Gas Turbine Performance Analysis

Gas turbines may seem too complicated or overwhelming at first glance, but for regular field monitoring on a relative basis, it is not all that difficult. A regular check on the overall efficiency can tell a lot about the condition of the turbine and help decide if further investigation is necessary. All that is needed is the driven power and fuel consumption. A little more information can provide a breakdown between the air compressor portion of the gas turbine and the hot gas expander section to further pinpoint problems that may develop over time.

Example A client had a series of gas turbine driven compressors to boost gas pressure in a natural gas pipeline system. In order to better schedule maintenance on the equipment, routine efficiency assessments are completed and plotted over time. The gas turbine fuel is taken from the natural gas pipeline.

The natural gas centrifugal compressor is made up of two single stage bodies driven through a gear by a gas turbine burning pipeline gas. There is no intercooling between the compressors thus they are treated as a single multi-stage compressor.

Natural Gas Centrifugal Compressor Performance

Table 1 notes the operating conditions for this compressor along with results. A computer program Gas Flex utilizing BWR equations of state was used to determine the compressor head, efficiency and power. These values were plotted on the OEM performance curve to show relative performance. As can be seen in Figure #1, the work input is very close to the predicted value, thus the power for the compressor can be considered to be accurate.

Table 1 Natural Gas Compressor & Gas Turbine Driver Operating Data

Ambient		
Atmospheric Pressure	psia	14.37
Atmospheric Temperature	F	73
Atmospheric Humidity	%	79
Compressor		
Inlet Presssure	psia	489.11
Inlet Temperature	F	64.4
Discharge Pressure	psia	1008.3
Discharge Temperature	F	185.5

Speed	rpm	4010
Inlet Volume Flow	cfm	11134
MW		16.45
Mass Flow	lb/min	17,005
Gas Power	Horsepower	24,111
Work, Adiabatic	ft-lb/lb	46,790
Head, Adiabatic	ft-lb/lb	36,497
Efficiency	%	78.0
Gas Turbine		
Mechanical Losses (Gear + Bearings & Seals)	Horsepower	603
Fuel Flow	scfh	190402
Overall Efficiency	%	32.7
Air Compressor Section		
Inlet Pressure	Psia	14.1
Discharge Pressure	psia	165.3
Discharge Temperature	F	689
Air Flow rate	scfm	149,667
Head, adiabatic	ft-lb/lb	101,942
Efficiency, adiabatic	%	87.1
Gas Power	Horsepower	41,090
Hot Gas Expander Section		
Inlet Temperature	F	2010
Exhaust Temperature	F	1044
Flow	scfm	152,840
Power	HP	77,817
Efficiency	%	86.7

Table 2, Gas Analysis, Mole %

C6+	0.003	
Propane	0.134	
i-Butane	0.0156	
n-Butane	0.1835	
i-Pentane	0.00675	
n-Pentane	0.005	
Nitrogen	1.17	
Methane	96.1973	
Carbon Dioxide	0.75	
Ethane	1.7	
MW	16.45	
Heating Value	1011.2	
Compressibility	0.9979	

