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ABSTRACT

MEASUREMENTS OF LOW LEVEL NO_x EMISSION FROM A CHENG CYCLE GAS TURBINE

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Mass steam injection into the combustor of a Cheng Cycle turbine can influence combustion characteristics and pollutant formation.

When using a Cheng Cycle system based on a Garrett 831 gas turbine liquid fuel, these influences were studied experimentally. Data obtained to date indicate that significant NO_x reduction can be achieved without suffering combustion inefficiency or instability.

INTRODUCTION

In recent years, the limitation of exhaust pollution from engines of all types has become a major concern, in order to preserve the quality of our environment. Legal limits have been established on the principal pollutants: nitrogen oxides, sulfur oxides, carbon monoxide, hydrocarbons, and particulates. These allowed limits will generally decrease in the future. At the same time, the increasing costs of fuel and the perceived future shortage of fuels has prompted both economic and legal requirements for better efficiency from our energy converters. Typically the requirements for reducing pollution are in conflict with the requirements for better fuel economy and efficiency; often the changes in operating conditions or designs which reduce pollution also reduce efficiency, and vice versa. However, the present paper presents evidence for one type of engine in which pollutant emission and fuel efficiency can be improved simultaneously; i.e. the Cheng Cycle combustion turbine.

For a combustion turbine NO_x is the major pollutant of concern, since hydrocarbon and particulate emission from gas turbines are generally well below acceptable environmental standards at present, and SO_x emission is also below such standards when fuels of reasonably sulfur-free quality are used. However, NO is rather efficiently formed by the oxidation of atmospheric nitrogen during the combustion process as analyzed by Zeldovich (Ref. 1). Gas turbine combustors have a turbulent diffusion flame and the combustion reaction occurs in a thin layer at nearly the stochiometric ratio at nearly adiabatic flame temperature. This temperature can be used to accurately estimate the NO_x formation rate. The usual methods of reducing NO_x formation: reducing flame temperature by running fuel rich or fuel lean, or injecting water or steam into the combustion zone, unfortunately also reduces efficiency. This paper, however, presents evidence that a gas turbine operated in the Cheng Cycle mode can reduce NO_x formation well below acceptable levels and at the same time increase the thermal efficiency significantly.

CHENG CYCLE ENGINES

The Cheng Cycle turbine was developed and patented by Dr. Dah Yu Cheng of International Power Technology, Inc. Details of the thermodynamics of the Cheng Cycle are given elsewhere in the the literature (Ref. 2) and only a brief summary will be provided here. Figure 1 shows a schematic diagram of the engine, a gas turbine with a dual-fluid working medium namely, hot gas, produced by the combustion of conventional hydrocarbon fuels mixed with superheated steam produced by waste heat recovery from the turbine exhaust. In other words, the Cheng Cycle is a parallel combination of a Brayton cycle, and a Rankine cycle. Such a combination of Rankine and Brayton cycles is unlike the "combined cycle" where the Brayton cycle turbine is supplemented by a Rankine cycle turbine.

Thermodynamic analysis of the Cheng Cycle (Ref. 2) shows that an optimum fuel-air-steam mixture exists where the efficiency of the system is maximum. Furthermore, the steam injected into the primary combustion zone reduces the flame temperature. Since nitrogen oxide formation is exponentically dependent on temperature (Ref. 1), a small amount of injected steam substantially reduces the NO_x produced.

EXPERIMENT

The experiments reported here were performed with a Garrett IE831-800 Gas Turbine, nominally rated at 500 Kw with peak power of 560 Kw, which was modified by International Power Technology, Inc. into a Cheng Cycle engine. A low-pressure, waste-heat boiler at the turbine exhaust (Fig. 1) provides the superheated steam. This boiler is an open cycle system using deionized tap water. The steam produced is injected into the compressor discharged air to promote rapid and uniform mixing before the mixture enters the combustion zone. Because of the nature of the reversed flow combustor, the steam/air mixture will first go in the dilluting zone, then the secondary combustion zones, and finally the primary zones. One needs to inject enough amounts of steam in the combustion zone for a reduction of NO_x but not exceedingly to influence combustion efficiency and instability. The geometry of the steam header and injection nozzles are as indicated in Figure 2.

Temperature and pressure sensors were placed at several locations in the Cheng Cycle system, signals from these output from these sensors and a fuel flow transmitter all fed into a data processing system which recorded the data every 20 seconds while the system was running, and also automatically reduced the basic data to provide on site operational information such as heat rate, air to fuel ratio, and injected steam flow. In addition, the exhaust gases from the turbine were sampled by probes which traversed a 3 ft. by 3 ft. cross section of the exhaust stack located at the outlet of the waste heat boiler. The probes could be introduced to the stack flow from three different ports, and nine sample stations were chosen, distributed over the stack cross section as shown in Figure 3. Velocity distribution in the stack could also be measured using a pitot probe.

The test program had two primary objectives: (1) to characterize nitrogen oxide, carbon dioxide, oxygen, and sulfur dioxide emission and exhaust gas moisture content for the Cheng Cycle engine operating at various load conditions and steam injection rates, and (2) to study the influence of combustion efficiency by monitoring carbon monoxide and hydrocarbon emission efficiency. Load conditions and steam injection rates were varied to give 12 different test conditions. These are summarized in Table I.

