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ABB´S ADVANCED EV BURNER - A DUAL FUEL DRY LOW NOx BURNER FOR STATIONARY GAS TURBINES

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ABSTRACT

A dual fuel burner has been developed to meet stringent NO_x goals without the use of water or steam injection. This combustion system is based on the proven ABB EV burner dry low NO_x technology and uses the same type of aerodynamic vortex breakdown flame stabilization. A more advanced aerodynamic design improves the quality of the fuel air mixture for both gaseous and liquid fuels. The design of the liquid fuel injection and the fuel-air-mixture preparation is described in this paper. Fuel air mixture homogeneity was improved with the help of experimental and numerical tools. This way an optimization in fuel atomizer design was possible. Distinct differences in fuel distribution were observed for different designs of pressure atomizers. Combustion tests of the burner were performed at pressures up to 20 bars. The NO_x levels measured under gas turbine full load conditions are <25 vppm using oil no. 2 and <10 vppm using natural gas. These results highlight the potential for achieving similar combustion low emission performance for gaseous and liquid fuels near perfect lean premix conditions.

Operating parameters and test results at part load conditions are discussed as well in this paper. The wide operating range of the burner in the full premix mode restricts the need for pilot application or burner staging to low load (<50 %) conditions. This allows for low emissions on NO_x, CO and UHC in the entire load range.

INTRODUCTION

The reduction of NO_x emissions from gas turbines (GT's) has become of increasing interest during the last decade. The main amount of the GT NO_x emissions are contributed by the thermal NO_x formation, the so-called Zeldovich mechanism. This NO_X contribution increases exponentially with temperature and with the square root of oxygen concentration in the reactant gas. Thus, reducing both the flame temperature and oxygen concentration constitute powerful measures for controlling the formation of thermal NO_X. The most effective way to lower NO_x is to minimize the peak temperature in the combustion zone. The simplest is water or steam injection into the reaction zone, which lowers the flame temperature, but leads to a decrease in overall efficiency. Therefore the dry low NO_x combustion is the preferred solution. In general three techniques of dry low NO_x combustion exist:

1. rich-lean staged combustion
2. lean premixed combustion
3. lean-lean staged combustion

In rich-lean staged combustion systems, the fuel bound nitrogen is converted into molecular nitrogen first. In the second stage, the final oxidation of the unburned fuel takes place. Rich-lean staged combustion is only of interest for particular fuels with a high amount of bound nitrogen, which is rather seldom for GT applications. Lean premixed combustion is very effective to reduce the flame temperature, since gas turbines are normally run in a very fuel-lean mode (with outlet O_2 at almost 15%). With this technique low NO_x emissions can only be achieved with "clean" fuel (i.e. without fuel bound nitrogen.). With lean-lean staged combustion systems, a further decrease in NO_x emissions is possible, but it requires a homogeneous mixture of fuel and air in both stages. The ABB GT family GT24/26 comprises the first implementation of this technique in combination with the highly efficient reheat cycle (Fig. 1).

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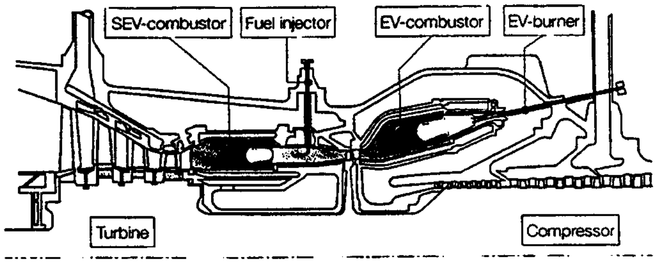

FIG. 1 LEAN-LEAN COMBUSTION IN COMBINATION WITH A REHEAT CYCLE - THE COMBUSTION SYSTEM OF ABB'S GT24/26

However, since the potential for further NO_x abatement of the lean premixed combustion (Fig. 2) is not used up so far in existing GT combustion systems, it is more effective for non reheat cycles to optimize the lean premixed combustion instead of elaboration of a staged systems.

