiency (η_C) of 5 percent
- a reduction in high-pressure turbine efficiency (η_{HPT}) of 5 percent
- a combined degradation of the three cases defined above.

Maintenance costs are included at a constant value, based on mean time between major overhauls. The hot section repair interval (HSRI) is typically 25,000–30,000 running hours.

The results are summarized in Table 1.

Gas turbine component degradation has a great impact on total operating costs. The extra operating costs due to deterioration represent approximately NOK 4.3 million a year. In addition, deterioration causes higher firing temperature, influencing maintenance costs and intervals. The present CO_2 tax is an investment in running at high thermal efficiency and reducing power consumption by process optimization and limiting the gas turbine deterioration.

Future regulations from Norwegian authorities may include taxation on NO_x pollutants to air. To highlight the impact of an NO_x tax, an analysis has been performed based on the Swedish tax level of approximately NOK 40 per kg NO_x. In this case, gas turbine component deterioration will have an even greater impact on operating costs and maintenance intervals. Based on the same degradation cases given above, Table 2 summarizes the *increase* in operating costs under an NO_x tax regime. The increase in operational costs is related to new engine total cost (6843 NOK/h).

It can be concluded from the analysis that the introduction of an NO_x tax will influence the optimum gas turbine maintenance intervals. Depending on actual tax level, the operating philosophy is affected. For some specific operating conditions it might pay to run two gas turbine drivers at part load, compared with one at full load. Extra maintenance costs due to increased replacement of hot section components must be taken into consideration.

Nomenclature

A_{NO_x} = reference coefficient
f = fuel/air ratio
h = enthalpy
H_N = lower heating value
m = mass flow
p = pressure
P = power
t = time
T = temperature
α = constant
η = efficiency
κ = adiabatic exponent
ζ = hot section cooling air factor
Φ = relative humidity

Indices

A = air
C = compressor
FG = fuel gas
HPT = high-pressure turbine
PT = power turbine
0 = ambient (atmospheric) conditions
2 = compressor suction
3 = compressor discharge
4 = high-pressure turbine inlet
5 = high-pressure turbine discharge
6 = power turbine inlet
7 = power turbine discharge

Abbreviations

CO = carbon monoxide
CO_2 = carbon dioxide
GFA = Gullfaks A platform
HPT = high-pressure turbine
HSRI = hot section repair interval
NO = nitric oxide
NO_2 = nitric dioxide
N_2O = nitrous oxide
NO_x = nitrogen oxides
NOK = Norwegian kroner
O_2 = oxygen
SFB = Statfjord B platform
UHC = unburned hydrocarbons

Table 2 Increased operating costs due to NO_x tax

Degradation costs (NOK/hr)	NO_x tax not included	NO_x tax included
Increased filter loss	49	147
Reduction in η_C	217	653
Reduction in η_{HT}	273	828
Combined degradation	539	1709

Table 3 NO_x emissions as a function of load and degradation

Load (MW)	Anti-icing valve position (% open)	High pressure turbine disch. temperature T_{54},(°C)	NO_x emission, ppmv, 15% O_2, dry.
14	0	737	136
14	50	760	134*
14	75	816	150
18	0	787	155
18	50	816	163

*feedback from anti-icing valve position missing

The introduction of taxes on emissions to air calls for increased focus on optimum energy conservation. The analysis underlines the importance of keeping the gas turbine performance drop within a certain limit. To control and reduce the effect of component deterioration, on-line condition monitoring systems are used. However, both periodic and condition-based maintenance are performed offshore.

Optimum Energy Conservation. An important challenge in the future development of North Sea reserves will be the exploration of new and possibly marginal fields using existing process equipment. This will necessitate process systems coping with feedstock and conditions well away from their original design base.

For some specific installations, machinery modifications have resulted in reduced operating and maintenance costs. Improvements of natural gas compressor and gas turbine operations extend both process equipment, compressor and turbine life, and major overhaul intervals. It is interesting to observe from the analysis that net savings are mainly made from low gas turbine speed and power consumption. Achieving optimum gas turbine operating conditions is an important challenge, which is given high priority in present research and development projects. Operating cost savings are for some specific installations estimated at NOK 10 million/year [3].

Optimum energy conservation for a gas turbine compression train is a complex function of operating conditions, process flexibility, and machinery condition. Existing development and analyses are based on:

- on-line condition monitoring, to detect machinery condition and component degradation
- prediction routines, to forecast degradation development as a function of time
- optimization routines, to predict optimum intervention time based on operating and maintenance costs (see Williams [4])
- relevant process control parameters, including interaction, product quality, and detection of operating cost savings.

