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APPLICATION OF AN INDUSTRIAL GAS TURBINE FOR COGENERATION AND PROCESS SERVICES

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ABSTRACT

The gas turbine is not limited to single service applications such as power generation or mechanical drive service. An application has been developed recently to use an industrial gas turbine to drive an electric generator for power while at the same time contributing to the heat balance of a refinery unit. Specifically, a G. E. Frame 5 gas turbine installed with a hydrogen reformer furnace can significantly reduce the overall heat input required by capturing the waste heat in the exhaust gas to preheat the feed to the furnace and to generate high pressure steam for the owner's refinery steam system.

The gas turbine selected for the projects described in this paper is the G.E. Frame 5, model "R" (5271 RA). The model "R" was originally described as a "single shaft mechanical drive" turbine but easily adapted to generator drive. The design is some 30 years old as it was developed in the 1960's. The term "single shaft mechanical drive" is somewhat strange to us in the process industries as we're more accustomed to mechanical drive gas turbines designed with two shafts for speed control purposes. Many of the design / construction features of this model make it ideally suited for this application.

The higher cost of fuels, and electrical power contribute significantly to making the economics attractive. First of all the heat of the turbine exhaust gas will reduce the fuel required for firing to heat the feed to the furnace. The steam generated in the heat recovery section then contributes to generating power in the steam side in the steam turbine. The results are fuel savings and electric power purchase savings.

The steam turbine portion of the cycle is designed to vary with the owner's steam system and balance. For that reason the steam turbine includes a high pressure inlet, medium pressure steam chest for extraction, a low pressure steam chest designed for induction or extraction and a surface condenser to condense the steam passed through.

Fuel flexibility is a major consideration of the unit design. Natural gas or methane rich gas is a base fuel that the gas turbine will fire most of the time. Alternate fuels however, such as propane or butane are commonly available in a refinery and could be fired in the gas turbine as currently configured.

INTRODUCTION

A gas turbine train can be added to a hydrogen reforming process unit in order to improve cycle efficiency and as an integral part of the process. In addition heat recovery features are used to produce steam. The gas turbine and steam turbine both drive electrical generators to generate electrical power for the owner's power needs. The gas turbine exhausts into a hydrogen reformer furnace to heat the feed. The available oxygen is utilized for supplemental firing in the heat recovery section. The overall energy consumption of the unit is subsequently reduced. A heat recovery section generates steam, fed to a condensing steam turbine creating a cogeneration cycle. The gas turbine generator and steam turbine generator portion is an enhancement to the "basic" hydrotreater, and new to refinery operations in the configuration described in this paper. Many refineries have cogeneration facilities, most of which are "stand alone" type.

As stated above the gas turbine utilized is a Frame 5, model M5271, "RA," single shaft mechanical drive turbine, but modified for generator drive. (Normally, a mechanical drive gas turbine is a two shaft turbine which made this unit an anomaly to begin with but more suited to generator drive.) It is also arranged for fuel flexibility to handle refinery gas, natural gas, and LPG type fuels such as butane and propane. Control of air (mass) flow-at varying ambient temperature through the gas turbine-is critical to maintain constant heat balance. In order to accommodate this requirement, for the hydrogen process, variable inlet guide vanes are incorporated on the inlet to the air compression section. The variable inlet guide vane design is a key feature of the Model "R" unit and make it ideally suited for this application.

Fuel selection becomes a function of availability and preference of the owner. Since the project / process is an integral part of a refinery almost any fuel is actually available from "refinery off gas" (gas produced in the refining process) to diesel oil, LPG, etc. For the projects recently designed, which this paper is based on, the gas turbine and reforming furnace were designed to fire natural gas and LPG. The alternate fuel is important to provide flexibility for the owner.

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THE PROCESS

In a refinery, the hydrogen reforming "process" (furnace, stack, induced draft fan) is either custom designed or purchased as a unit separately and functions only to generate hydrogen at some 80 to 100 psig pressure at a high purity which exceeds 99%. In this stand alone process the feed (usually natural gas, refinery gas, etc.) must be heated in the furnace. In the arrangement depicted in this paper the exhaust gas from the gas turbine provides much of the heat energy required to heat the reformer feed and the oxygen required to support combustion of the fired heater section of the furnace.