Note that two runs each were performed at test conditions 500 Kw load and 76% steam injection, and again at 200 Kw load and 100% steam injection rate, giving a total of 14 test runs. One of the repeat runs at each of these conditions involved a full 9-point traverse of the stack cross section to determine both velocity and emission profiles across the stack. Although velocity varied somewhat across the duct, the pollutant emissions were found to be essentially constant at all points; therefore a single sampling point located at the centerline of the stack was deemed sufficient for all the other test runs.

Test data were collected jointly by personnel of the Department of Engineering Research of the Pacific Gas and Electric Company, and Research Scientists of International Power Technology Inc. The responsibility of the P.G.&E. team was to measure emission concentrations as a function of load and steam injection rates, along with stack gas moisture content, for each test condition. The responsibility of the IPT team was to provide an on-line computer to reduce and analyze the data automatically and to provide the operational information such as steam flow rate, fuel flow rate, air to fuel ratio, and heat rate for each test. All of the tests of Table I were conducted using No. 2 diesel oil, which has very low fuel-bonded nitrogen content (less than 0.2%). Thus it was assumed that all NO_x observed came from the fixation of atmospheric nitrogen.

SAMPLING AND ANALYSIS PROCEDURES

A fully equipped P.G.&E. gas test van was used for measurement of pollutants and water vapor in the turbine exhaust stack. The van included analyzers, strip chart recorder, and calibration gas cylinders. The instruments were calibrated at the beginning of each day using National Bureau of Standards traceable gas samples. The calibration was checked at approximately two hour intervals throughout the test runs. Pollutant concentration data were continuously recorded on the strip chart recorder. The analyzers used are listed in Table II.

A schematic of the gas sampling system used for the tests is shown in Figure 4. Three separate sample extraction probes were used:

1. A probe connected to the converter which measures NO_x concentration (that is both NO and NO_2. When this converter is bypassed, only NO concentration is measured.)
2. A probe sampling the remaining emission concentrations (O_2, CO, CO_2, SO_2 and hydrocarbons).
3. A probe sampling the water content.

All probes were of stainless steel. The sample lines were teflon tubing for probes 1) and 2) and plastic tubing for probe 3). Flue gas moisture was measured using the EPA Reference Method 4 (Ref. 3). The water vapor sampling system is shown in Figure 5; water in the stack gas was condensed and determined volumetrically by passing a known volume of stack gas through three Greenberg-Smith impingers. These moisture condensers (impingers) were all constructed of glass.

Pollution emission and velocity profiles over the stack cross section were measured for 2 of the 12 test conditions (see Table I). The velocity traverses were conducted using an S-type pitot tube, in accordance with EPA Reference Method 2 (Ref. 4).

RESULTS AND DISCUSSIONS

Table III summarizes the results of tests conducted on the Cheng Cycle engine. The emission and velocity profiles measured during Test 1 and Test 8 are given in Table IV. The profiles show that there was no stratification of any single pollutant in the duct and it was therefore assumed that all other tests had the same pattern.

Figure 6 shows the change in NO (calculated as lbs $NO_2/10^6$ BTU) as a function of load for no steam, 50% steam, and 100% steam injection. At 100% injection, all the steam produced by the heat recovery steam generator is injected back to the gas turbine. NO is compared rather than NO_x since the NO data were found to be more consistent; however the NO_x emissions never exceeded NO emissions by more than seven percent.

Without steam injection, the NO_2 emission per unit energy output increases with load in the usual way for the Garrett IE831 gas turbine (Ref. 5). At about 370 Kw load, the emission has reached the level proposed by the California Air Resources Board (CARB) for gas turbine engines, namely $.2\,\mu g$ NO_x/Joule output. In Cheng Cycle mode of operation, at 1/2 steam input of the NO_x emission is reduced to about 54% of this standard and is relatively independent of load. With full steam injection in the Cheng Cycle, the NO_x emission actually decreases with load, being 46% of the CARB standard at idle, and only 37% of this standard at more than 400 Kw output.

Steam and water injection have, of course, been used to reduce NO_x emission from gas turbines for a number of years now. Typical steam or water to fuel ratios used have been about 1.0. In the Cheng Cycle operation, steam to fuel ratio is, typically between 3 and 7. However, the steam actually reaching the primary combustion zone is about 10% - 15% of the total injected steam, which is the same order of steam as water heretofore used for NO_x control alone at rated power. Figure 7 shows that NO is reduced as the steam injection rate increases more or less independently of the load applied. The NO emission is given in ppm by volume normalized to 15% O_2 at ISO standard conditions. For comparison, the Federal EPA NO_x Regulations for Stationary Gas Turbines as of September 10, 1979 limit the output to 150 ppm for engines rated from 1000 to 10,000 shaft horsepower, and 75 ppm for engines rated over 10,000 shaft horsepower, and 75 ppm for engines rated over 10,000 shaft horsepower (without added allowances for increased efficiency and fuel bound nitrogen). One can see that even this small and therefore relatively inefficient engine can meet these standards for large engines if operated in the Cheng Cycle mode.

The output of the remaining pollutants (CO, CO_2, SO_2 and hydrocarbons) is seen in Table III to be relatively constant for the tests performed with No. 2 Diesel fuel: CO appears in concentrations of about 40-45 ppm, CO_2 about 2-3.5%, and SO_2 about 15-30 ppm, and negligible output of hydrocarbons. These are all well within acceptable levels under present EPA or CARB standards. The estimated level of uncertainty in gas sample analysis is about 5%, and the limit of hydrocarbon detection for the analyzer used was less than one ppm. The negligible increment of hydrocarbons indicates that combustion efficiency is not reduced of steam injection.