The procedure given is a useful tool to evaluate the potential of new technology and systems. Attempts to perform on-line water wash on aero-derivative gas turbines have for some installations shown fewer improvements in component efficiency than expected. This is mainly due to the type of deposits, and available cleaning fluids in offshore applications.

This analysis underlines the importance of keeping the gas turbine performance drop within a certain limit. Consequently, it is important to detect machinery condition and component degradation in a reliable manner.

In future, the offshore oil and gas industry expects even harder taxes on pollution to the atmosphere. Increased tax level on CO_2, combined with a new tax or maximum upper limit on NO_x, calls for an even better optimization of energy conservation on existing offshore oil and gas production platforms. Optimum operation of offshore gas turbines is therefore an important challenge. For new installations, the air pollution taxes will affect the conceptual design either by utilizing multiphase technology to move the process from the offshore production platform to land, or by using hydropower from the onshore power grid to supply the installation.

Field Measurements and Simulated Data

The work is centered around a field test program, which allows the development of an empirical equation required for calculating emissions at different operating and ambient conditions, including typical machinery component degradation.

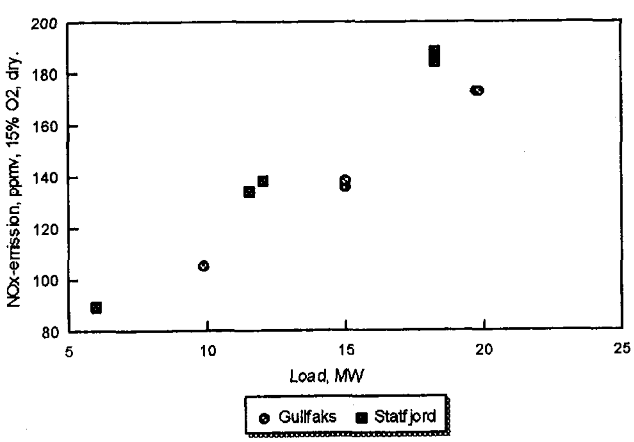

Fig. 1 Emissions of nitrogen oxides versus load from LM2500 PC and PE turbines

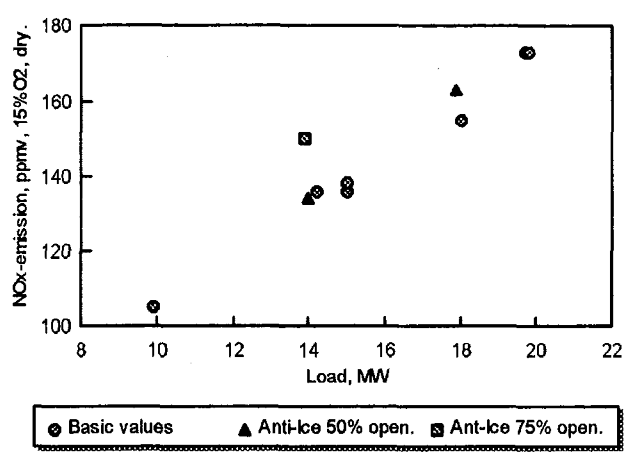

Fig. 2 Emissions at actual anti-icing valve position

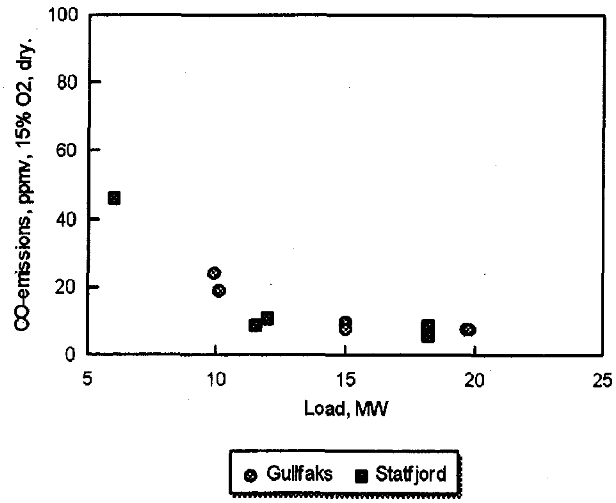

Fig. 3 Emissions of carbon monoxides versus load from LM2500 PC and PE turbines

In addition to field tests, measured data from the gas turbine supplier have been used. Two simulation programs have also been used in enhancing the data material. V-deck is a program developed by General Electric/Dresser Rand, which simulates an LM 2500 PE version (22 MW) gas turbine. The other model used is TUSIPRO, an in-house simulation model based on the work of M. White [3]. In this model, several NO_x correlations have been implemented to perform the present work.