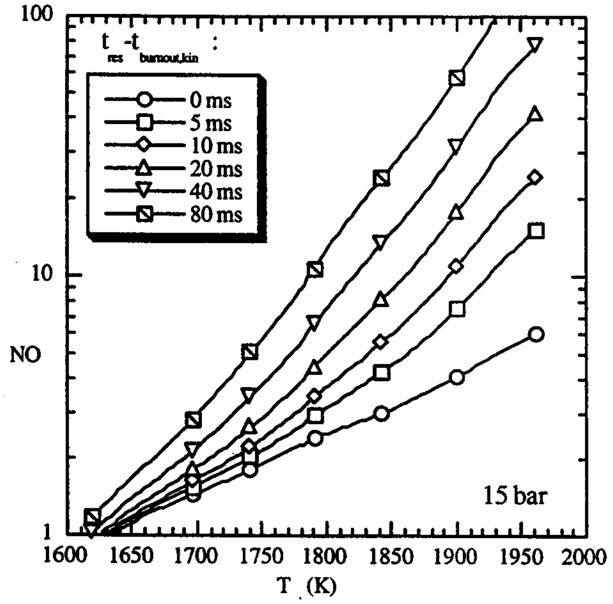

FIG. 2 NO-ABATEMENT POTENTIAL OF KINETICALLY CONTROLLED GAS TURBINE COMBUSTORS (SEE REF. 1)

Since 1984, when the first Dry-Low-NO_x combustor of ABB went into service, the combustor development program at ABB continued to make best use of the lean premixed combustion potential. An important step in that development was the introduction of the ABB EV-burner (see Ref. 2) which is now available for the entire ABB gas turbine family and offers Dry-Low-NO_x combustion of natural gas with less than 25 vppm (@ 15% O2). For liquid fuels the mixture preparation process is much more complicated than for gaseous fuels. Thus, water or steam injection is commonly used for NO_x emission control for liquid fuels. The goal of the advanced EV burner (AEV) program was to develop a burner capable of Dry-Low-NO_x combustion for gaseous and liquid fuels. Some fundamental aspects of lean premixed combustion are described next, followed by a description of the development process of the burner and the achieved high pressure test results.

LEAN PREMIXED COMBUSTION OF LIQUID FUEL

Liquid fuels are more difficult to mix homogeneously with air and hence to burn premixed than gaseous fuels, because the mixture preparation process consists of four coupled steps (Fig. 3). All these processes need to be controlled in a way so that a fully evaporated fuel air mixture is achieved by the time the reactants reach the flame front.

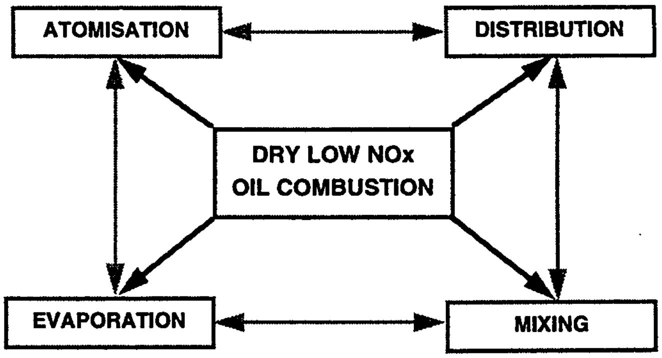

FIG. 3 THE ISSUES OF OIL MIXTURE PREPARATION IN LEAN PREMIX BURNERS

The macro scale fuel distribution is controlled by the penetration of the liquid fuel jet and the centrifugal forces acting on the non-evaporated fuel droplets in a swirling flow field. A dimensional analysis (see Ref. 3) of the penetration distance shows that for a given burner air flow field and injected fuel volume the penetration of a liquid jet is proportional to the square root of the injection pressure and to the drag coefficient of the jet, which is determined by the spray angle or shape. The quality of the liquid fuel atomization is of high importance because it controls mainly the time for evaporation under given operating conditions (d^2-law). In case of pressure fuel atomizers the Weber-similarity law indicates that the droplet size is inversely proportional to the injection pressure. Hence the injector design is of high importance for lean premixed oil combustion, because it influences the main mixture preparation processes. The final micro-scale gas phase mixing between gasified fuel and air is similar to the mixing of gaseous fuels and is highly dependent on the turbulence in the burner flow field.

Besides the homogeneity of the fuel air mixture, the flow field of the burner is of special importance. It has to provide a high flame stability as well as safety against flame flash back into the mixing zone. The velocity profiles at the exit of a conical swirler can be calculated with a simple analytical solution neglecting friction losses in a first approximation (see Ref. 2).