Along with emissions, flue gas moisture content was measured at each test condition. Figure 8 shows the results of these measurements. The uncertainty in these data is about 8%. The water content is roughly constant (about 3-4%) independent of load when no steam is added. As one expects, the water content increases as steam is injected and also increases with load in the Cheng Cycle mode of operation reaching about 17% at 420 Kw load with full steam injection.

Excess air as a function of load and steam injection rate is plotted in Figure 9. Air flow was actually about constant for all test points and the decrease in air to fuel ratio was primarily due to the change in fuel flow (see Table 3). The no steam injection case is typical of the amount of excess air used in gas turbines of this design. In the Cheng Cycle mode of operation, the engine operates with a somewhat greater amount of excess air for a given load because the steam fluid performs a sizeable fraction of the work and less fuel is needed (see Table 3).

The efficiency shown in Figure 10 is based on the heat rate of the system. Operation of the engine in the Cheng Cycle with full steam injection increases the efficiency about 2% independent of the load. Nominal efficiency at full load is about 19% for this type of turbine, at the 20 inch water column back pressure imposed by the boiler. At the Cheng Cycle mode of operation this value increases to about 24% at rated power.

CONCLUDING REMARKS

The tests described above show that the Cheng Cycle engine can reduce NO emission to very acceptable levels without suffering combustion in efficiency and in stability as shown by the fact that no hydrocarbons were measured and that CO production was minimal.

We believe that reducing NO_x formation without common penalty of combustion inefficiency and instability is to have an uniformly mixed steam/air mixture in the primary combustion zone. Otherwise local hot spots will occur in the combustion zone which will result in production of some NO_x as the case of water injection.

Acknowledgement:

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Table 1. Test Points

Steam Rate	Load (Kw)				
	Idle	200	300	450	500
0	X	X	X	X	
1/2	X	X	X		
Full	X	XX(1)	X		X

(1) A 9-point traverse determining velocity and emission profiles were conducted at these test conditions.

Table 2. Analyzers Used for Gaseous Analysis

Analyzer	Description	Rangers Used	Calibration Point
$NO-NO_x$	Teco 10 AR,	0-100 ppm	60 u ppm
	Chemilumi-nescent	0-250 ppm	
O_2	Teledyne 326 fuel cell	0-20%	Ambient
CO_2	Anarad 500 nondispersive infrared	0-20%	7.1%
CO	Horiba PIR 2000, nondispersive infrared	0-1000 ppm	292 ppm
SO_2	Western Research ultraviolet absorption	0-500 ppm	302 ppm
HC	Beckman 400 flame ionization detector	0-400 ppm	343 ppm

Table 3. Test Results Summary

BTU/KW-HR %vol PPMV %vol VOL

Test No.	(1) Load (KW)	Steam Rate (lb/s)	Fuel Flow (lb/min)	Exhaust (oF) Temp.	Heat Rate	Flue Gas Moisture Content	NOx	NO	O2	NO @15% O2	CO (ppm)	CO2 %	SO2 (ppm)	HC (ppm)
1	168	0.442	3.96	619	26031	-	-	26	18.6	66	45	2.1	16	4
2	168	0.442	3.96	619	26031	11.80	30	28	18.5	68	45	2.1	20	4
3	168	0.226	4.28	672	28135	7.80	43	41	18.4	98	45	2.3	20	negl
4	252	0.510	4.50	665	19818	13.30	35	33	18.2	72	45	2.4	20	negl
5	252	0.261	4.88	726	21538	9.50	52	50	17.9	99	40	2.6	20	negl
6	420	0.669	5.73	794	15067	17.10	39	39	17.2	62	45	3.1	25	negl
7	420	0.512	6.09	816	15993	14.50	57	57	17.5	98	40	3.2	20	negl
8	420	0.512	6.09	816	15993	-	-	57	17.6	102	40	3.2	18	negl
9	idle	0.286	2.90	516	-	7.90	26	25	19.5	103	40	1.6	12	negl
10	idle	0.146	3.10	549	-	5.60	32	31	19.4	122	35	1.6	12	negl
11	idle	0	3.32	586	-	3.10	41	40	19.2	136	40	1.8	15	2
12	168	0	4.69	728	30832	3.30	63	62	18.5	153	35	2.4	20	negl
13	252	0	5.43	804	23776	3.70	86	84	18.0	171	40	2.8	25	negl
14	-	0	-	-	-	-	-	-	-	-	-	-	-	-
15	378	0	6.64	927	17447	4.50	120	120	17.20	191	40	3.5	30	negl

(1) Based on steam flow from vortex shedding meter.

(2) Based on actual load.

Table 4. Emission and Velocity Profiles for Tests 1 and 8.