A schematic diagram of the process with the gas turbine is shown in figure 1.

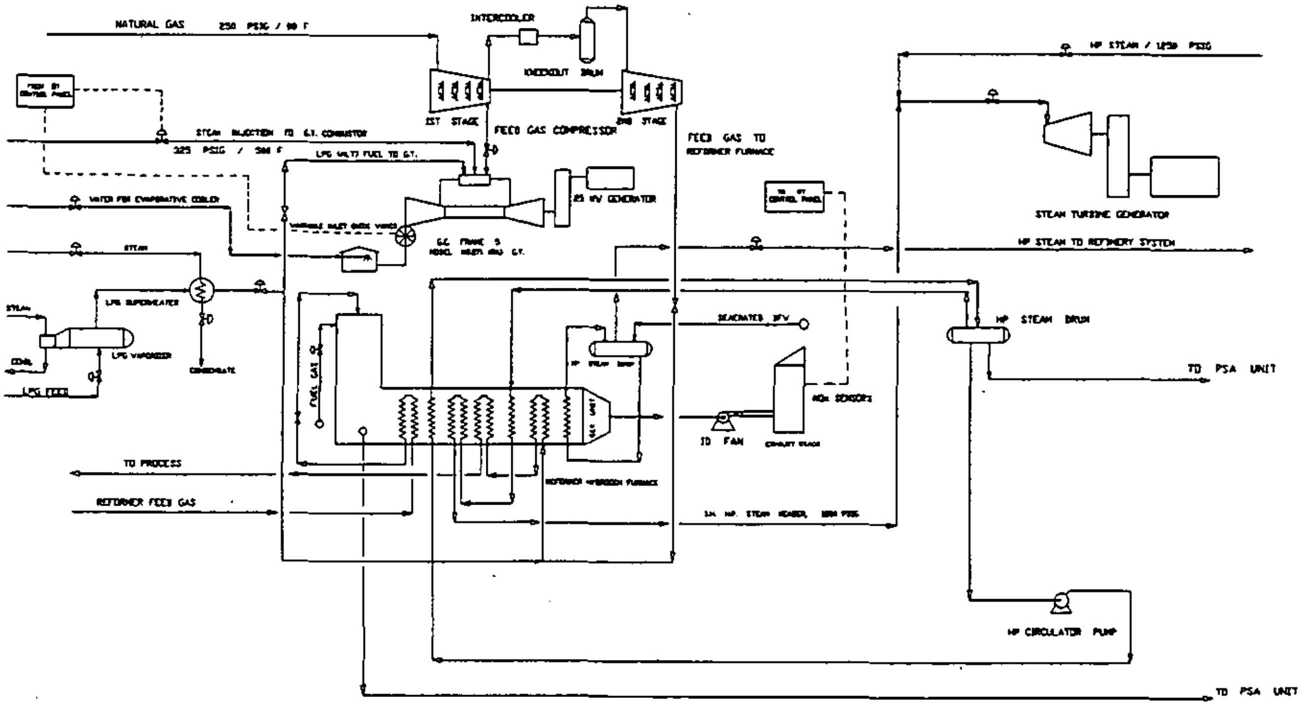

FIGURE 1 - PROCESS DIAGRAM OF GAS TURBINE IN A REFINERY PROCESS

GAS TURBINE SELECTION CONSIDERATIONS

The gas turbine selection revolved around two significant factors or features that the machine was required to possess. First the gas turbine must have the ability to modulate the air flow to a value not exceeding approximately 700,000 lbs / hr regardless of the ambient air temperature. As the ambient temperature changes the inlet guide vanes must be reset (modulate) in order to control heat balance of the process. For the location studied (Southern California) the ambient air temperature varied from between 35°F in Winter to approximately 90°F in Summer and with humidity from low values to 90%.