The measurements were made by a third-party company, and were performed to ISO TC 192/WG 2, 1989 standard (Draft).

Instrumentation was calibrated at site according to ISO-DIS 11042/1, 1992. Experimental apparatus setup and errors are given in [6]. In addition to emission measurements, gas turbine performance, i.e., pressure and temperatures, fuel gas rate, and composition, was logged to be used in the parameter evaluation. Predicted values have been corrected according to international standards: 15 percent O_2, dry.

Field Measurements and Results. NO_x emissions were measured as a function of load and component degradation. On the Statfjord field, generator turbines of the PC version (20 MW) were measured, whereas PE type turbines (22 MW) were analyzed on the Gullfaks field. Figure 1 shows the measured values.

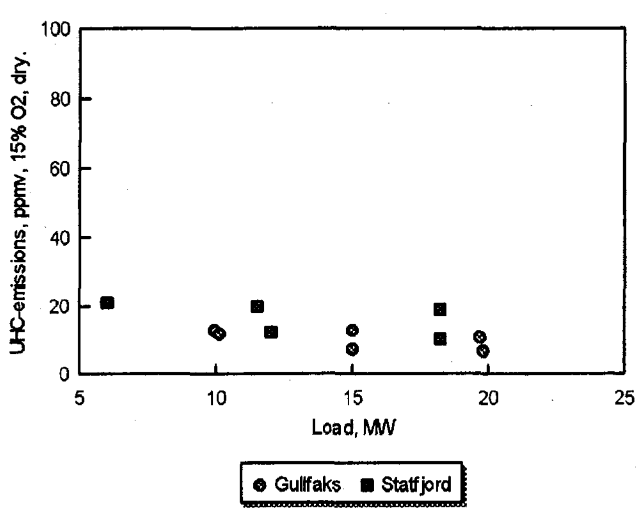

Fig. 4 Emissions of unburned hydrocarbons versus load from LM2500 PC and PE turbines

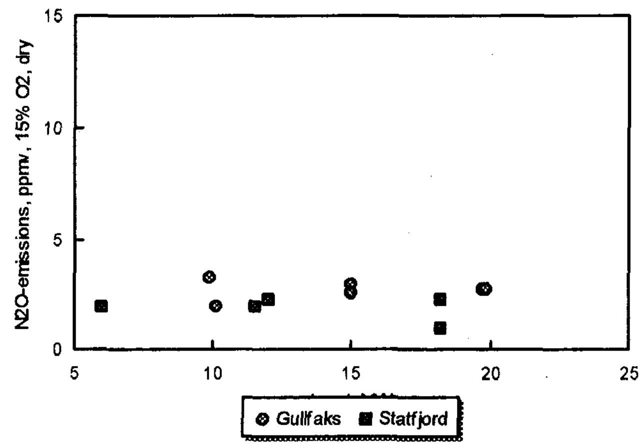

Fig. 5 Emissions of dinitrogen oxides versus load from LM2500 PC and PE turbines

Emission trends show that PC turbines give higher NO_x emissions than the PE variety, which is in accordance with manufacturer's data.

NO_x emissions were also studied as a function of load while varying the anti-ice valve position. This was done in order to establish NO_x emission levels at changed pressure, temperature and flow pattern through the gas turbine at a constant load. Current data for these emissions are given in Table 3, and a comparison with basic emissions is given in Fig. 2.

The gas turbine temperature control restricts the variation in load and anti-icing valve position. Emission data are consequently limited to an output of 18 MW. The impact of component deterioration is higher as the output increases up to full load.

Emissions of carbon monoxides (CO), unburned hydrocarbons (UHC), and dinitrogen oxide (N_2O) have also been measured as a function of load. Except from UHC, emission components are measured by a nondispersive infrared sample conditioner train with electronic interference compensation for CO and CO_2. UHC were measured as proane-equivalence on wet basis with preheated equipment. The results, which are presented in Figs. 3–5, are in accordance with data previously published. Note that the scale varies on these figures to illustrate the curve trends better.