Table 4a. Test 1: 168Kw, 100% steam

Point No.*	No, ppm	O2, %	CO2, %	CO, ppm	SO2, ppm	HC, ppm
1a	25	18.7	2.1	45	16	4
1b	25	18.7	2.1	45	16	4
1c	25	18.7	2.1	45	16	4
2a	25	18.7	2.1	45	17	4
2b	26	18.7	2.1	45	17	4
2c	26	18.7	2.1	45	17	4
3a	26	18.7	2.1	45	17	4
3b	26	18.7	2.1	45	18	4
3c	27	18.7	2.1	45	19	4

Table 4b. Test 8: 420Kw, 76% steam

Point No.*	No, ppm	O2, %	CO2, %	CO, ppm	SO2, ppm	HC, ppm
1a	57	17.6	3.2	40	15	negl
1b	57	17.6	3.2	40	15	negl
1c	57	17.6	3.2	40	15	negl
2a	57	17.6	3.2	40	15	negl
2b	57	17.6	3.2	40	15	negl
2c	57	17.6	3.2	40	15	negl
3a	57	17.6	3.2	40	15	negl
3b	57	17.6	3.2	40	15	negl
3c	57	17.6	3.2	40	15	negl

*See Figure 3

Table 5. Water Content by Volume: Measured and Calculated.

Test	Measured	Calculated*
420 Kw, 100% Steam	17.1	15.7
Idle, 0% Steam	3.1	3.0

*Based on 75% relative humidity.

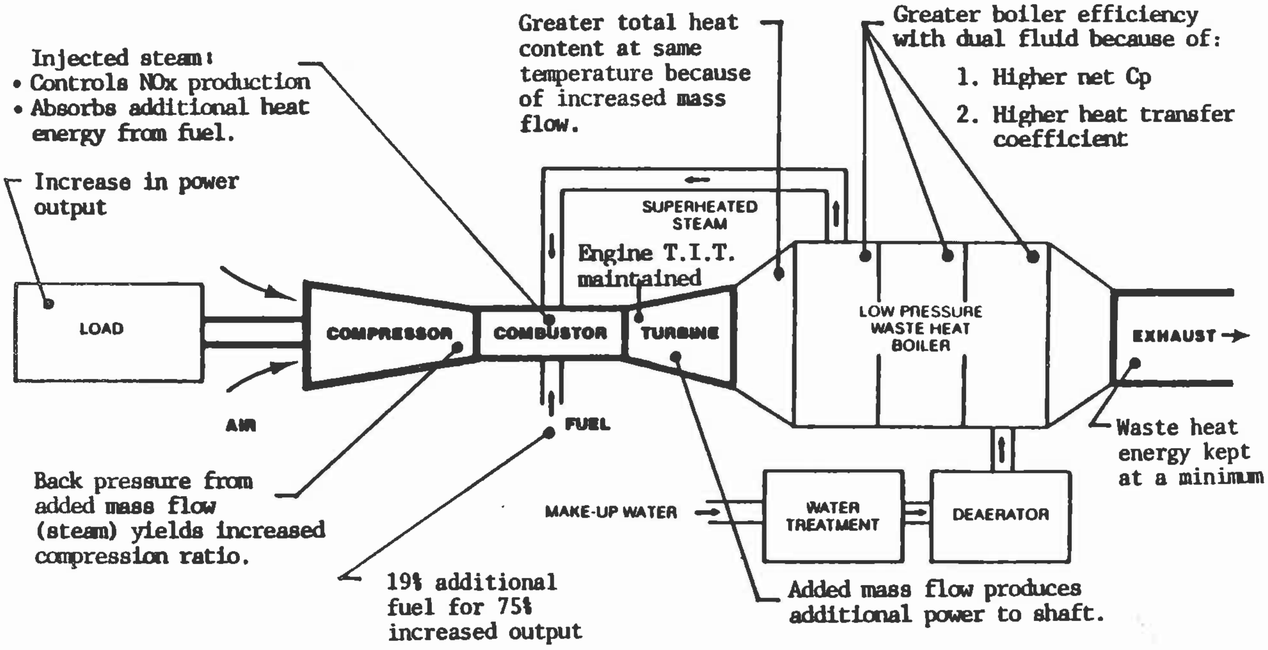

Figure 1. Cheng Cycle Engine Schematic.

