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TESTING OF A SMALL COMBUSTION TURBINE BURNING REFORMED METHANOL

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ABSTRACT

As part of ongoing research into high-efficiency alcohol fuels utilization at the Solar Energy Research Institute, a gas combustion turbine was modified for use with reformed methanol and tested. The reforming process for this application uses waste engine heat to convert methanol and steam in the presence of a catalyst into hydrogen and carbon dioxide. We modified the standard combustor of a Garrett Model GTCP85-397 combustion turbine to burn the hydrogen and carbon dioxide mixture. Heat exchangers to boil and reform a methanol and water mixture were sized, purchased, and connected to the turbine exhaust. Instrumentation was added to monitor turbine temperatures, pressures, and exhaust emissions. Turbine performance and emissions were measured at various loads with a distillate fuel and compared with performance on reformed methanol. Reformed alcohol yields a significant improvement in efficiency because waste heat is reclaimed as chemical energy in the fuel. The larger mass flowrate of fuel to the combustor increases power output, and emissions are substantially reduced.

1. INTRODUCTION

As a part of ongoing research into high-efficiency alcohol fuels utilization at the Solar Energy Research Institute (SERI), the Fuel Utilization and Systems Engineering Group has undertaken the modification and testing of a combustion turbine for use with steam reformed methanol. The reforming process for this application uses waste engine heat to convert methanol and steam in the presence of a catalyst into hydrogen and carbon dioxide. A previous study by SERI and Westinghouse Electric Corp. states that there are several expected advantages to the use of reformed alcohol (Davies et al. 1983). First, waste engine heat is converted to chemical energy in the fuel, resulting in an overall increase in efficiency. Turbine power output is increased because greater fuel mass flowrates are required with reformed alcohol compared to distillate. Hydrogen has a low luminance flame resulting in potentially greater unit lifetimes and improved reliablity. Finally, NO_x emissions were predicted to be substantially lower than NO_x emissions from distillate fuels.

Methanol can be reformed to hydrogen and carbon monoxide or carbon dioxide by strongly endothermic reactions. The reactions occur at temperatures between 200° and 350°C in the presence of a catalyst. Heat in this temperature range is available in the exhaust of piston engines and combustion turbines. The increase in fuel heating value as a result of methanol reformation is shown in Table 1.

A system to take advantage of this reaction for automotive applications is described by Finegold et al. (1982) and for combustion turbine applications by Janes (1979).

2. SYSTEM DESCRIPTION

The process and instrumentation for the steam-reformed methanol combusion turbine experiment is shown in Figure 1. Exhaust from the turbine flows to the methanol-water boiler, to the reformer, or is bypassed. The methanol-water fuel mixture is filtered and then pumped into the boiler. From the boiler, vapor flows through a flow measurement orifice and then to the reformer. The

Table 1. Heating Value Increases Resulting from Methanol Reformation

Reaction	Increase in Lower Heating Value
$CH_3OH + heat \rightarrow 2H_2 + CO$	20%
$CH_3OH + H_2O + heat \rightarrow 3H_2 + CO_2$	15%