The radial profile of the axial velocity component u can be expressed as

$$u = U_0 \frac{\beta^2}{\beta^2 + r^2} , \qquad (1)$$

the corresponding tangential velocity component w as

$$w = U_0 \frac{\beta \cdot r}{\beta^2 + r^2} \qquad (2)$$

with the parameter

$$\beta = \frac{n \cdot b}{2 \cdot \pi \cdot \sin \gamma} \qquad (3)$$

where n is the number of air intake slots, b is the slotwidth, γ the half opening angle of the conical shells and U_0 is the maximum axial velocity on the centerline. Fig. 4 shows a comparison of the analytical solution and measured velocity profiles in the mixing section. The calculation with a 30% reduced real slot width (i.e. effective slot width, including friction losses) agrees well with the measured data which proves the applicability of the analytical frictionless solution for the AEV burner. The AEV burner - as the currently applied EV burner - relies on a vortex breakdown to secure proper flame stabilization. To achieve the vortex breakdown, the swirler has to be designed with the help of the above mentioned theory to give a proper flowfield.

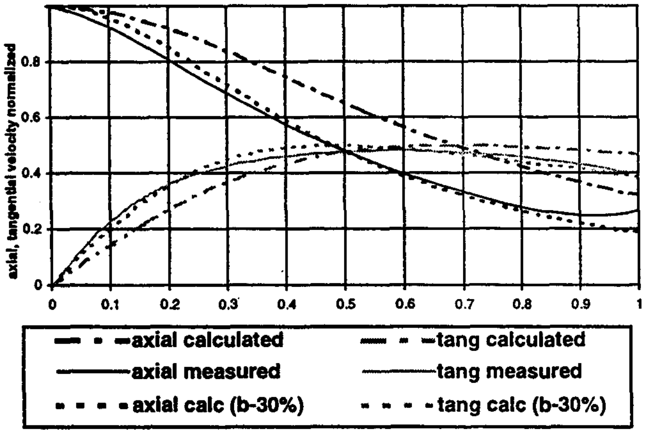

FIG. 4 COMPARISON OF THE ANALYTICAL SOLUTION OF THE AEV FLOW FIELD AND MEASURED VELOCITY PROFILES

For the AEV burner the swirler was optimized with special emphasis on liquid fuel application. By using four instead of two inlet slots, the distribution of the radial inlet flow is more even which makes the swirler completely safe against wall impingement of fuel droplets. The addition of a mixing tube allows for a longer evaporation time and for additional mixing in the gas phase.

From the axial and tangential velocity profiles shown in Fig. 5 one can tell that a jet like flow field with a distinct small body vortex core is rapidly formed within the conical swirl generator. At the exit of the swirler the maximum axial flow velocities on the centerline are in excess of 2 times the bulk velocity. This high velocity jet flow is maintained throughout the mixing tube thus providing high flashback safety. Even close to the mixing tube walls high axial velocities can be achieved by proper admission of small amounts (<10% of total air flow) of additional air (Fig. 6). In combination with the dilution effect of this air addition flashback along the mixing tube walls can be suppressed very effectively.

OIL MIXTURE PREPARATION IN THE AEV BURNER

Since liquid fuel atomization, penetration and evaporation are all heavily dependent on the surrounding atmosphere, it is difficult to find experimental techniques for investigations at real engine conditions. Numerical simulations are very helpful in this case, but due to the present state of models for two phase flow (especially concerning droplet disintegration and the evaporation of multicomponent fuels), they can not be used without experimental validation.

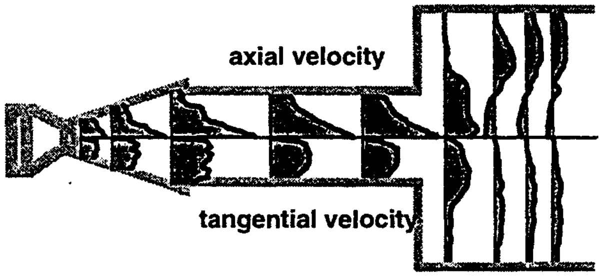

FIG. 5 AXIAL (TOP) AND TANGENTIAL (BOTTOM) VELOCITY PROFILES (DATA FROM WATER FLOW TESTS)

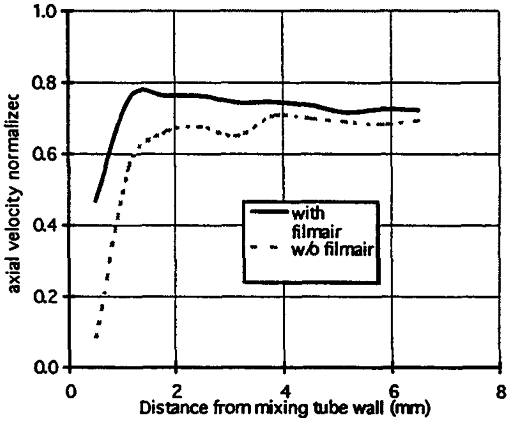

FIG. 6 NEAR WALL AXIAL VELOCITY PROFILES IN MIXING TUBE (DATA FROM WATER FLOW TESTS)

