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THE POSITION OF GAS TURBINE POWER PLANTS WITH RESPECT TO THE EMISSION OF NITROGEN OXIDES BY FOSSIL-FUELED ENERGY INSTALLATIONS

Erwin Kaiser

Translation of "Die Stellung der Gasturbinenkraftwerke innerhalb der Stickoxidemission von Energieanlagen mit fossilen Brennstoffen," Energietechnik, Vol. 26, No. 3, 1976, pp. 132-134

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16. Abstract

The amount of nitrogen oxides introduced into the atmosphere by gas turbines is very significant in relation to the total amount of nitrogen-oxide emissions produced by chemical installations and combustion engines. Turbine manufacturers are therefore working to develop combustion chambers with sufficiently low nitrogen-oxide emission concentrations. Attention is given to aspects of nitrogen-oxide formation in gas turbines, the parameters which determine this formation, and suitable approaches to reducing nitrogen-oxide emissions.

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1. Introduction /132*

The low NO_x concentrations in gas turbine emissions (from 20 to 200 ppm) are among the lowest contained in industrial emissions and may at first sight seem negligible compared to the high concentrations released by chemical installations and combustion engines. However, the rates of NO_x emissions, in kilograms per hour, are quite high when compared to those of other combustion systems. For this reason gas turbine manufacturers are working to develop combustion chambers with sufficiently low NO_x emissions. These low concentrations must be taken into account in developmental programs for monitoring devices.

2. Emission Values

The top graph in Fig. 1 shows how low the NO_x emission concentrations of gas turbines are compared with engines and steam generators. But it is misleading to rank these systems purely in terms of concentration. Disregarding the special conditions of NO_x formation (e.g., flame temperature, mixture, residence time in primary zone), we may say the following: Combustion engines, steam generators and gas-turbine combustion chambers could be operated with the same fuel (fuel oil) and same air ratio $\lambda \approx 1$ ($\lambda = \dot{V}_L/\dot{V}_{Lmin}$). Unfortunately the gas temperature

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* Numbers in the margin indicate pagination in the foreign text.

cannot be exploited in the gas-turbine blading as it can in the discontinuously-operating combustion engine or the boiler tubes of the steam generator, because there is at present no material with adequate creep strength under high temperatures. Secondary air must therefore be introduced into the combustion chamber, with a resultant increase in the exhaust flow. The air ratio /133 in the primary zone (λ_{prim}), which is critical for NO_x formation, ranges from 1.1 to 2 at rated load, depending on the fuel, while the air ratio balanced over the whole combustion chamber λ_{tot} ranges from 4 to 8, depending on the turbine intake temperature required [11]. The exhaust volume per unit fuel quantity

$$v_e = a + b\lambda \tag{1}$$

(where a and b denote fuel characteristics) is thus larger for gas turbines than for engines and steam generators, so that small NO_x concentrations K mean considerable emissions.

Current regulations in the GDR [1] are based on the emission e (in kg/h), which is calculated from the concentration K (in mg/m^3) and the exhaust volume flow ($m_b \cdot v_e$):

$$e = K \cdot m_b \cdot v_e. \tag{2}$$

Because the references cited in Fig. 1 do not contain all information necessary for calculating the emission e, the NO_x concentrations K were related to fuel energy:

$$\frac{K \cdot v_e}{H_u} \text{ (in g } NO_x\text{/J)}. \tag{3}$$

(Allowable emissions are stated in this form in some countries [10, 12].) This value makes it possible to compare the different systems in terms of NO_x emissions (Fig. 1, bottom). It is of little use in the present case to relate the emission to the useful output (g NO_x/kWh), because the system-specific losses mask the combustion conditions of interest.[1]