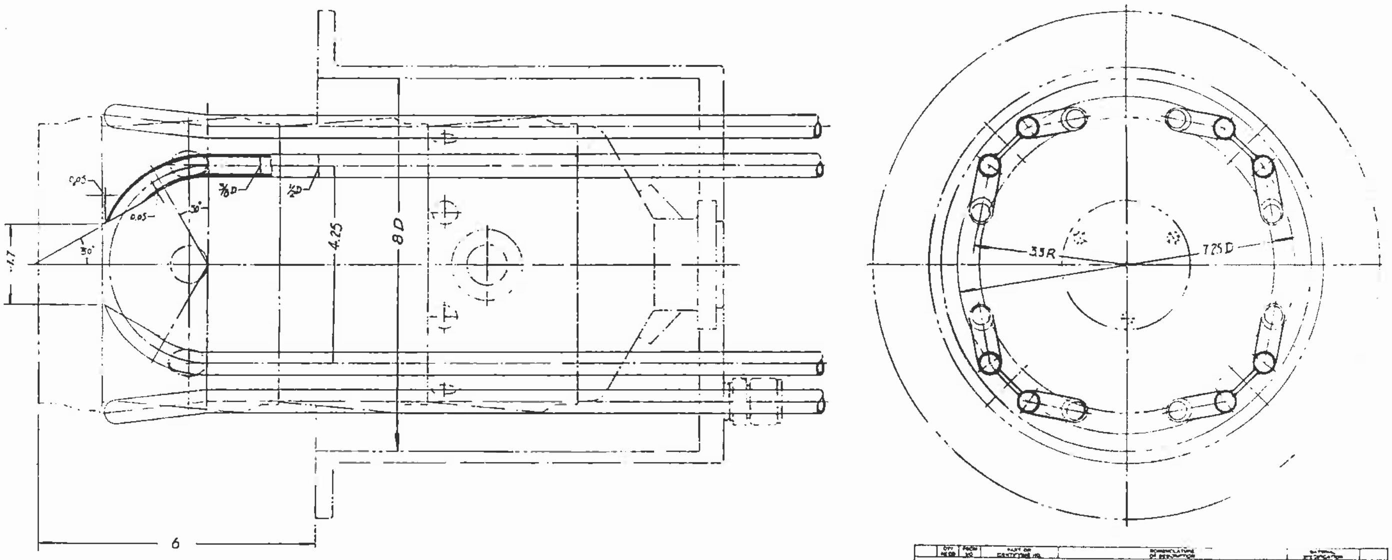

Figure 2. Steam Injection Arrangement.

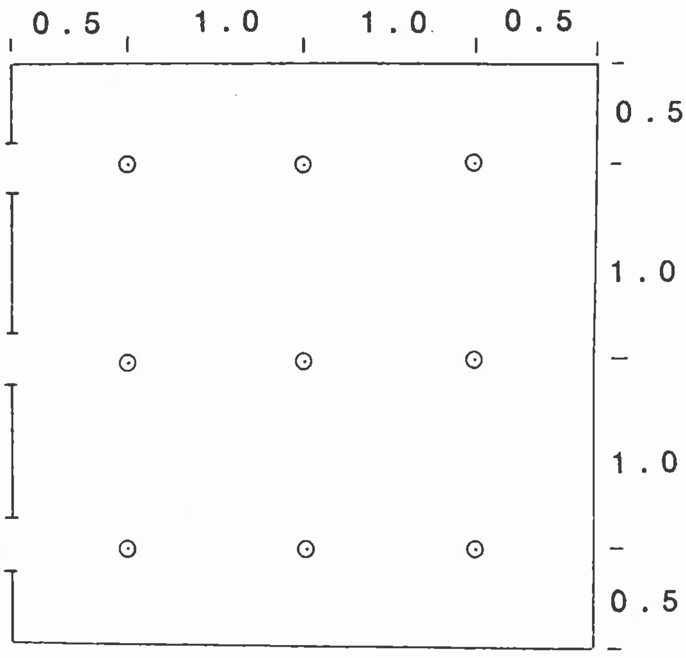

Figure 3. Sample Station Distribution in the Stack
(Dimensions in feet)