In order to gain better understanding of the fuel spray distribution in the high pressure burner air flow, a closed loop model test rig filled with SF_6 (Sulphurhexaflouride) high density gas has been used. SF_6 allows the simulation of gas phase densities up to 5 kg/m^3 at atmospheric conditions. Fig. 7 shows the experimental set-up of the test rig. With consideration of the aerodynamic similarity laws, Eq. (4) to (6) for droplets respectively sprays an accurate simulation of the spray distribution is possible.

Momentum Ratio Liquid/Gas .

$$\frac{\dot{I}_{liq}}{\dot{I}_{gas}} = const \tag{4}$$

Weber Number

$$We = \frac{\rho_{gas} \cdot D_{drop} \cdot v_{rel}^2}{\sigma} \tag{5}$$

Droplet Reynolds Number ($c_D = f(Re)$)

$$Re = \frac{\rho_{gas} \cdot D_{drop} \cdot v_{rel}}{\mu_{gas}} \tag{6}$$

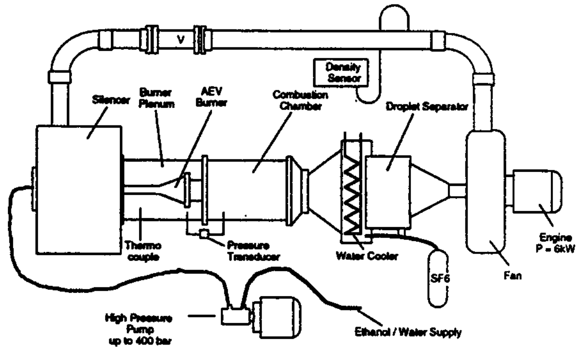

FIG. 7 CLOSED LOOP SPRAY DISTRIBUTION TEST RIG

With a laser light sheet and perspex models of the burner, the spray distribution in selected planes were observed. Using a CCD camera the laser light scattered by the droplets was recorded. Fig. 8 shows an example of the spray distribution with a central oil nozzle in the tip of the conical AEV swirler. The oil nozzle used was of simplex swirl type with 40° full spray cone angle. Although the scattered light intensity does not directly correlate with the fuel distribution, this technique gives insight into the fuel penetration and distribution. At the inlet slot, the turbulent mixing of air and liquid spray is visible. However, since the evaporation of the fuel is not simulated with these tests, the results are only valid for the near nozzle region and for moderate preheat temperatures.

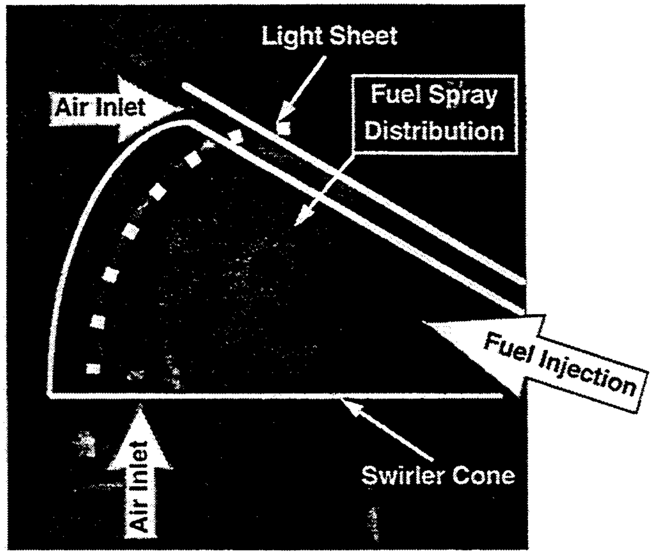

FIG. 8 SPRAY DISTRIBUTION IN THE AEV SWIRLER

To overcome this limitation, tests at real combustor conditions are necessary. Particle imaging using a laser light sheet indicated that it is very difficult to gain useful images of the spray distribution downstream of the swirler because of the rapid evaporation of the fuel. Other Laser techniques such as LIF to measure fuel concentration without deterioration of the burner flow are difficult to apply to fuel oils because of the wide band fluorescence of the fuel vapour. Therefore, a traversible sampling probe (Fig. 9) was chosen to determine the fuel vapour distribution inside the mixing section of the burner. Although this technique itself is well known in combustion applications, it has to be handled with care at gas turbine combustion conditions because it implies the risk of flame flashback due to distortions in the burner flow. Measured fuel profiles are valuable for the optimization of the fuel injector design. Fig. 10 shows an example for two different fuel nozzle designs, the fuel distribution in form of the equivalence ratio (Φ) over the normalised burner radius and the resulting NO$_x$-Emissions. It is clearly indicated that small areas with stoichiometric fuel/air ratio (Φ=1) lead to a significant increase in NO$_x$-Emissions.