Performance Evaluation. In the evaluation of component deterioration effects on emission levels, the turbine performance is to be established. By using the existing condition monitoring system, all relevant parameters are detected. The accuracy of the emission measurements is directly related to the uncertainties of each analyzer. The uncertainties are shown in Table 4. In addition, some inaccuracy in measuring fuel gas consumption and

Table 4 Given uncertainties in analyzers used

Analyser	Uncertainty
NO	± 0.5 % of measured value *
UHC	± 1.0 % of measured area (0-10 ppm)
N_2O	≤ ± 2.0 % of measured area (0-100 ppm)
CO	≤ ± 2.0 % of measured value *
CO_2	≤ ± 2.0 % of measured value *
O_2	≤ ± 0.1 % of measured value *

* Actual measured value given in figure 1 - 5

Table 5 Measured and logged parameters during field tests

Parameters	Symbol	Unit
Operating hours		hr
Time, measurement starts	t1	hr, min
Time, measurement ends	t2	hr, min
Fuel gas analysis	(Compositional)	mole %
Fuel gas flow	m_F	kg/s
Lower heat value	H_n	MJ/kg
Emission data		
Oxygen	O_2	ppmv
Carbon monoxide	CO	ppmv
Carbon dioxide	CO_2	ppmv
Nitrogen oxides	NO	ppmv
Nitrogen dioxides	NO_2	ppmv
Dinitrogen oxides	N_2O	ppmv
Unburned hydrocarbons	UHC	ppmv
Turbine data		
Atmospheric pressure	P_0	mbar
Atmospheric temperature	T_0	°C
Relative humidity	Φ	%
Plenum air pressure	P_2	bar
Plenum air temperature	T_2	°C
Compressor disch. pressure	P_3	bar
Compressor disch. temperature	T_3	°C
PT turbine inlet pressure	P_6	bar
PT turbine inlet temperature	T_6	°C
PT turbine outlet pressure	P_7	barg
PT turbine outlet temperature	T_7	°C
PT turbine speed	TNL	rpm
HPT turbine speed	TNH	rpm
Anti-ice valve position		% open
Generator load	DW	MW

generator power (1–2 percent of measured value and $\leq \pm 0.2$ MW, respectively) must be considered.

Measured values and logged parameters are listed in Table 5. All values have been logged in three series, giving mean values representing the measurement period.

Emission Scaling

An interesting alternative to in-stack emission monitoring is to establish NO_x emissions by parametric monitoring. The challenge of this approach lies in testing and modeling emissions with respect to actual operating conditions and machinery degradation.

Several empirical and analytical emission models have been proposed in the literature to provide estimates of the exhaust emission of NO_x, CO, and unburned hydrocarbons. However, very few of the proposed emission models are used to perform continuous emission control at site conditions. Tuning the emission model to actual site and machinery conditions is therefore of great importance.

The objective of introducing parametric monitoring for emission control is to provide the offshore industry with a cost-effective methodology. Using the existing on-line condition monitoring system, all relevant parameters are made available, including machinery component degradation.

Emission Kinetics

Formation Mechanisms. NO_x is a term common for all nitrogen oxides, and is often represented as the sum of NO and NO_2, on weight basis. The formation of NO_x is mainly related to the thermal effects, which were first considered more than 20 years ago [5].

The concentration of important pollutants in exhaust is governed by the mean residence time in the combustion zone, the chemical reaction rates, and the mixing rates. Oxides of nitrogen are produced in the central hot region of the combustor by oxidation of atmospheric nitrogen, and most of the NO_x emitted in the exhaust is nitric oxide, NO. If fuel contains organically bound nitrogen, some of this nitrogen might form fuel NO. Particularly with fuel-rich flames, the oxidation of atmospheric nitrogen has been observed to produce prompt NO. The first three mechanisms describe the NO formation, while the last one describes the formation of NO_2.