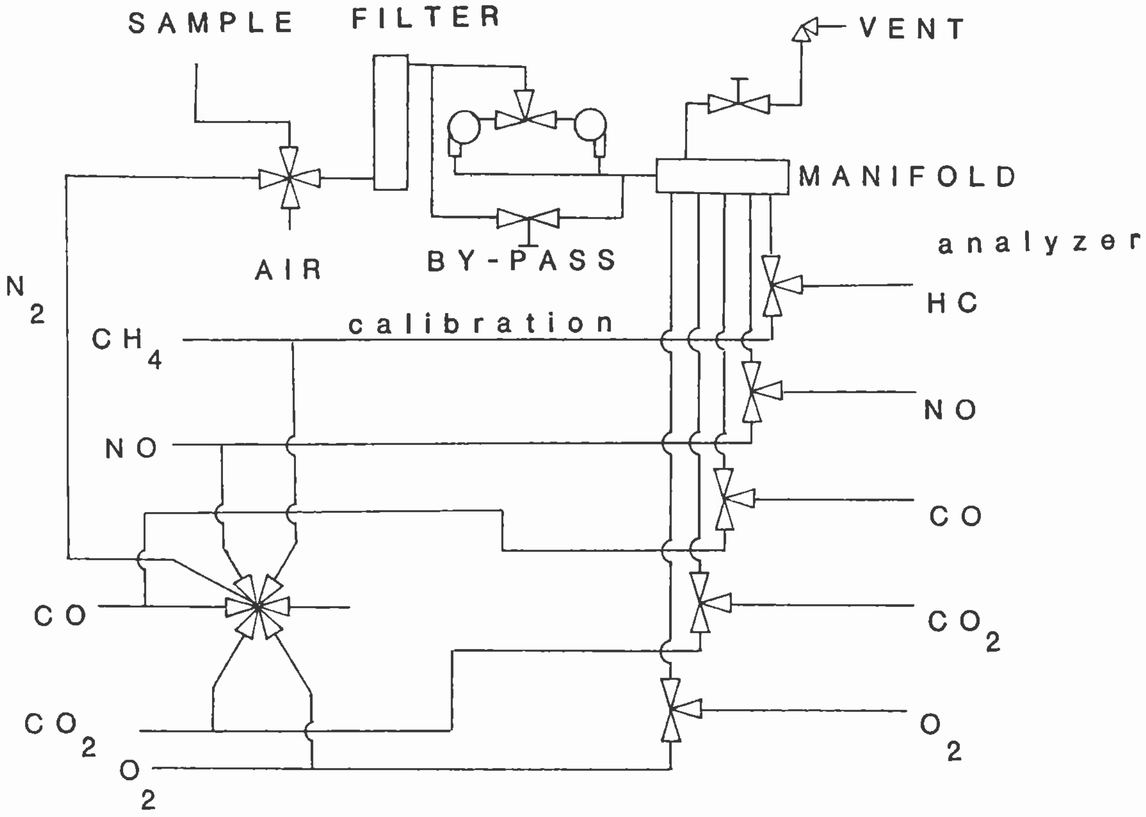

Figure 4. Gas Sampling Train

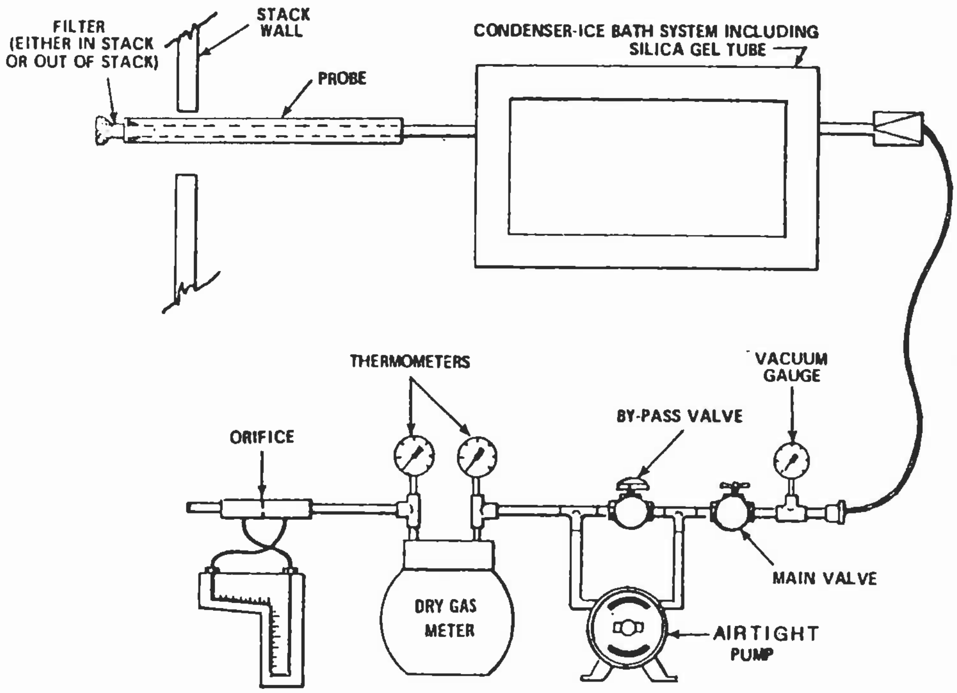

Figure 5. Moisture Sampling Train

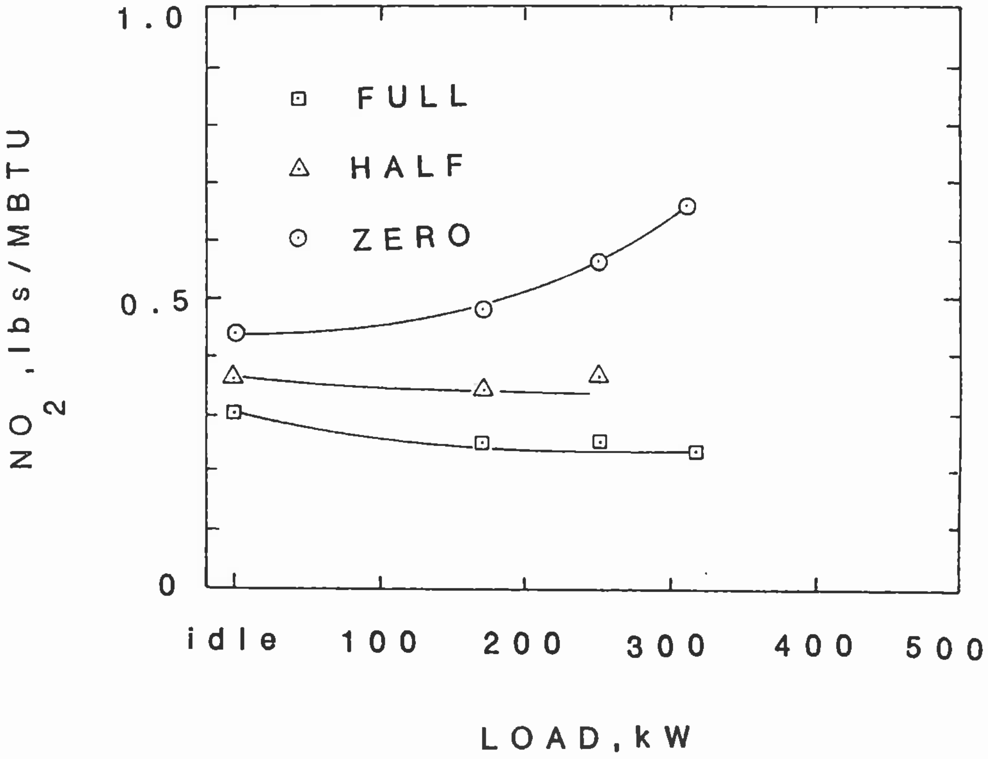

Figure 6. NO_2 Emission at Varied Total Steam/Fuel Radio

