Steam and Gas Turbine Combined Cycle Equipment Currently Available for Natural Gas Pipelines

R. P. LANG
Mem. ASME

D. L. CHASE
General Electric Co.,
Schenectady, N.Y.

The high thermal efficiency of the combined steam and gas turbine cycle makes it an attractive candidate for gas pipeline drivers. This paper discusses some aspects of the performance which can be achieved, and the economics associated with this cycle using currently available equipment. One equipment selection has an output capability of over 20,000 hp with a net thermal efficiency of approximately 40 percent. A second equipment selection has an output capability of over 35,000 hp with a net thermal efficiency of approximately 47 percent.


Copies will be available until December 1, 1979.
Steam and Gas Turbine Combined Cycle Equipment Currently Available for Natural Gas Pipelines

R. P. LANG D. L. CHASE

ABSTRACT

The high thermal efficiency of the combined steam and gas turbine cycle makes it an attractive candidate for gas pipeline drivers. This paper discusses some aspects of the performance which can be achieved, and the economics associated with this cycle using currently available equipment. One equipment selection has an output capability of over 20,000 hp with a net thermal efficiency of approximately 40%. A second equipment selection has an output capability of over 35,000 hp with a net thermal efficiency of approximately 47%.

INTRODUCTION

A combined cycle is a thermodynamic power cycle formed by combining two or more power cycles. The incentive for combining the cycles is to form a system with a thermal efficiency higher than that of the basic cycles. One such combination includes the Brayton Cycle using a gas turbine and the Rankine Cycle using a steam turbine. This combination of steam and gas turbines has several advantages over other possible combinations because:

1. A combined cycle is a straightforward manner due to the fact that the two cycles are thermodynamically complementary. That is, the heat rejected by the Brayton Cycle gas turbine is at a temperature level that can be used conveniently by the Rankine Cycle steam system.
2. The two working fluids --- air and water --- are readily available, inexpensive, non-toxic, and non-flammable.
3. Equipment for these cycles is well developed, field proven, and available from several manufacturers.

Some aspects of the performance obtainable with this cycle using currently available equipment are discussed in this paper. The equipment is selected to be appropriate for driving natural gas pipeline compressors.

BASIC EQUIPMENT ARRANGEMENT AND SELECTION

The basic equipment arrangement for discussion in this paper is shown in Figure 1. Major elements include a simple cycle gas turbine, an unfired steam generator which recovers some of the heat in the exhaust of the gas turbine, a steam turbine, and an air cooled condenser. The gas turbine and the steam turbine are both direct connected to a common load --- a double ended centrifugal compressor. The gas turbine and the steam turbine could drive individual loads, however, such an arrangement requires a more complicated control system and the performance is more difficult to analyze, especially under "off design" operating conditions. An air cooled condenser is used instead of a water cooled condenser because condenser cooling water is not readily available in many remote areas traversed by gas pipelines.

Gas turbines are available in specific models or sizes because for every size machine a very large
Investment must be made in development, testing, and manufacturing facilities. On the other hand, steam equipment is readily available in a wide range of sizes and a wide range of operating conditions. So, for a combined cycle system, it is desirable to "build" the system around a particular gas turbine, selecting the steam equipment to match the exhaust heat conditions of that gas turbine.

The performance data and economic analysis which follow are based on systems built around two different gas turbines:

1. The General Electric M3142 Industrial Gas Turbine. This is a simple cycle heavy duty machine with a continuous rating at ISO conditions of 14600 hp (10660 kW), and a thermal efficiency of approximately 26.7% (LHV) burning natural gas.

2. The General Electric LM2500 Industrial Gas Turbine. This is a second generation aircraft derivative machine, with a continuous rating at ISO conditions of 27500 hp (20500 kW), and an average engine thermal efficiency of approximately 36.7% (LHV) burning natural gas.

Also, for this paper, the system performance data is based on site conditions of sea level elevation, 5° H (170 m bars) pressure drop in the gas turbine inlet (inlet filters, silencing, etc.) and 12" H2O (406 m bars) pressure drop in the gas turbine exhaust (heat recovery steam generator and exhaust ducts).