The second key feature was nitrous oxide (NO_X) emissions. Environmental agencies (SCAQMD - South Coast Air Quality Management District) required a limit of 42 ppm from the turbine exhaust and 15 ppm downstream of the catalytic converter going into the environment. Steam injection is selected due to the experience of the unit selected and availability of steam at the proper pressure level.

Air flow control to a steady state process is of concern to the process engineer. A constant heat and mass flow system from each component in the system is a requirement in order to maintain a constant level of hydrogen production, oil processing, etc. To achieve the objective the G.E.'s frame 5, model 5271 RA was selected because of the variable inlet guide vane arrangement available with this model. Again this area was key to this gas turbine/process configuration. The inlet guide vanes as stated previously are used to control air flow at approximately

700,000 lbs / hr at rated conditions (90°F) and then vary the flow (inlet guide vanes) at other ambient (air density) conditions to maintain a constant heat input to the furnace. The exhaust temperature is a controlled constant so that with constant flow and constant temperature of the exhaust the heat input to the hydrogen reformer would be essentially constant.

The exhaust gas from the gas turbine performs two functions to the process and one to the steam cycle. The constant heat input provides (1) preheating of the hydrogen reforming furnace feed used to make the hydrogen, and (2) provides the oxygen to support combustion of the burners that further heat the feed in the furnace.

Residual heat of the gas turbine exhaust gas is further used to contribute to generating steam in the heat recovery coils in the same furnace.

TABLE 1 "HEAT BALANCE DATA"

1250 PSIG STEAM COILS:	
A COIL	127 MM BTU/HR
B COIL	45 MM BTU/HR
E COIL	33 MM BTU/HR
600 PSIG STEAM COILS:	
B COIL	63 MM BTU/HR
75 PSIG STEAM COILS:	
G COIL	45 MM BTU/HR
FEED GAS COILS:	
D COIL	9.0 MM BTU/HR
F COIL	9.0 MM BTU/HR

Air Flow / Control of Air

The controls supporting the variable inlet guide vanes on the turbine's compressor are supported from the digital electronic control panel. In the case of G.E. it is their Mark IV redundant microprocessor control system. Modifications are necessary to include an algorithm especially configured to set the inlet guide vanes to correspond to the ambient air temperature sensed that provides the heat energy desired. Coordination is required between the process designer and the gas turbine manufacturer to insure proper algorithms are developed. The heat energy stated here is the heat input required to produce the hydrogen required for the process needs.

A control signal from the digital electronic gas turbine control panel to the inlet guide vane control is shown in figure 1. Since the actuator is pneumatic a transducer in the system will convert the electronic signal to pneumatic. The setting is determined by ambient air temperature sensors, furnace parameters, and process inputs.

GAS TURBINE DETAILS

Besides the inlet guide vane feature significant attention must be given to the fuel system(s) and emissions system.

Dual Fuel System

As stated above, the owners' own refinery fuel preferences determine the fuels that the gas turbine is required to fire. For this study and paper two fuels are used, natural gas and LPG. The natural gas is a blend of utility gas and refinery off gas produced in the refinery. LPG is also produced in the refinery and could be propane or butane liquid.

The LPG liquid is vaporized in an exchanger prior to entering the fuel system of the gas turbine. Heat exchange occurs in a shell and tube exchanger using refinery steam. The LPG is further superheated is the LPG superheater. Heat input is again from refinery steam.

Current design of G.E.'s 5271 RA gas turbine utilizes a dual fuel system of nozzles in the combustors, one for each specified fuel.

NO_x Emissions Controls

Nitrous oxide formation has been documented in much gas turbine literature[1, 2]. G.D. Lewis published findings in 1981 in an ASME paper relating NO_x to combustion temperature. Another ASME paper was published by M. Odgers & D. Kretschmer in 1985 with similar relationships. These papers show lower NO_x formation at lower combustion temperatures. Therefore, it is reasoned that to reduce the nitrous oxide formation one needs to reduce the combustion temperature. This is exactly the function of the steam injection system supplied. These oxides of nitrogen are formed both during and after the combustion process.