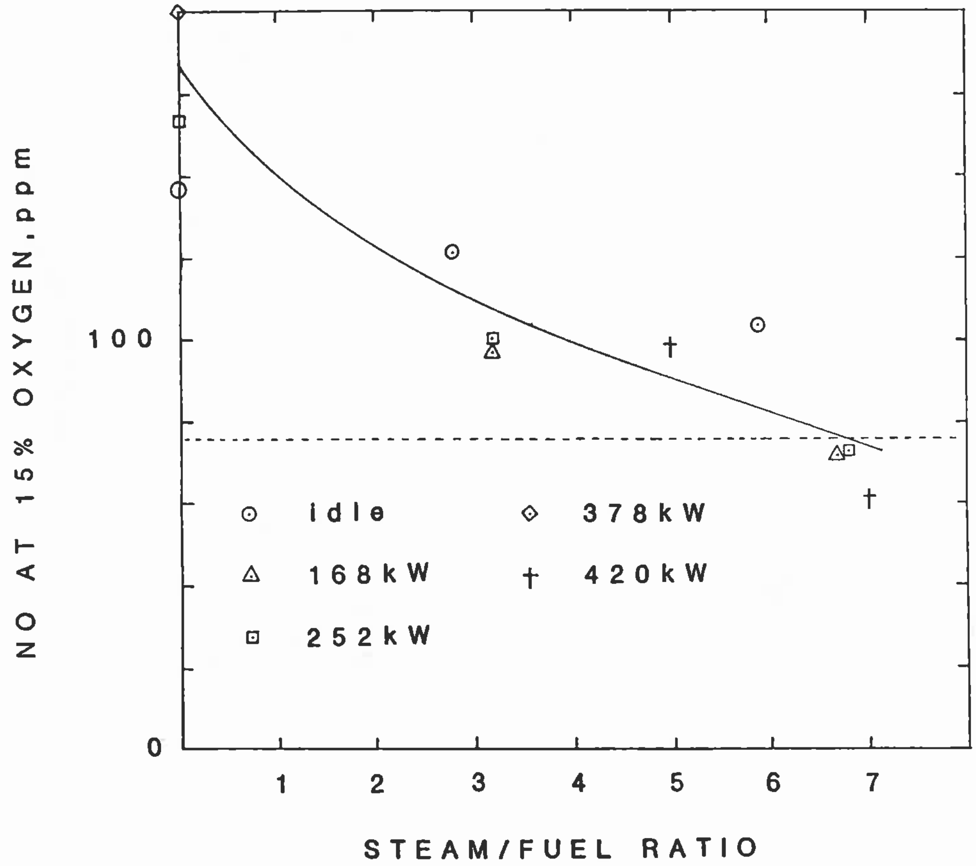

Figure 7. NO Emission at Varied Total Steam/Fuel Ratio

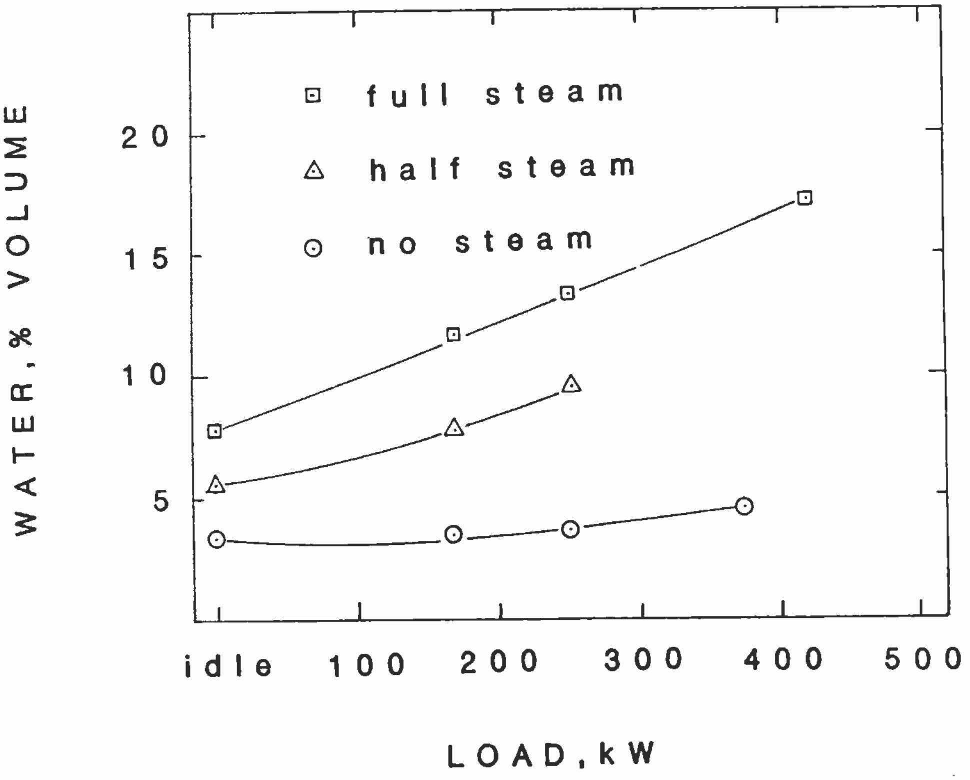

Figure 8. Moisture Content in a Cheng Cycle Turbine Exhaust