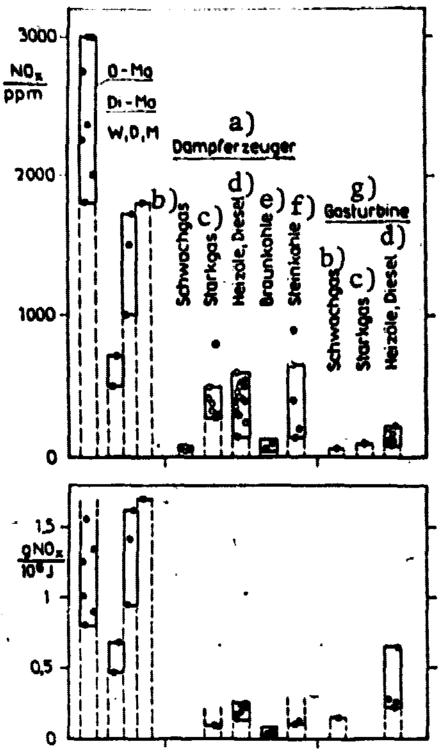

Fig. 1. NO_x concentrations at emission point at rated load without NO_x control measures (Otto engine [14, 15, etc.], diesel engine with divided combustion (W), direct fuel injection (D) and M process (M) [2], steam generator [3,5,7,13,16,etc.], gas turbine [4,9,10,etc.]) (top).
NO_x emission per unit fuel energy (bottom).

Key: a) Steam generator
b) Lean gas
c) Rich gas
d) Fuel oil, diesel
[Key cont. next page]

Fig. 1 shows that the NO_x emission of gas turbines per unit converted fuel energy can be higher than that of steam generators. This fact has led to requirements for higher allowable NO_x emissions for gas turbines than for steam generators [10]. On the other hand, gas turbines give rise to better dispersion conditions "at the stack" than do steam generators due to their higher exhaust flow; this is regarded as an effective increase in stack height in legal regulations [1].

Having quantified the NO_x emission of gas-turbine combustion chambers, we shall next discuss the possible means of reducing this emission.

Determining Factors

Factors critical for the formation of nitrogen oxides are the combustion temperature, temperature distribution and residence time in the primary zone of

1. Diesel engine: 4 to 16 g NO_x/kWh [2]; gas turbine systems: 2.5 [5], 2 to 7 g NO_x/kWh (measurements by Department of Measurement Technology).

[Key to Fig. 1, cont.]

e) Lignite
f) Anthracite
g) Gas turbine

the gas-turbine combustion chamber. These factors are dependent on the air excess, air intake temperature, fuel heating value, mass throughput and geometry. The NO_x concentrations generally attain a maximum near the combustion conditions which are energetically optimal: small air excess, high combustion temperature and minimal CO and smoke emissions. To be more precise, the maximum NO_x emission is not yet attained at the air ratio of the highest combustion temperature (e.g., $\lambda \approx 1$), but increases only as the oxygen supply is boosted, until the influence of decreasing temperature becomes predominant [12, 13]. The working range of gas-turbine combustion chambers is generally near the NO_x maximum; the NO_x levels decrease with decreasing turbine output or increasing air excess (Fig. 2). In contrast to steam generators, the NO_x emissions of gas turbines cannot be reduced by a constant small air excess, because in the simple systems considered here the air flow and the division into primary and secondary air are not subject to control. Reducing NO_x emissions by lowering the air intake temperature is not possible /134 in gas turbine systems without heat exchangers, the air intake temperature being determined by the compression ratio of the compressor.

The use of fuels with a low heating value, and thus a lower combustion temperature, leads to smaller NO_x concentrations (Fig. 2). Due to its high activation energy, free nitrogen in combustion gases (Fig. 1 and 2: lean gas 35% CH_4 in N_2) does not increase the production of NO_x; this occurs only when fuels with bound nitrogen are used [9, 12]. Even though the NO_x concentrations are often lower in gas-fired systems than in oil- and coal-fired systems [4, 5, 13], the type of fuel used is not the critical factor, but rather the local maximum combustion temperature, the residence time in these combustion zones, and the level of free oxygen.