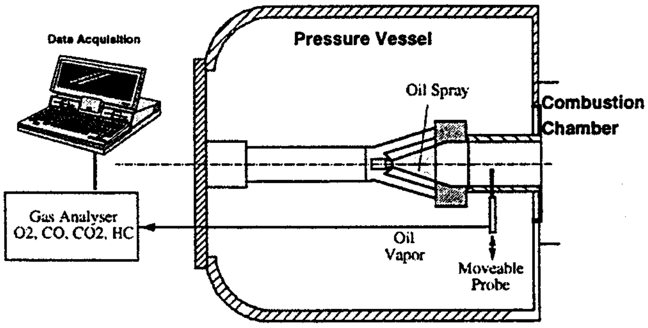

FIG. 9 APPLICATION OF THE FUEL VAPOUR PROBE IN THE AEV-BURNER

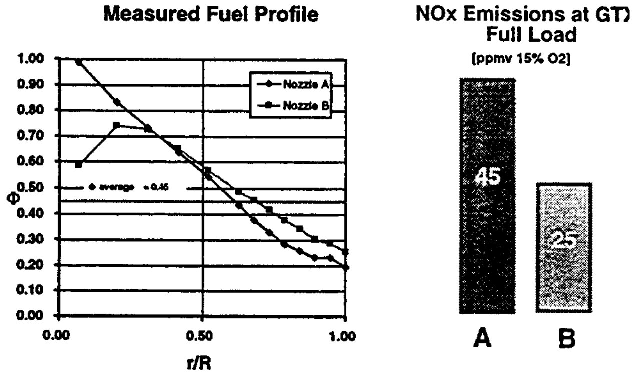

FIG. 10 COMPARISON OF MEASURED FUEL PROFILES AND NO_x-EMISSIONS

Although numerical simulations can not yet completely replace testing, they have been extensively used for the investigation of the liquid fuel preparation within the AEV burner.

The experimental set-up, the measurement technique and the details of the numerical model are given in Ref.4. The simulated velocity-diameter correlation's showed a good agreement with the measured data close to the nozzle, further away from the nozzle, where turbulent particle-gas phase flow interaction is important, the simulated velocity-diameter correlation deteriorated. The boundary conditions of the dispersed phase have a high importance for the accuracy of the numerical simulation. Droplet size and velocity distributions have to be given close to the nozzle exit in order to include the strong interaction between droplet and gas phase right from the origin of the spray (see Ref. 5). Of course this is in conflict with the problems of droplet sizing and velocity measurement in high density sprays.

An alternative strategy is the "calibration" of the numerical results by adjusting input parameters to measured fuel vapour profiles as given in Fig. 10. In combination with parameter studies this allows a preselection of relevant variants and thus reduces the number of expensive high pressure tests. As an example, the effect of droplet size is shown in Fig. 12. In this specific case the larger droplets appear to give a better fuel distribution. A comparison of CFD results with experimental data is included in the graph as well.