Thermal NO. Referred to as the extended Zel'dovich mechanism, NO is formed by an oxidation of atmospheric nitrogen (N_2). The formation is very temperature dependent, i.e., a higher combustion temperature increases the NO_x formation. This mechanism is the main contributor to gas turbine NO_x formation:

$$O + N_2 = N + NO \quad (1)$$

$$N + O_2 = NO + O \quad (2)$$

$$N + OH \rightarrow NO + H \quad (3)$$

Due to its temperature sensitivity, the thermal NO is formed in the narrow region of the reaction zone. Several expressions for the rate of change of NO have been published. A representative one is given by [6]:

$$\delta[NO]/\delta t = 2AT^{\alpha}e^{-38440/T}[N_2][O_2] \ (\text{mole/cm}^3\ \text{s}) \quad (4)$$

The prompt mechanism. NO is formed as a reaction of hydrocarbon fragments and atmospheric nitrogen, which are subsequently oxidized to form NO. The prompt mechanism is less understood, but is formed in the reaction zone at the fuel side. The formation is much less temperature sensitive than thermal NO:

$$CH + N_2 \rightarrow HCN + N \quad (5)$$

$$N_2 + O_2 \rightarrow 2NO \quad (6)$$

Fuel nitric oxides. Organically bound nitrogen in the fuel oxidizes to NO. This mechanism is of less importance for combustion of natural gas, due to small amounts of nitrogen compounds in the fuel. The gross characteristics of the reaction mechanism can be represented as:

$$\text{Fuel N} >\!\!-\ \text{HCN} >\!\!-\ NH_i \begin{cases} + \text{oxidants} \rightarrow NO \\ + NO \rightarrow N_2 \end{cases} \quad (7)$$

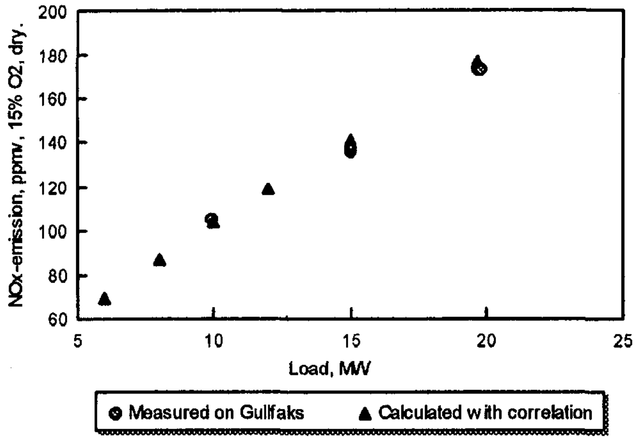

Fig. 6 NO_x emissions on Gullfaks

Oxidation of NO. NO_2 is formed by oxidation of NO, mainly by low temperatures:

$$NO + O \rightarrow NO_2 \qquad (8)$$

NO_x Emission Parameters. The objective of this project has been to establish the formation of NO_x emission from the GE-LM 2500 gas turbines, without utilizing, for instance, three-dimensional combustor performance codes, with mathematical expressions based on detailed chemical kinetics schemes. This approach necessitates detailed information regarding combustor geometry, for instance.

A correlation has been developed, based on the overall NO_x producing mechanism as described above. Proposed parameters should:

- describe the most important factors affecting NO_x formation, combustion temperature, and residence time
- include parameters that are sensitive to gas turbine site conditions, e.g., component degradation
- be available in the existing condition monitoring or process control system

In the evaluation of important scaling parameters, emphasis is put on describing the physical and chemical processes governing the pollutant formation on an overall scale. Component deterioration entails deviation in the normal pressure/temperature path through the gas turbine, which should be included in the parametric emission model. A numerical study was conducted to determine the separate effects of such parameters as system temperature and pressure, residence time, and fuel/air ratio. The following emission parameters are most important:

- compressor discharge pressure (p_3)
- fuel-to-air ratio (f)
- combustor discharge temperature (T_4)

Compressor Discharge Pressure, p_3. Combustor inlet condition is an important factor in the formation of NO_x. Increased combustor inlet temperature and pressure affects the adiabatic flame temperature, and thus the NO_x formation.

Through the 1970s and up to the present, several analyses have been performed on the effect of the combustor pressure. Increased combustor pressure affects the preheating of air to the combustor. The numerical study performed, and analyses made by others, conclude that pressure has a significant effect on the diffusion flame temperature. The emission measurements performed are all on gas turbines with diffusion flames. Related to component degradation, deviation in pressure and temperature profile along the gas turbine is important and the combustor pressure is therefore one major parameter in the formation of NO_x. Increased pressure also affects the mean residence time. Compressor discharge pressure is measured in the condition monitoring system.