PERFORMANCE OF M3142 COMBINED CYCLE AT DESIGN CONDITIONS

A schematic diagram of the combined cycle using the M3142 gas turbine is shown in Figure 2. The gas turbine exhaust enters the heat recovery steam generator at 968°F (520°C) and exits at approximately 330°F (166°C). The energy given up in this temperature reduction generates 51900#/hr of steam at approximately 600 psig (42 Kg/cm.) 850°F (454°C) for use in the steam turbine. The steam turbine exhaust is condensed at 2" HgA (68 m bars) and the condensate is collected in a hot well and pumped back to heat recovery steam generator. At design conditions, the gas turbine produces 15500 hp (11560 kW) and the steam turbine approximately 8000 hp (5960 kW), so the total horsepower available at the load (the pipeline centrifugal compressor) is 23500 hp (17520 kW). The fuel required by the gas turbine is 145.7 x 10^6 Btu/hr (153.7 GJ/hr) (LHV). This represents a gross heat rate of 6200 Btu/hp hr (8773 kJ/kW hr) or an efficiency of 41.0%. About 350 hp (260 kW) of electrical power is required for the auxiliaries such as the condenser fans, feedwater pump, etc., so the net efficiency is slightly lower --- approximately 40.4%.

PERFORMANCE OF LM2500 COMBINED CYCLE AT DESIGN CONDITIONS

A schematic diagram of the combined cycle using the LM2500 gas turbine is shown in Figure 3. Here again some of the energy in the gas turbine exhaust is recovered by the heat recovery steam generator and 57300#/hr of steam is produced at 600 psig (42 kg/cm.) 850°F (454°C) for the steam turbine. At design conditions, the gas turbine produces 28890 hp and the steam turbine approximately 8610 hp (6420 kW), so the total power available at the load is 37500 hp (27960 kW). The fuel consumed by the gas turbine is 202.1 x 10^6 Btu/hr (213 GJ/hr) (LHV). This represents

FIG. 2 SCHEMATIC DIAGRAM M3142 COMBINED CYCLE

HEAT RATE = 145.7 x 10^6 / 23500 = 6200 BTU/HP HR

FIG. 3 SCHEMATIC DIAGRAM LM2500 COMBINED CYCLE

HEAT RATE = 202.1 x 10^6 / 37500 = 5389 BTU/HP HR
A gross heat rate of 5389 Btu/hp hr (17.25 kJ/kW hr) or an efficiency of 47.2%. About 400 hp (300 kW) of electrical power is required for the auxiliaries, so the net efficiency is approximately 46.7%.

Comparison of the heat balance information presented in Figures 2 and 3 indicate that the steam turbine horsepower in the M3142 combined cycle is about one half that of the gas turbine, whereas in the LM2500 combined cycle the steam turbine horsepower is less than one third that of the gas turbine. The reason for this is that the LM2500 gas turbine by itself is more efficient than the simple cycle M3142 so there is less energy per output horsepower in the exhaust of the LM2500. Also, as can be seen, the LM2500 combined cycle is considerably more efficient than the M3142 combined cycle. Part of this is due to the fact that the LM2500 fuel use is based on "average engine" performance and the M3142 is not. Typically, performance on an average engine basis reflects a 3% improvement in fuel use. This difference in fuel use base accounts for some of the system efficiency difference. However, most of the difference is due to the fact that the LM2500 has a higher simple cycle efficiency and, since the gas turbine supplies most of the system power, the combined cycle performance reflects this higher component efficiency.

PERFORMANCE AT "OFF DESIGN" CONDITIONS

The performance data shown on the schematic diagrams is for design conditions -- rated output at rated speed for 30°F (0°C) ambient air temperature. However, gas pipeline compressor drivers seldom operate at design conditions so it is important to consider the "off design" performance characteristics of the combined cycle. This includes the effects of ambient temperature change, reduced load, and reduced speed.

The effect of ambient temperature change and of reduced load is shown in Figure 4. Here the thermal efficiency of the LM2500 combined cycle system is shown for a load range of 20,000 hp (14900 kW) to 37500 hp (27960 kW) for three different ambient air temperatures. In this case the speed is constant at 100% of design speed for all outputs. The efficiency decreases as the load decreases, from about 47% at 37500 hp (27960 kW) to about 41% at 20,000 hp (14900 kW), however, for any particular load the ambient temperature change has only a minor effect.