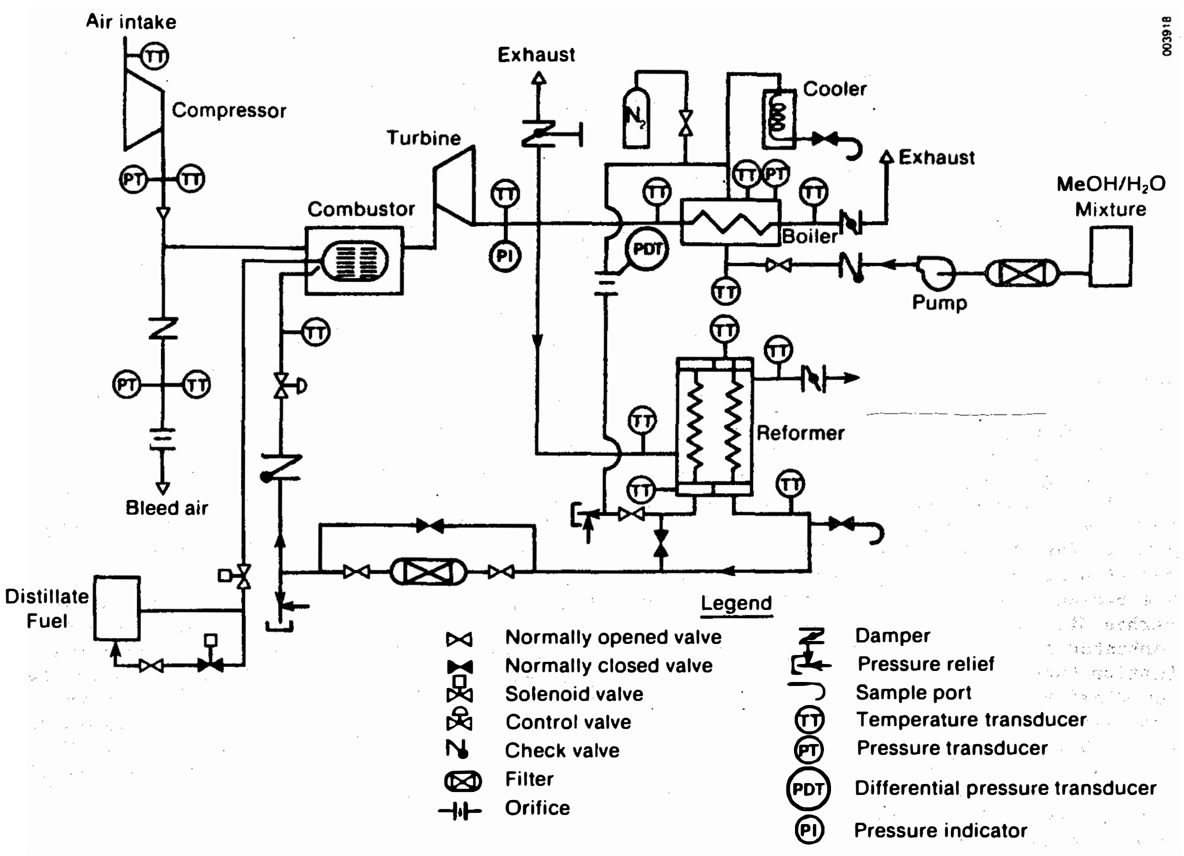

Figure 1. Steam-Reformed Methanol Combustion Turbine Process Diagram

reformer product gas is filtered on its way through a speed control valve to the combustor. There are two gas sampling ports in the system: one at the boiler exit, the other at the reformer exit. A nitrogen purge prevents catalyst oxidation after shutdown.

The turbine used for testing was a Garret Model GTCP85-397 combusion turbine, obtained on loan from the U.S. Air Force. This unit was designed to supply both pneumatic power, as heated compressed air from the compressor, and electrical power from a 60 kW AC generator connected to the shaft. The unit is rated at a total shaft output of 132 kW (177 hp) at standard temperature and pressure. At zero electrical output, the unit can supply 3402 kg/h (7500 lb/h) of heated bleed air at a pressure of 338 kPa (49 psia) and a minimum temperature of 177°C (355°F).

Instrumentation was installed on the turbine to monitor temperatures, pressures, and emissions. Several tests were then conducted to obtain baseline performance data with a distillate fuel. Baseline performance was characterized by plotting efficiency, exhaust temperature, and CO, and O_2 emissions as a function of These data also established design conditions, such as temperatures and fuel flowrates, needed to size and design the methanol reformation equipment.

Upon completion of baseline testing, work was begun on modifying the turbine and assembling the hardware needed to reform methanol. The combustor was modified to burn a gaseous fuel, and the distillate fuel system was modified to allow the transition to reformed methanol. Concurrently, heat exchangers to boil a methanol-water mixture and reform the vaporized mixture were purchased. The equipment was received and assembled at the test site.

The heat exchangers were mounted next to the turbine and turbine exhaust air routed to them with stainless steel piping. Dampers were placed at the heat exchanger exits and at a bypass to control the exhaust flow. Temperature controllers maintained boiler and reformer temperature. Turbine speed was measured with a magnetic sensor and input into a controller, which positioned a pneumatic control valve to maintain the desired turbine speed.