It should be noted that NO_x formation is also a function of combustor design, fuel type, humidity, steam to fuel ratio, and power level. In this application and paper concern is only with reducing combustion temperature through steam injection to reduce nitrogen oxide formation. Manufacturer's such as G.E. concentrate on combustion temperature reduction in the primary zone where the fuel and air first come together.

Nitrous oxide emissions are currently limited to 15 ppm @ 15% O_2 , corrected to ISO conditions, to the atmosphere according to Rule 1134 of the *SCAQMD Rules and Regulations* [3] (effective 12-31-95, this limit changes to 9 ppm corrected to ISO conditions and 12 ppm without SCR.) As mentioned above compliance is achieved using injection of superheated steam at approximately 350 PSIG directly into the combustors. With this scheme NO_x from the gas turbine is reduced to approximately 42 ppm, corrected to 15% O_2 with steam injection, and then to the final value of 15 ppm in the catalytic converter just before release through the stack to the environment. This regulatory restriction applies only to operation on natural gas fuel. NO_x increase to approximately 65 ppmv when the gas turbine operation is on LPG fuel.

Steam injection for NO_x reduction is injected directly into the turbine's combustors. It acts to reduce the flame (combustion) temperature and therefore, the resultant NO_x levels/nitrous oxide formation rate(s).

Guaranteed steam injection rates to achieve the NO_x levels is 6500 lbs / hr at the site rated temperature of 90°F.

Control of NO_x level from the gas turbine only is through the digital electronic Speedtronic™ control system. Algorithms are written to correlate steam injection rates to load, environmental conditions, etc. in order to achieve the 42 ppmv NO_x. This function can be performed either theoretically or from direct measurements of NO_x in the turbine's stack.

The steam injection system has a side benefit for the operator and owner. Power is augmented with steam injection due to the additional mass passing through the power turbine.

Performance

Tables 1 and 2 show gas turbine generator performance for operation on natural gas and LPG, with the evaporative cooler added at the inlet of the gas turbine compressor.

Maximum output is approximately 18490 kW at the site rated conditions of 90°F with relative humidity of 60% and with the evaporative cooler added.

TABLE 2 "PERFORMANCE - M5271 (RA) GT NATURAL GAS WITH EVAPORATIVE COOLING"

SITE CONDITIONS:	
Elevation, feet	100
Barometric pressure, psia	14.7
Inlet loss, inches water	5
Exhaust loss, inches water	10
Relative humidity, %	60
Fuel LHV, BTU / CF	1000
PERFORMANCE DATA:	
Compressor inlet temperature, F	90
Power output, kW	18,490
Exhaust gas flow x 10-3, lb/hr	779.0
Exhaust gas temperature, F	972
Steam injection for NOx, lb/hr	9,610
NOx ppm @ 15% O2	42
CO, ppmvd	10
CO, lb/hr	7
UHC, lb/hr	3

Tables 2 and 3 present performance of the gas turbine generator for LPG fuel and natural gas with the effects of an evaporative cooler in operation. As with natural gas fuel performance, the gas turbine fired on LPG fuel and with an evaporative cooler has higher output than without the cooler.

TABLE 3 "PERFORMANCE - M5271 (RA) GT LPG FUEL WITH EVAPORATIVE COOLING"

SITE CONDITIONS:

Elevation, feet	100
Barometric pressure, psia	14.7
Inlet loss, inches water	5
Exhaust loss, inches water	10
Relative humidity, %	60
Fuel LHV, BTU / LB	19,667

PERFORMANCE DATA:

Compressor inlet temperature, F	90
Power output, kW	18,230
Exhaust gas flow x 10-3, lb/hr	779.0
Exhaust gas temperature, F	972
Steam injection for NOx, lb/hr	6,620
NOx ppmvd @ 15% O2	65
CO, ppmvd	10
CO, lb/hr	7
UHC, lb/hr	3

Heat rates are shown in Table 4. This is a rather comprehensive table as it shows heat rates for the M5271 (RA) gas turbine for both fuels with evaporative cooling feature added.