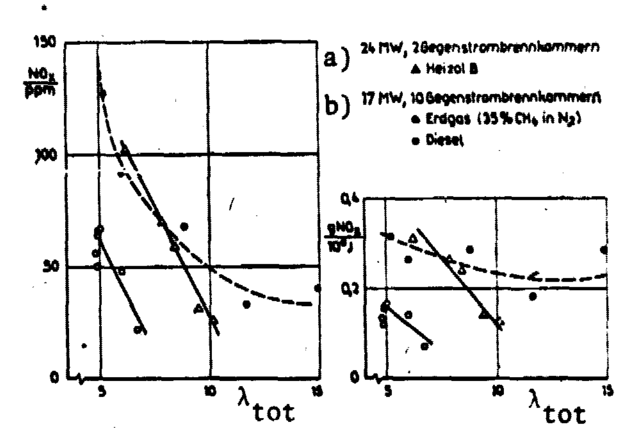

Fig. 2. NO_x concentrations, measured and per unit fuel energy, as a function of λ_{tot} of two gas turbine systems without heat exchangers. (Δ – modified Griess process; ● – titration and PDS process; o – titration process).

Key: a) 24 MW, two counterflow combustion chambers, Δ fuel oil B
b) 17 MW, 10 counterflow combustion chambers, o natural gas (35% CH_4 in N_2), ● diesel.

NO_x-limiting modifications in combustion conditions require corresponding system modifications in order to maintain satisfactory operating and energy parameters. It is known that low energy densities (i.e., the liberated fuel energy per unit combustion-chamber volume or cross-section) lead to small NO_x emissions [13]. Low energy densities require optimal mixing conditions, which are better achieved in small combustion chambers. It has been shown experimentally in [10] that the increase in NO_x with increased load which is typical of normal gas turbine combustion chambers can be corrected. By lowering the air excess in the primary zone and modifying recirculation, opposite or load-independent NO_x characteristics can be achieved. The increase in smoke emission as well as other partially-combusted exhaust components is acceptable in view of the high allowable values.

The exhaust recirculation and two-stage combustion employed in steam generators [3, 7, 12, 14] are less suitable for gas turbines. Exhaust recirculation is possible only within the combustion chamber due to the pressure level. We are unaware of studies on jet engines with afterburners or systems with high- and low-pressure combustion chambers employing the principle of two-stage combustion to reduce NO_x emissions.

NO_x reductions by 15 to 50% [5, 6, 10] by the injection of water or steam into the primary zone are of particular interest due to the associated increase in output, but previous experience indicates that NO_x reduction cannot be optimally combined with a power increase. The mixing zone has proved to be the most favorable site for power enhancement by the injection of steam into the combustion chamber [8], i.e. after the primary zone, thus having little effect on NO_x formation. The introduction of inert substances into the primary zone poses a formidible task in terms of control [6], because even small overloads will adversely affect the flame as well as CO and rust emissions, thereby limiting the increase in output. An optimized combustion chamber, i.e. one made low in NO_x at rated load by a small air excess in the primary zone, is preferable to a combustion chamber with hydroinjection [10]. The influence of natural fluctuations in air moisture content on the concentration of nitrogen oxides can be as high as 10%.

4. Summary

The NO_x concentrations in gas turbine systems are low compared to combustion engines and steam generators, but due to the large specific exhaust volume the emissions per unit fuel energy are as high as those of steam generators (Fig. 1). Whereas the contribution of NO_x to total toxicity is exceeded by SO_2 in lignite-fired steam generators, NO_x is the most significant combustion product of gas turbines fired by sulfur-bearing fuel. For a system with fuel oil B (Fig. 2), the emission ratio ($e/e_{allowable}$) for NO_x is 2.8 times higher than for

SO_2. The testing of NO_x-limiting measures has shown that the emission of NO_x can be curtailed even without additional apparatus by optimizing the primary zone.

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