A summary of boiler specifications is given in Table 2. These specifications were sent to heat exchange vendors for bids. Thermxchanger Inc. of Oakland, Calif., supplied the heat exchanger. The heat exchanger is a shell-and-tube unit with turbine exhaust gas on the tube side and boiling occurring on the shell side in a kettle boiler configuration. The boiler tubes are 38.1-mm (1.5-in.) diameter 304 stainless steel. The shell is 0.61 m (24 in.) in diameter and is made of carbon steel. The total length of the heat exchanger is 2.44 m (96 in.). Boiler design pressure is 1380 kPa (200 psig).

Reformer specifications are shown in Table 3. The methanol reformer was also supplied by Thermxchanger Inc. It consists of a tube-and-shell heat exchanger, methanol vapor and steam flowing on the tube side, and turbine exhaust on the shell side. The vertical tubes are 25.4 mm (1 in.) in diameter and are packed with catalyst pellets. The first pass through the reformer heats the methanol vapor and steam mixture to reaction temperatures. The first pass is 13 tubes in a co-flow configuration with the exhaust gas. The second pass, where the methanol is reformed, consists of 65 tubes and is in a counterflow configuration. The heat exchanger shell, tubes, and tube sheet are 304 stainless steel because of the maximum temperature of the turbine exhaust, which is 650°C (1200°F).

The catalyst used to reform the methanol vapor and steam mixture is a commercially available copper-zinc oxide on an alumina substrate, United Catalyst T2107. The catalyst pellets are 3.2-mm (1/8-in.) diameter, 3.2-mm (1/8-in.) long cyclinders.

More instrumentation was added to monitor boiler and reformer operating conditions, and a differential pressure meter was added at a fuel orifice to calculate the methanol flowrate. All pressure and temperature measurements were automated with a computer-controlled data acquisition system, which collected and averaged data obtained during an experimental distillate or reformed methanol run. Information on ambient conditions, loading, and fuel flowrate were recorded during a run for subsequent computer processing.

Table 2. Methanol-Water Boiler Specifications

	Exhaust Gas	Process Gas
Flowrate	2584 kg/h (5700 lb/h)	472 kg/h (1050 lb/h)
Pressure drop	1.73 kPa (0.25 psi)	--
Inlet temperature	643°C (1190°F)	159°C (318°F)
Heat duty	240 kW (821,000 Btu/h)	240 kW (821,000 Btu/h)

Table 3. Reformer Design Parameters

	Exhaust Gas	Process Gas
Flowrate	5284 kg/h (5700 lb/h)	472 kg/h (1050 lb/h)
Pressure drop	1.61 kPa (0.234 psi)	58.6 kPa (8.5 psi)
Inlet temperature	643°C (1190°F)	159°C (318°F)
Outlet temperature	383°C (721°F)	316°C (600°F)
Heat duty	226.2 kW (722,000 Btu/h)	226.2 kW (722,000 Btu/h)

During testing, problems encountered with the emissions equipment and turbine operation did not allow a complete set of data to be taken. However, enough data were gathered to adequately characterize turbine performance on reformed methanol.

3. RESULTS AND DISCUSSION

3.1 Turbine Performance

Turbine performance was characterized by plotting efficiency and exhaust temperature (corrected for ambient temperature) against turbine power output. The turbine power output was the sum of pneumatic power and electrical power. Efficiency versus power output is shown in Figure 2 for distillate and reformed methanol load points. The solid line