The steam conditions for this range of reduced loads -- for the 30°F (0°C) ambient air condition --- is shown in Figure 5.

When analyzing these curves it should be noted that there is a stop valve (not shown in Figure 1) but no throttle in the steam line to the steam turbine. The steam turbine simply takes all the steam provided by the heat recovery steam generator -- at whatever pressure and temperature satisfies the system. The steam flow, temperature, and pressure, and resultant steam turbine horsepower all decrease as energy in the gas turbine exhaust decreases.

This variation in steam pressure and temperature as well as steam flow is also noticeable when the ambient temperature changes. This is shown in Figure 6 which presents the steam conditions for ambient temperatures at 30°F (0°C) to 90°F (32°C) --- all with a constant gas turbine output of 20000 hp (14915 kW). Note that as the ambient temperature increases there is more steam in the system. This of course is to be expected because -- at constant output -- the gas turbine exhaust temperature increases as the ambient temperature increases. This increase in steam tends to compensate for the normal decrease in gas turbine efficiency as the ambient air temperature increases. Thus, the combined cycle system efficiency -- for this particular selection of steam equipment --- is fairly constant with ambient temperature changes. Actually, since the steam flow, pressure, and temperature all increase with increasing ambient temperature, the steam horsepower would increase at an increasing rate as the ambient temperature increases.
At this point a brief description of the major components selected for the two combined cycle systems is in order. All of the components are well proven, currently available, "in production" equipment. The gas turbines were described earlier in the introduction paragraphs. The heat recovery steam generators are unfired, forced circulation, factory assembled packaged units using extended fin heat transfer surfaces. Many of these are currently in service in combined cycle electric utility power generation plants. The steam turbines are typical industrial mechanical drive type units especially designed for adjustable speed service. The one selected for use with the M3142 gas turbine has 7 stages in the rotor and a design speed of 6500 RPM to match the speed of the gas turbine. The one selected for use with the LM2500 gas turbine has 8 stages in the rotor and a design speed of 3600 RPM, again, to match the gas turbine speed. The condensers, also as noted earlier, are air cooled, designed to provide 2" HgA (68 m bars) back pressure on the steam turbine at 30 F (0 C) ambient and permit the back pressure to rise to 8" HgA (270 m bars) at 90 F (32 C) ambient. They include electric motor driven fans for forced air flow at high ambients and the fans have variable pitch blades so the air flow can be reduced at low ambients. Similar units have been in service at Prudhoe Bay and other Arctic installations for a number of years with no freeze-up problems. Condensate from the condenser drains into a hot well and a centrifugal type boiler feed pump returns the condensate to the heat recovery steam generator. Separation of non-condensable gases from the feedwater occurs in the condenser heat exchanger tube bundles. These non-condensables are extracted by a vacuum pump and exhausted to atmosphere.

A typical plant plan and elevation arrangement drawing showing the major components of the LM2500 combined cycle is shown in Figure 7. This arrangement has the heat recovery steam generator and the air cooled condenser on the ground next to the turbine building, and provides a general idea of the relative size of the various components. A lube oil supply system independent of that in the gas turbine package is included to supply the compressor and the steam turbine. A single water/glycol to air heat exchanger is provided to furnish cooling water to both the gas turbine and the compressor/steam turbine lube supply systems. The long shaft between the steam turbine and the compressor is required so the compressor internal bundle can be pulled for maintenance. This arrangement also includes a bypass stack and dampers to permit diverting the gas turbine exhaust to atmosphere in case it is desirable or necessary to

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Load 1</th>
<th>Load 2</th>
<th>Load 3</th>
<th>Load 4</th>
<th>Load 5</th>
<th>Load 6</th>
<th>Load 7</th>
<th>Load 8</th>
<th>Load 9</th>
<th>Load 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>35</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>45</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>55</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>60</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>65</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>70</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>75</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>80</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>85</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>90</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
operate without the steam system.

SYSTEM OPERATION AND CONTROL

The steam equipment includes a number of electric motor driven fans and pumps plus several sub-systems for control of water levels etc. In control requirements these are similar to the pumps, fans, etc. on the basic gas turbine, and can be set up to operate just as automatically. The one major difference is that the boiler must be blown down and chemicals added periodically to keep the solids and pH factor at the desirable level.