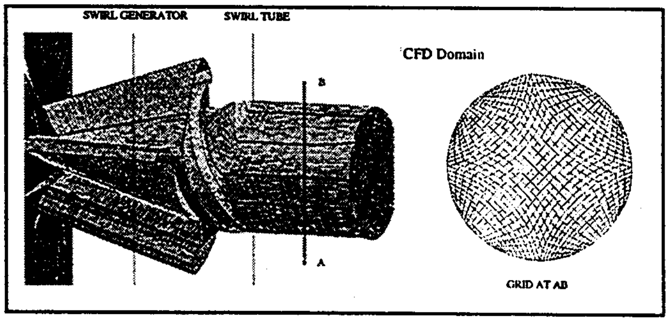

FIG. 11 COMPUTATIONAL DOMAIN AND GRID OF THE AEV

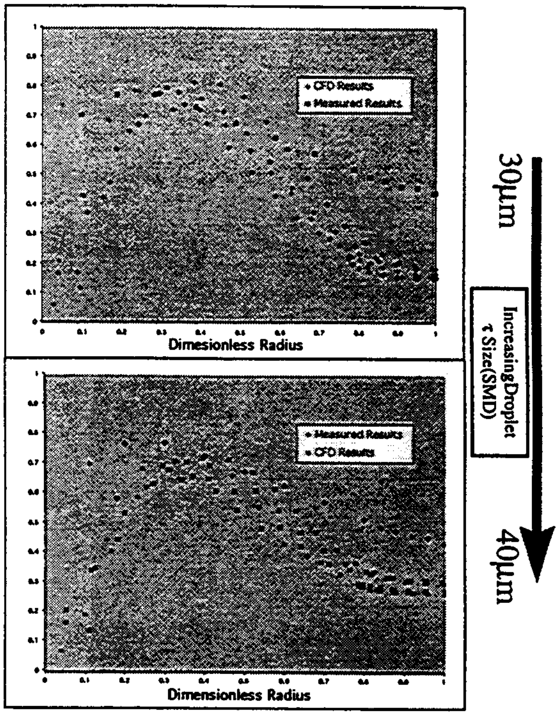

FIG. 12 CALCULATED AND MEASURED FUEL PROFILES IN THE BURNER MIXING SECTION

TESTING OF THE COMBUSTION PERFORMANCE UNDER HIGH PRESSURE CONDITIONS

The final high pressure tests were performed at the high pressure test facilities at the CIAM test centre near Moscow. A full scale (3.8 MW) convectively cooled single burner segment with the appropriate combustor geometry was used. The combustor was equipped with pressure, temperature and emission measurement probes. The burner was tested in the full operation range of the GTX 100 gas turbine. Fig. 13 shows the NO_x emissions under varying load conditions for liquid fuel (oil No. 2). The measured values are in the range of the emissions of natural gas (see Ref. 6), taking into account the offset due to the conversion of the fuel bound nitrogen in case of fuel oil combustion. With part load conditions included as well these results show the wide premix oil operation range of the AEV burner. Only for very low loads (< 25%) measures had to be taken to avoid flame extinction. Combustion oszillations which can excite pressure pulsations did not occur except close to the lean blow off limit. The ongoing development of the AEV burner does include the application of a wide range of liquid fuels with viscosities in the range from 0.5 to 8 mm^2/s at 20 °C. First tests with naphtha (0.5 mm^2/s) have already shown promising results with NO_x emissions <50 vppm at GTX full load conditions.

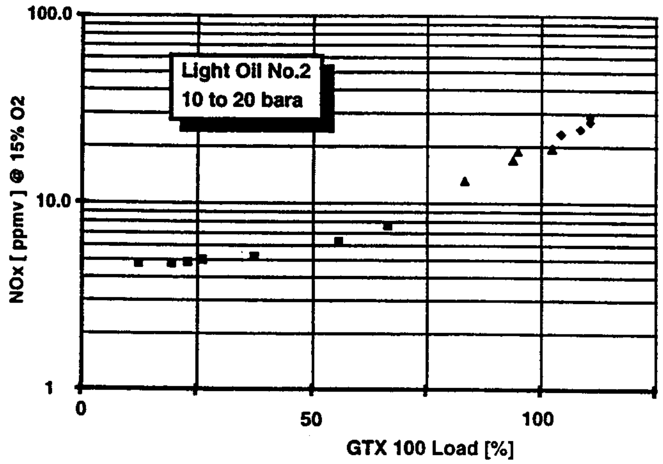

FIG. 13 NO_x EMISSION ON LIQUID FUEL (WITHOUT WATER INJECTION FOR NO_x CONTROL)

SUMMARY,

By the combination of elaborated aerodynamic tests and design methods, basic mixture preparation investigations and systematic application of experimental and numerical tools, a burner capable of premixed combustion for liquid fuels was designed. The results show that mixture preparation is mainly influenced by the fuel nozzle design.

The burner was extensively tested at GT conditions. NO_x emissions below 25 vppm on oil No. 2 were achieved for full load conditions. The high flame stability of the AEV burner allows for a operation in a premixed mode in a wide load range which in turn leads to very low emissions (CO and $NO_x < 10$ vppm) and a robust and simple fuel system.
First tests with a variety of different liquid fuels (oil #2, marine-diesel, Naphta) show the potential of the AEV burner design to be used for a wide range of fuels.

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