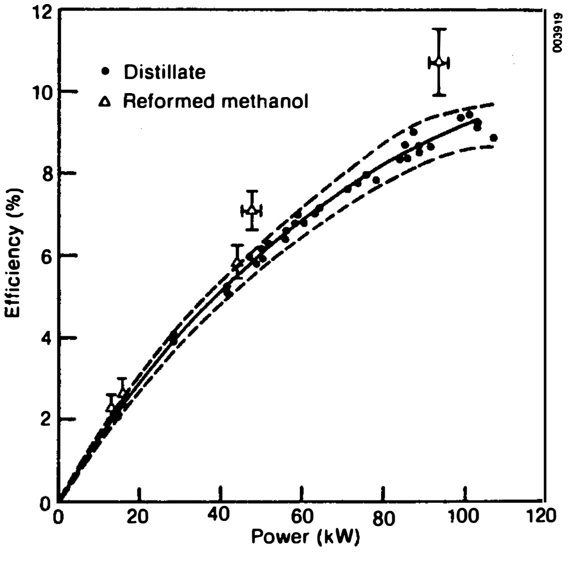

Figure 2. Efficiency versus Load for Distillate and Reformed Methanol

indicates the trend for distillate data, and the dashed lines show the maximum uncertainty (one standard deviation) associated with the distillate data. Thus all uncertainties associated with the distillate data are enclosed within the dashed lines. Reformed methanol efficiencies are shown, with their uncertainty indicated by the error bars. As expected, there was no significant improvement at low loads because of the extra load imposed by back pressure through the heat exchangers. However, at higher loads the fractional loading associated with back pressure decreased, and efficiency improved significantly--20% at 93 kW. The extra load placed on the turbine by back pressure can be estimated by observing the distillate fuel flow increase observed when all of the exhaust flow is transferred from the bypass to the reformer and boiler. The magnitude of the back pressure load was evaluted by obtaining a distillate fuel flowrate measurement when a constant 6.7 kPa (27 in. H_2O) of back pressure was applied at idle. This increased fuel flowrate to 55.4 kg/h compared with approximately 49.0 kg/h without back pressure. Typical back pressure was 3.7 kPa (15 in. H_2O).

3.1.1 Turbine Exhaust Temperatures

Figure 3 shows corrected turbine exhaust temperatures as a function of power. Since turbine exhaust temperature depends on the temperature of the air initially drawn into the compressor, the corrected exhaust temperature was reported as the turbine exhaust temperature minus compressor inlet temperature. This corrects the temperatures to a common reference for comparison at different ambient conditions. As expected, exhaust temperature increased with increasing load, independent of the type of loading.

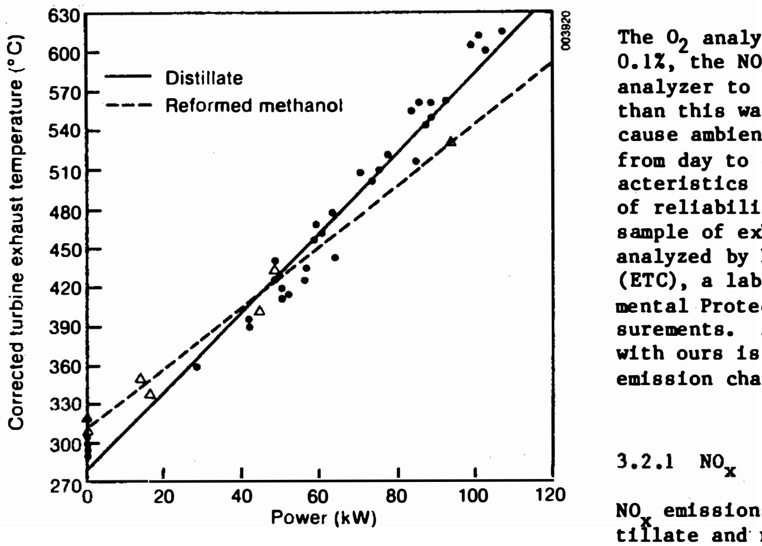

Figure 3. Corrected Exhaust Temperature versus Load for Distillate and Reformed Methanol

Straight lines have been drawn through exhaust temperature data for distillate and reformed methanol to analyze trends. At low loads, back pressure increases the exhaust temperature for reformed methanol. At higher loads, this back pressure load becomes insignificant, and the increased power output is evident for the same exhaust temperature. If the data are extrapolated to near the maximum exhaust temperature for this particular turbine, an 18% increase in power output would be achieved.