Prior to starting the system, various manual (or remote controlled) functions and sequences must be completed which put the auxiliaries into operation and establish the proper water level in the heat recovery steam generator drum and the condenser hot well. Startup is then initiated by cranking the gas turbine. After purging the gas turbine, fuel is admitted and ignited and the turbine is accelerated to self sustaining speed under the combined power of the starting device and the gas turbine; the starting equipment clutch then disengages.

The unit then automatically comes to a low speed "plant warm-up" condition by control of the gas turbine fuel flow. This condition is held for a period of time during which the heat recovery steam generator comes up to operating temperature and starts to generate steam. The initial steam is utilized to heat the steam piping and establish steam seals on the steam turbine shaft so the vacuum pump can establish condenser vacuum. After this warmup period, the gas turbine fuel flow is ramped up until the system reaches the desired operating condition. The entire startup period from a cold condition to rated load takes approximately 30 minutes.

During normal operation the steam turbine shutoff valve is wide open and steam flow to the steam turbine varies with the amount of steam generated by the steam generator. The steam generated in turn varies with the gas turbine exhaust air flow and temperature which is the inlet gas flow to the steam generator. Therefore, the output of the system is controlled entirely by fuel control to the gas turbine.

During load changes there is a time lag between the change in gas turbine exhaust gas temperature and flow and the steam flow change to the steam turbine. Hence any change in load is imposed directly on the gas turbine and only after a time delay the steam system follows this change — eventually reducing the load change effect on the gas turbine. This time lag is in the order of two to three minutes before the output of the gas turbine and the steam turbine stabilize at the new value.

To stop the system, the fuel flow to the gas turbine is simply reduced and eventually cut off. As in the load change operation, the steam flow change follows the gas turbine exhaust energy change so the steam system will follow the gas turbine down.
and eventually the steam stop valve may be closed. In those instances where the system has to stop very rapidly, the steam stop valve can be closed immediately, however it may then be necessary to dissipate the energy stored in the steam system by blowing steam to atmosphere or directly to the condenser through a boiler pressure relief valve.

ECONOMICS

The additional equipment required for the combined cycle system results in a higher first cost than that of a basic gas turbine. However, when fuel is expensive, this higher first cost may be justified. This is illustrated in Figure 8 which shows the results of an annual expense comparison of a typical installation using simple cycle and combined cycle equipment.

ECONOMICS

To accommodate the fact that the simple cycle gas turbine provides 20,000 hp (14915 kW) whereas the combined cycle system (using the same simple cycle gas turbine also at 20,000 hp) provides 26390 hp (19680 kW), the results of the annual expense analysis are presented on a $/hp basis. For this comparison, the simple cycle has the lower annual expense when the cost of fuel is less than $2.50 per million Btu ($2.37 per GJ), and the combined cycle has the lower annual expense when the cost of fuel is more than $2.50.

SUMMARY

Combined cycle systems using currently available gas turbines and steam equipment can provide thermal cycle efficiencies over 40%, and in some cases as high as 47%. Since the gas turbine provides the major portion of the power output, the combined cycle system basic performance characteristics are similar to those of the gas turbine, however, there are some differences, particularly in ambient temperature effects and in transient load effects. The first cost of the combined cycle system is considerably higher than that of the basic gas turbine, however the savings in fuel offsets this higher first cost, and when fuel is expensive, typically $2.50 or more per million Btu ($2.37 per GJ), the combined cycle may be economically attractive.

---

**FIG. 8 ANNUAL EXPENSE COMPARISON**

**TYPICAL SIMPLE CYCLE AND COMB. CYCLE**

The equipment and operating conditions assumed for this comparison are shown in Table 2. It is also assumed that the equipment operates 7500 hours per year, the annual fixed charges are 20% of the Installed Cost, and the combined cycle has an added charge of $210,000 per year to cover the cost of makeup water and steam system maintenance. Gas turbine maintenance and operators are not included.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Avg. Operating HP (kW)</th>
<th>Efficiency</th>
<th>Installed Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple Cycle</td>
<td>20,000 (14915)</td>
<td>33.5%</td>
<td>$5,250,000</td>
</tr>
<tr>
<td>Combined Cycle</td>
<td>26,390 (19680)</td>
<td>44.2%</td>
<td>$10,400,000</td>
</tr>
</tbody>
</table>