Evaporative cooling is utilized in areas such as Southern California. The high ambient, low relative humidity offer the user the opportunity to increase power with a water spray into the inlet air stream.

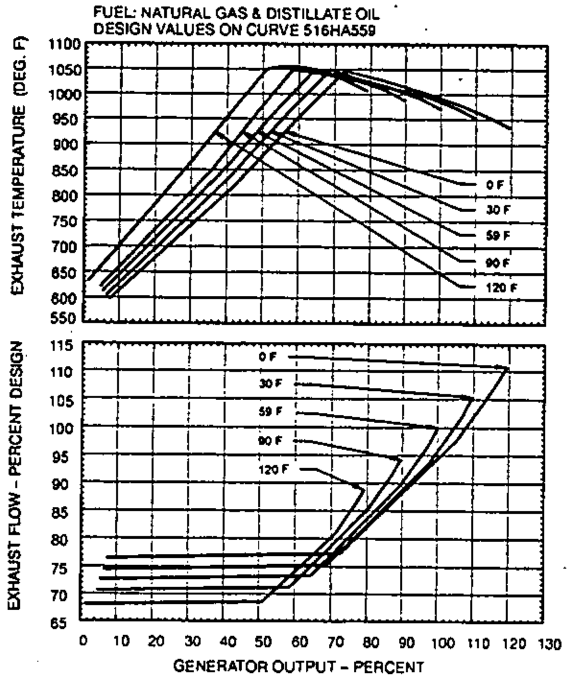

Figure 2 Effect of Modulated Inlet Guide Vanes on Exhaust Flow and Temperature As a Function of Output and Compressor Inlet Temperature.

As stated above and shown in figure 1 much of the heat in the exhaust gas is utilized by the process in the hydrogen reforming furnace to preheat the feed to the furnace and then to contribute to steam production. Table 1 above shows the relative heat transfer for each of the major sections of the hydrogen process.

TABLE 4 "HEAT RATES OF M5271 (RA) GT (BASED ON EVAPORATIVE COOLING @ 90 F)

NATURAL GAS FUEL PERFORMANCE:	
Output, kW	18,490
Heat Input, BTU/HR X 10-6 (LHV)	246.1
Heat Rate, BTU/KWH (LHV)	13,310
Exhaust gas temperature, F	988
Exhaust heat, BTU/Hr x 10-6	172.8
LPG FUEL PERFORMANCE:	
Output, kW	18,230
Heat Input, BTU/HR X 10-6 (LHV)	242.6
Heat Rate, BTU/KWH (LHV)	13,308
Exhaust gas temperature, F	988
Exhaust heat, BTU/Hr x 10-6	170.4

STEAM TURBINE ARRANGEMENT

In Figure 1 above the basic steam flow of a typical refinery steam system is shown around the steam turbine generator. Basically high pressure superheated steam and medium pressure steam is produced in the heat recovery section(s) of the steam reforming furnace from residual heal in the gas turbine exhaust gas plus using supplementary firing of duct burners.

The steam turbine design shown in this paper has three (3) inlet nozzle blocks. The initial inlet is at 1250 psig, a second inlet nozzle is at 600 psig and the third connects the low pressure steam system at approximately 75 psig. The low pressure nozzles control either induction or extraction requirements depending on the steam balance requirements of the unit/facility. The condensing section of the turbine is then piped directly to a water cooled condenser.

Figure 3 shows the details of the steam flow described and the steam balance for the example in this paper. The pressure levels, flows and outpul are similar to actual projects designed.

Due to the complexity of controlling such a steam turbine a state of the art digital electronic governor is shown. The systems provided on the market today will also provide for generator control for such functions as synchronizing and automatic voltage regulation.