3.2 Emissions

Emissions were the most difficult measurements to obtain because problems were encountered trying to measure low turbine emissions. The emissions bench was originally set up to measure automotive emissions, which are typically greater than turbine emissions. Therefore, we added a low-range CO analyzer, but this analyzer was not available for all of the tests. Additionally, the NO_x analyzer developed a problem with NO to conversion; this problem was not until late into the testing.

The O_2 analyzer was typically accurate to 0.1%, the NO_x analyzer to 1 ppm, and the CO analyzer to 10 ppm. A much greater variance than this was seen between load points because ambient operating conditions changed from day to day and thus combustion characteristics changed. To determine the degree of reliability of our measurements, a bag sample of exhaust emissions was collected and analyzed by Environmental Testing Corporation (ETC), a laboratory certified by the Environmental Protection Agency for emission measurements. A comparison of ETC's results with ours is shown on the following plots of emission characteristics of the turbine.

3.2.1 NO_x

NO_x emissions as a function of load for distillate and reformed methanol are shown in Figure 4. The solid line shows the expected NO_x levels for this turbine as supplied by Garrett (Hasis 1982). The ETC analysis

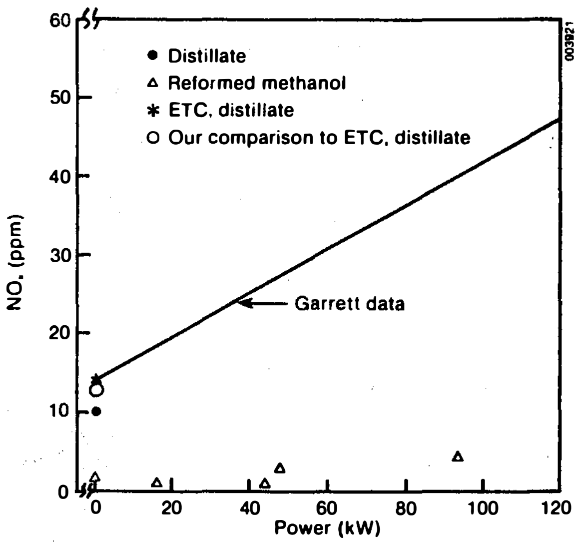

Figure 4. NO_x Emissions versus Load for Distillate and Reformed Methanol

showed an NO_x level at idle, burning distillate of 13.5 ppm; we measured 13 ppm. Because of this close agreement, we have confidence in the reported NO_x emission data shown in Figure 4.

As shown in Figure 4, the NO_x levels for reformed methanol were significantly lower than distillate NO_x levels. There is a sixfold decrease at idle and a tenfold decrease at 93 kW load. This confirmed our expectation of the ability of reformed methanol to significantly lower NO_x levels from gas turbines.

3.2.2 CO

CO emissions versus load are shown in Figure 5 for distillate and reformed methanol, as well as the ETC analysis. ETC obtained a CO emission of 620 ppm corrected to 15% O_2, and we obtained 580 ppm corrected to 15% O_2. Since the results agree within 7%, this also confirmed our CO emissions data. Note that two separate lines for each fuel are shown: one is for electrical loads only and the other is for bleed air load with or without electrical loads. Bleeding air from the compressor effectively increases CO concentration because less dilution air is added to the exhaust. We chose to represent this as two separate lines to clarify what is happening. As with NO_x, CO emissions were substantially reduced with reformed methanol.

3.2.3 O_2

O_2 emissions as a function of load for distillate and reformed methanol are shown in Figure 6. If the trend was analyzed, O_2 emissions were less at low loads and more at higher loads. This corresponds to the trend previously seen with turbine exhaust temperatures. Since exhaust temperature reflects fuel usage and thus oxygen consumed, the trend of O_2 emissions following exhaust temperatures is not unexpected.