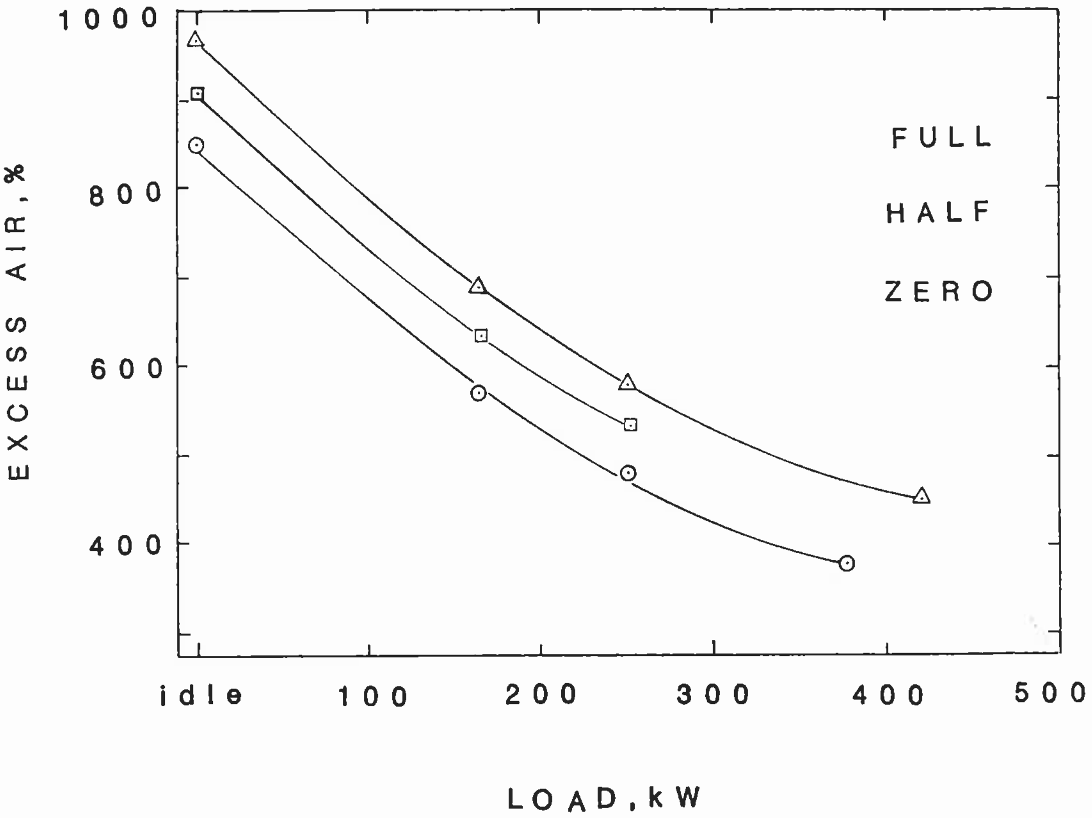

Figure 9. Excess Air in the Exhaust of a Cheng Cycle Turbine

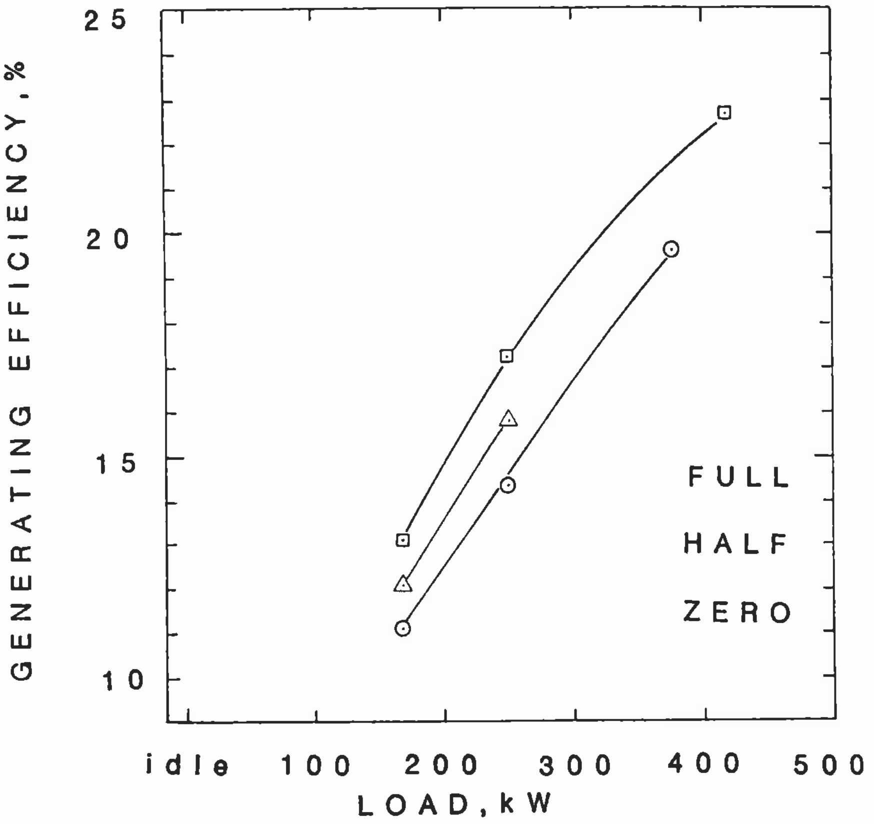

Figure 10. Generating Efficiency as the Function of the Load for a Cheng Cycle Turbine