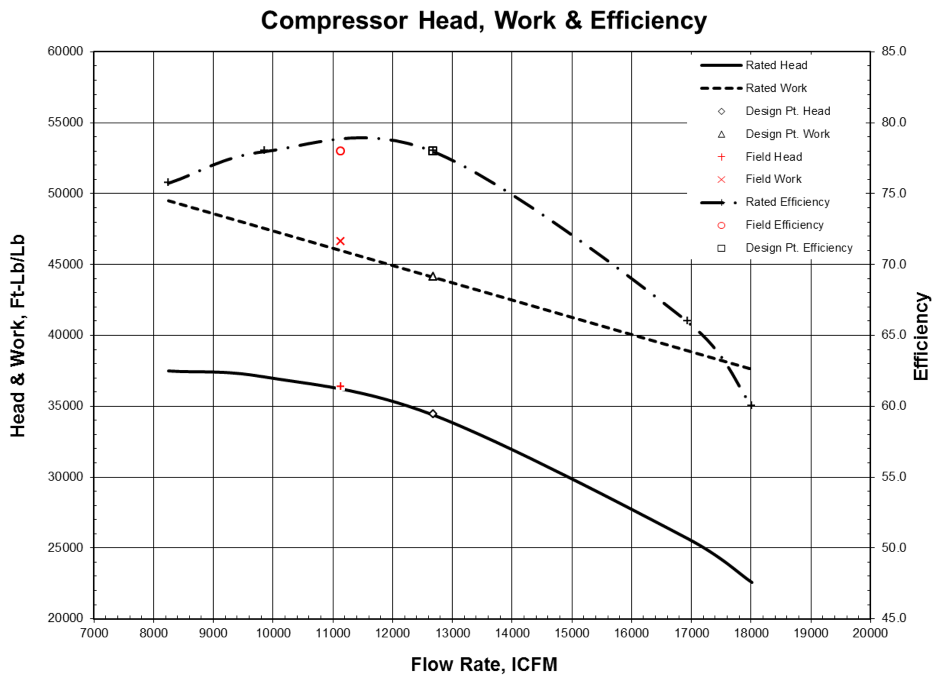

Figure 1, Natural gas compressor performance. Note that the operating data has been corrected for speed using fan laws. Also note that the work input is close to the predicted values, thus the performance values can be deemed reliable.

Gas Turbine Overall Efficiency

The gas turbine overall efficiency can be calculated by:

$$\eta = \frac{(BHP)(2544.43)}{Q \times Heating\,Value}$$

Where:

η = Overall thermal efficiency of gas turbine

BHP = Brake horsepower of driven equipment (Generator, pump or compressor power + bearings & seal losses, include bearing and seal losses for gas turbine), horsepower

Q = Fuel flow rate, natural gas, std cubic feet/hour

Heating Value = Btu/std cubic feet

Notes – for Pittsburgh Natural Gas:

1. Normal air flow required for combustion of natural gas, 10.62 std. cu ft air/ std. cu ft gas.*
2. Net heating value = 1021 btu/std. cu ft gas
3. 106.2 gross Btu/std. cu ft air
4. Gas volume flow is for gas saturated with water vapor at 60 F and 29.92 inches of mercury absolute.
5. Typical Pittsburgh Natural Gas analysis: CH4, 83.4%, C2H6, 15.8%, N2, 0.8% - % by volume.
6. Typical exhaust gas from combustion of natural gas: CO, 0.223; CO, 0.228; N2, 0.535; H2, 0.014

*Note: While 10.62 cu ft is the required amount of air required for the burning of 1 cu ft of natural gas (primary air), significantly more air is used to keep the engine cool (secondary air). 2, 3 or even 4 times as much air may be used for this purpose.

Overall gas turbine efficiency is calculated:

$$\eta = \frac{(24{,}111+603)(2544.43)}{190{,}402\times1011.2}$$

$$\eta = 32.7\%$$

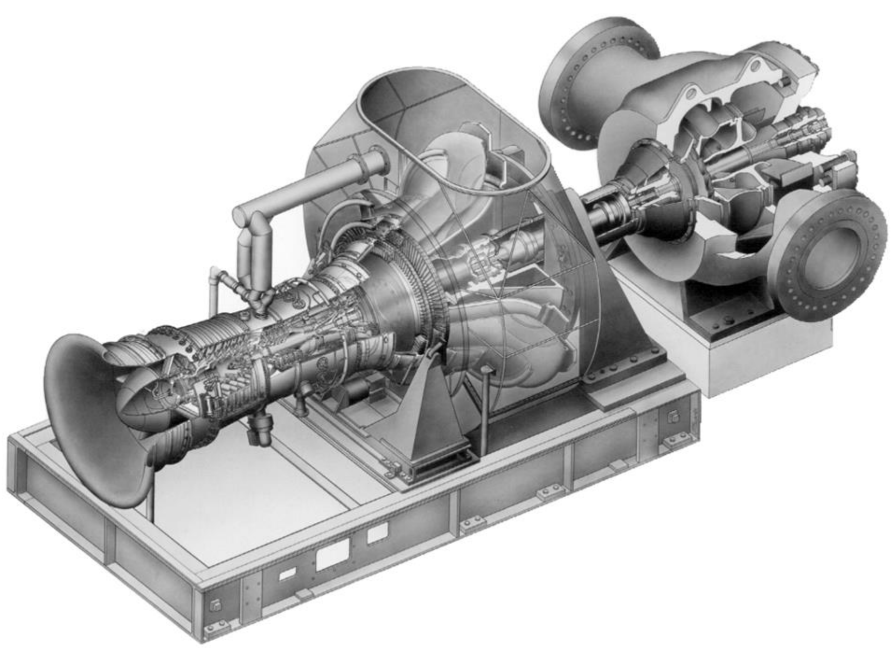

Figure 2. Gas Turbine driving natural gas compressor.

Thermal Efficiency of Air Compressor Section of Gas Turbine

Procedure: Calculate adiabatic head, eq 7.5a, Adiabatic Efficiency, eq 7.8, and adiabatic power, eq 7.13, ref #3.

$$H_{ad} = RT_1\left(\frac{k}{k-1}\right)\left[\left(\frac{P_2}{P_1}\right)^{(k-1)/k} - 1\right] \qquad (7.5a)$$

$$\eta_{ad} = \frac{T_1\,[P_2/P_1)^{(k-1)/k} - 1]}{T_2 - T_1} \qquad (7.8)$$

$$\mathrm{GHP}_{ad} = \frac{H_{ad} \times Q_1 \times 144 \times P_1}{\eta_{ad} \times T_1 \times R \times 33000} \qquad (7.13)$$

See note #1 above to determine air flow.

Assuming dry air and using Note #1 above, the air compressor section results are (see Table #1) shown below. A computer program using the adiabatic equations shown above was used for computing the results.

Flow rate = 149,667 cfm
Head = 101,942 ft-lb/lb
Efficiency = 87.1
Power = 42,090 HP

Thermal Efficiency of Hot Gas Expander Section of Gas Turbine

The efficiency of the hot gas expander section can be calculated by:

$$\eta = \frac{(BHP)(2544.43)}{Q \times Heating\ Value}$$

Where:

η = Thermal efficiency of hot gas expander section of gas turbine

BHP = Brake horsepower of driven equipment (Generator, pump or compressor power + bearings & seal losses, include bearing and seal losses for gas turbine) + the power of the air compressor section of the gas turbine, horsepower

Q = Fuel flow rate, natural gas, std cubic feet/hour

Heating Value = Btu/std cubic feet

If upstream and exhaust pressures and temperatures are available, use a hot gas expander calculation. For hot gas flow rate, consider note #1 above for estimating air flow. Add air flow to fuel flow to determine total flow through the hot gas expander.

Note the typical gas analysis of a hot gas expander is: O2, 1.0%, N2, 71.0%, H2O, 11.0%, CO2, 17.0%

Using equation 9.2, the efficiency for this expander is:

$$\eta = \frac{(24{,}111+603+41{,}090)(2{,}544.43)}{190{,}402\times 1{,}011.2}$$

$$\eta = 86.96\ \%$$

Using the BWR gas properties program Gas Flex, an efficiency of 86.96% was calculated for the expander section of the gas turbine.

References:

1. PTC-22, Gas Turbine Power Plants, Performance Test Code, 1985
2. North American Combustion Handbook, North American Manufacturing Co, Cleveland, Ohio, 1965
3. Compressor Performance: Aerodynamics for the User, MT Gresh