Fuel-to-Air Ratio, f. The fuel/air ratio is defined as the fuel flow rate divided by the compressor discharge air flow rate ($f = m_{FG}/m_A$). The highest combustion temperature is achieved by stoichiometric combustion, that is, equal molar amounts of fuel and oxygen. An excess or shortage of oxygen lowers the combustion temperature, and the NO_x formation. This makes the fuel/air ratio an important factor in determining the NO_x formation and concentrations. In addition to influencing the temperature, the air flow rate also affects the mean residence time. An increase in air flow rate decreases the mean residence time, and thus the NO_x formation. The thermal NO residence time is a function of combustor diameter, air jet velocity, and stoichiometry in the primary zone.

The fuel flow rate, m_{FG}, is continuously measured in the condition monitoring system. The air flow rate is calculated by the relationship:

$$P_{PT} = [(m_A(1 - \zeta) + m_{FG})(h_6 - h_7)]/\eta_{PT} \qquad (9)$$

The enthalpies are calculated from power turbine pressures and temperatures. All the parameters are included in the condition monitoring system.

Combustor Discharge Temperature, T_4. The adiabatic flame temperature is an important parameter in the formation of NO_x. Combustor discharge temperature and pressure allow the discrimination between pressure effects and temperature effects. To reflect the combustion temperature, and include high-pressure turbine deterioration, the combustor discharge temperature is important. Combustor discharge temperature, T_4, is calculated from the thermodynamic relation:

$$T_4 = T_5(p_4/p_5)^{(\kappa-1)/\kappa\eta_{\mathrm{HPT}}} \qquad (10)$$

This relationship includes the high-pressure turbine efficiency, η_{HPT}, which reflects the turbine degradation. T_4 represents the combustion temperature and thereby NO_x formation better than compressor discharge temperature. The procedure includes, however, several measured parameters, which may to some extent affect the accuracy.

NO_x Correlation. Several empirical and analytical emission models have been proposed in the literature to provide estimates of the exhaust emission of NO_x, CO, and unburned hydrocarbons. The calculation procedure for most models is based on the concept that the concentration of various species is governed by reaction rate, mean residence time, and the mixing process.

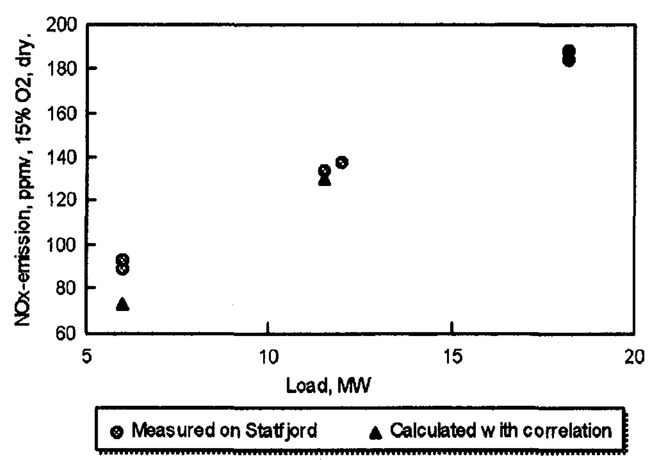

Fig. 7 NO_x emissions on Statfjord

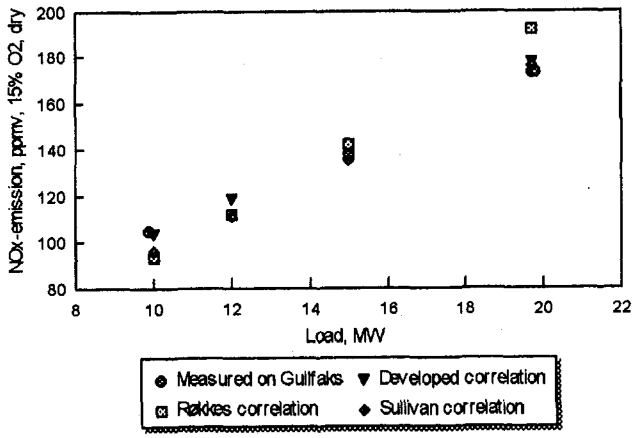

Fig. 8 NO_x emission calculated from different correlations

Dependent on purpose, the emission models are of different levels of fidelity. Improvement in prediction accuracy is made by emission models that combine analytical capabilities of three-dimensional combustor performance codes with mathematical expressions based on detailed chemical kinetics schemes. This approach necessitates detailed information regarding combustor geometry, for instance, giving a powerful tool in optimization of the combustor design to minimize pollutant formation and maintain satisfactory stability and performance.