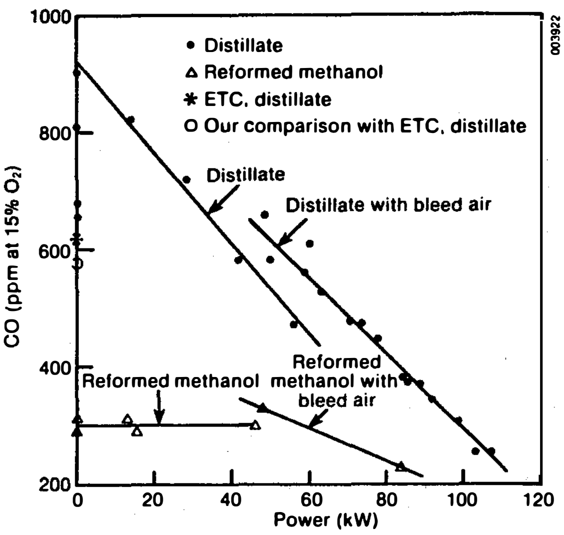

Figure 5. CO Emissions versus Load for Distillate and Reformed Methanol

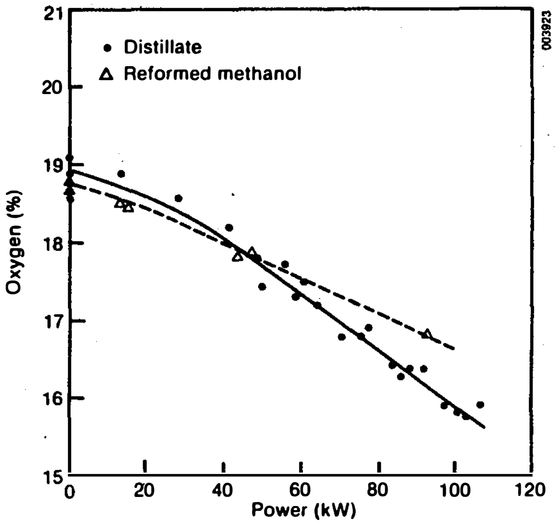

Figure 6. O_2 Emissions versus Load for Distillate and Reformed Methanol

Table 4. Reformer Analysis

Run No.	S/C[a]	Reformer Product Temperature (°C)	Load (kw)	Composition (%)[b]					Carbon Balance	Hydrogen Balance	Oxygen Balance
				H_2	CO	CO_2	H_2O	CH_3OH			
4R	1.42	208	0	--	--	--	--	--	--	--	--
5R	1.23	221	15.5	--	--	--	--	--	--	--	--
6R	1.62	229	43.5	60	0.8	20	19	0.7	0.94	1.00	1.02
7R	1.56	247	47.2	63	1.8	19	16	0.5	0.95	1.04	1.00
8R	1.44	300	93.4	--	--	--	--	--	--	--	--

[a] Steam-to-carbon molar ratio.

[b] Figures do not add up to 100% due to roundoff error.

3.3 Reformer Performance Analysis

Table 4 shows an analysis of reformer products and conditions, including the incoming steam-to-carbon ratio; the reformer gas exit temperature; load; sample composition; and atomic carbon (CB), hydrogen (HB), and oxygen (OB) balances. The reformed product analysis and atomic balances were performed in-house by techniques previously described (Finegold et al. 1983). The balances indicate accuracy of 94%-100% on the analysis of composition. Technical problems with collecting and analyzing samples did not allow all of the runs to be analyzed.

Examination of the two samples on which data were obtained shows good conversion of methanol to hydrogen as indicated by the low concentration of unreacted methanol, even though the reformer product temperature was not near the 300°C design point. The large concentration of water is expected, considering the large amount of excess steam being mixed with the methanol. This excess steam helped to significantly reduce the NO_x emissions from the turbine.

4. CONCLUSIONS

Although only a few reformed methanol data points have been obtained thus far, the significant improvements in efficiency and power are well documented. In all cases, the efficiencies of reformed methanol runs were greater than baseline distillate data, and in most cases significantly greater. The trend of exhaust temperatures confirmed that power improvements can be expected and are projected at 18% based on equal turbine outlet temperature. Both of these results confirmed the theoretical predictions of the Westinghouse study.

As expected, significant reductions in NO_x emissions were achieved, again confirming the prediction of the Westinghouse study. The surprisingly low results were verified by an independent EPA-certified laboratory. A reduction in CO emissions was also achieved, but this depends on the degree of reformation and amount of water in the fuel.

The experiment demonstrated that commercially available equipment and catalysts can be obtained to reform methanol for combustion turbine applications.

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