STEAM BALANCE SUMMARY		
HP STEAM	PRESS. PSIG	1250 PSIG
	TEMP. F	850 F
	FLOW, LB/HR	400,000 LB/HR
MP STEAM	PRESS. PSIG	600 PSIG
	TEMP. F	800 F
	FLOW, LB/HR	250,000 LB/HR
LP STEAM	PRESS. PSIG	75 PSIG
	TEMP. F	320 F
	FLOW, LB/HR	+/- 75,000 LB/HR
CONDENSER	PRESS. PSIG	4 INCHES HGA
	TEMP. F	125 F

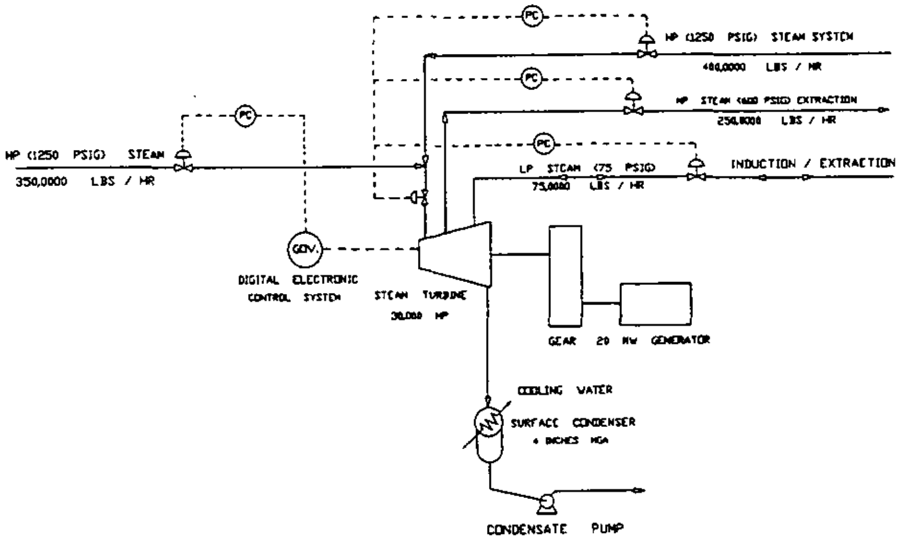

FIGURE NO. 3 - STEAM FLOW / STEAM BALANCE

The economics of the steam turbine system are estimated in table 5. Power savings is just over $ 21MM. Installed cost is approximately $ 11 MM. To these numbers one must add the fuel and maintenance costs to arrive at the full tradeoff analysis. But from even these figures it appears that this cycle is economic.

TABLE 5 "ECONOMICS OF THE STEAM TURBINE CYCLE / POWER SAVINGS"

Installed cost of 20 MW S-T generator	$ 21,000,000
Rating of hydrogen reformer, BTU/HR	600,000,000
Heat recovered in steam, BTU / HR	280,000,000
Power generated @ 8000 hrs / yr., kWh	160,000,000
Equivalent cost of Power, $ / yr	$ 14,400,000

(If purchased from a utility @ $ 0.09 / KWH)

CONCLUSION

An industrial gas turbine has been shown being applied in a oil refinery process as an integral component of a hydrogen reforming unit and as a part of an overall cogeneration arrangement involving the hydrogen reforming furnace. The key feature was to treat the gas turbine as a piece of process equipment and control it as such. A gas turbine with variable inlet guide vanes has been selected for this service.

The variable inlet guide vanes are available on the G.E. frame 5, model M5271 RA industrial gas turbine. It is this feature that makes this unit most attractive for this application and service. Since the process operates steady state the variable inlet guide vanes serve to control the air flow to match the constant heat balance requirement of the process.

ACKNOWLEDGMENTS

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REFERENCES

(1) Lewis, G.D., "Prediction of NOx Emissions", ASME paper No. 81-GT-119, December, 1981.

(2) Odgers, J. & Kretschmer, D., "The Prediction of Thermal NOx in Gas Turbines", ASME paper No. 85-GT-126, September, 1985.

(3) South Coast Air Quality Management District, Rule 1134, "Emissions of Oxides of Nitrogen from Stationary Gas Turbines," Adopted August 4, 1989.