For the purpose of on-line prediction of NO_x emission, the empirical approach has been used. In these models the effects of system pressure, temperature, and residence time account for the lack of rules in controlling the reactions (reaction term). The proposed correlation is given in Eq. (11):

$$NO_x = 62 * p_3^{0.5} * f^{1.4} * \exp(-635/T_4) \qquad (11)$$

Pressure is given in Pa, massflow in kg/s, and temperature in °C. The correlation has been developed from field measurements and simulated data at standard ambient conditions (T_0 = 15°C, p_0 = 1 bar, and ϕ_0 = 60 percent). Correlation factors and exponents are developed by a numerical parameter analysis.

NO_x emission predictions have been compared with field measurements on Gullfaks and Statfjord. The results are presented in Figs. 6 and 7.

The calculated NO_x emissions from the developed correlation give good agreement with the measured values. The deviation between calculated and measured values in the normally operated load area is approximately 2 percent. Two previously developed correlations have given good approximation to measured values. These are Sullivan [6] and Røkke et al. [7], which correlations are given in Eqs. (12) and (13), respectively. The proposed correlation by Sullivan:

$$NO_x = A_{NO_x} * p_3^{0.5} * f^{1.4} * m_A^{-0.22} * \exp(T_3/250) \qquad (12)$$

A_{NO_x} is a reference coefficient, p_3 is given in Pa, m_A in kg/s, and T_3 in Kelvin. Sullivan's correlation has been developed based on laboratory tests of heavy-duty gas turbines, and the result is given in ppmv, wet basis. In comparison with the other correlations, the calculated value from Sullivan's correlation has been recalculated into dry basis and 15 percent O_2. The proposed correlation by Røkke et al.:

$$NO_x = 18.1 * (p_3/p_2)^{1.42} * m_A^{0.3} * f^{0.72} \qquad (13)$$

Mass flow of air is given in kg/s and the result is given in ppmv, 15 percent O_2, dry. The correlation has been developed for smaller gas turbines, and has proven to correspond to measurements from some LM2500 PC machines.

A comparison between presented correlations and measured data from Gullfaks is given in Fig. 8. The figure shows that all correlations give fairly good representation of the data, whereas Røkke's correlation is more sensitive to load. The proposed correlation is specifically developed to include deterioration effects. To confirm this effect, different degradation scenarios have been analyzed. The proposed correlation is compared with Røkke's correlation in five scenarios:

1 No degradation
2 60 mm H_2O filter loss
3 5 percent reduction in compressor efficiency
4 5 percent reduction in high-pressure turbine efficiency
5 Combined degradation.

The result is given in Table 6, and the difference between best and worst case (scenarios 1 and 5) is illustrated in Fig. 9. The correlation given by Sullivan is not presented.

The analysis proves the developed correlation to be sensitive to degradation, a feature that will be useful for implementation and continuous calculation of NO_x emissions. Among the degradation types analyzed the correlation is more sensitive to reduction in high-pressure turbine efficiency. Figure 9 shows the relation between load and sensitivity to degradation on the NO_x formation.

Table 6 Effect of degradation on NO_x emissions

Correlation Load, MW	No degradation	Filter loss	5 % red. in η_C	5 % red. in η_{HP} turbine	Combined degr.
Developed	NO_x-emissions		(ppmv, 15 % O_2, dry)		
6 MW	61.4	62.5	76.3	77.7	103.9
11 MW	100.3	101.6	120.8	123.7	160.3
16 MW	136.5	138.3	159.4	163.5	209.1
22 MW	183.3	185.6	205.4	209.9	265
Røkke	NO_x-emissions		(ppmv, 15 % O_2, dry)		
6 MW	55.1	56	55.9	55.9	59.9
11 MW	99.9	101.4	101	100.8	107.5
16 MW	149.1	151.2	150.1	149.8	159.3
22 MW	215.7	218.8	215.3	214.8	228.1

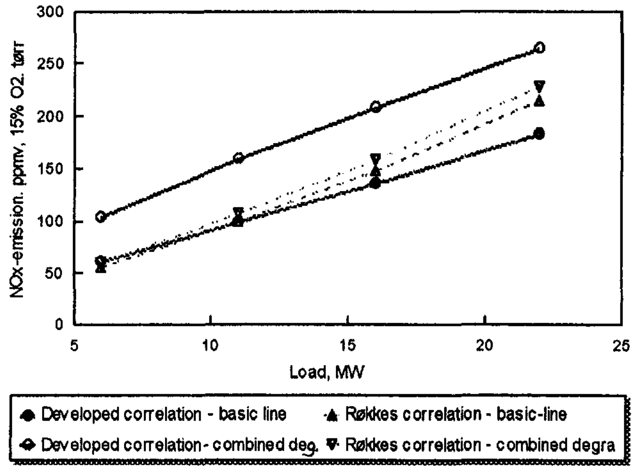

Fig. 9 Illustration of sensitivity to degradation for two NO_x correlations

Implementation. Several empirical and analytical emission models have been proposed in the literature to provide estimates of the exhaust emission of NO_x, CO, and unburned hydrocarbons. However, very few of the proposed emission models are used to perform continuous emission control at site conditions. Tuning the emission model to actual site and machinery conditions is therefore of great importance.

The objective of introducing parametric monitoring for emission control is to provide the offshore industry with a cost-effective methodology. Using the existing on-line condition monitoring system, all relevant parameters are made available, including machinery component degradation.

The proposed correlation is implemented in the condition monitoring system on Sleipner A. The "principle" of parametric emission monitoring will be extensively verified by control measurements on the Sleipner A installation. A total of 150 MW is installed, representing several gas turbines to be evaluated.

The method should be verified by extensively testing a number of gas turbine prime mover types. It is important to evaluate field instrumentation requirements and test procedures, including base line emission maps for the individual machine.

The development has required working closely with the Norwegian authorities to ensure possible acceptance of the method. A final approval is intended to be included in the National Act for Emissions to Air. In this respect, factors like component deterioration effects on NO_x emissions are to be verified.

Summary and Conclusions

Environmental regulations represent an important consideration in energy production. At present, offshore gas turbines are operated, encouraging high thermal efficiency and low power consumption. High thermal efficiency normally demands operation close to full load, which may increase the emission of specific components. However, due to the introduction of taxes on certain emitted components, this philosophy might have to be revised.

Gas turbine component degradation has a great impact on total operating costs. The extra operating costs due to deterioration represent approximately NOK 4.3 million a year. In addition, deterioration causes higher firing temperature, which influences maintenance costs and intervals. The present CO_2 tax is an investment in running on high thermal efficiency and reducing power consumption by process optimization and limiting gas turbine deterioration.

In the future, the offshore oil and gas industry expects even higher taxes on pollution to the atmosphere. Increased tax levels on CO_2, combined with a new tax or maximum upper limit on NO_x, call for an even better optimization of energy conservation on existing offshore oil and gas production platforms. It can be concluded from the analysis that the introduction of an NO_x tax will influence the optimum gas turbine maintenance intervals. Operating philosophy will be affected by the actual tax level. For some specific operating conditions it might pay to run two gas turbine drivers at part load, compared with one at full load. Extra maintenance costs due to increased replacement of hot section components should be taken into consideration.

The analysis underlines the importance of keeping the gas turbine performance drop within a certain limit. Consequently, it is important to detect machinery condition, component degradation, and emission levels in a reliable manner.

NO_x emissions have been measured as a function of load and component degradation, and a correlation has been developed, based on the overall NO_x producing mechanism. In the evaluation of important scaling parameters, emphasis is put on describing the physical and chemical processes governing the pollutant formation on an overall scale. Component deterioration entails deviation in the normal pressure/temperature path through the gas turbine, which should be included in the parametric emission model. A numerical study was conducted to determine the separate effects of such parameters as system temperature and pressure, residence time, and fuel/air ratio. The following emission parameters are most important:

- compressor discharge pressure (p_3)
- fuel-to-air ratio (f)
- combustor discharge temperature (T_4)

Based on these parameters, a NO_x prediction model is proposed:

$$NO_x = 62 * p_3^{0.5} * f^{1.4} * \exp(-635/T_4) \tag{11}$$

The calculated NO_x emissions from the developed correlation give good agreement with the measured values. The deviation between calculated and measured values in the normally operated load area is approximately 2 percent.

The NO_x correlation is implemented in the condition monitoring system on the Sleipner A installation. This represents an interesting alternative to continuous in-stack emission monitoring, and provides the offshore industry with a cost-effective methodology for emission control. However, more rigorous testing of the proposed model will be required before it can become an alternative to in-stack emissions monitoring.

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