International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 6, June - 2014

Integrating Gas Turbines with Cracking Heaters in Ethylene Plants

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Abstract—The use of gas turbines (GT) to produce power while simultaneously utilizing the hot, oxygen rich exhaust gas as combustion air in the cracking furnaces is a very attractive means of reducing energy requirements per unit of ethylene production. The use of turbine exhaust gas (TEG) is an effective means providing high level air preheat lowering the heater's fuel requirement. However, unlike air preheat systems, because of the reduced oxygen content of TEG; the total mass flow of flue gas passing through the furnaces is increased.

This results in increased steam production in the convection (heat recovery) section of the pyrolysis module.

The power produced by the gas turbine can be used either for mechanical drives or to produce electric power for in-plant use or export.

In this paper, the technical considerations as well as the design characteristics of the gas turbine/pyrolysis module of the integration systems are discussed. The impact of TEG on utilities balance and NOx emission reviewed. Finally cost information for gas turbine integration of heaters has been presented.

Keywords—Ethylene Plant, Cracking Furnace, Integrating Gas Turbines, NOx Emission formatting.

I. INTRODUCTION

Olefin production is the most energy consuming processes in the chemical industry. The core process for olefin production is steam cracking, which converts hydrocarbon feedstocks (naphtha, propane, ethane, etc.) to olefins (ethylene, propylene, etc.) and other products [1]. The worldwide demand and production of olefins are higher than any other chemicals [2]. Daily goods are primarily derivatives of steam cracking products. In Western Europe, 95% of ethylene and 70-75% of propylene are produced through steam cracking [2]. The rest of propylene comes from refinery fluidized catalytic cracking (FCC) units (28%) and propane dehydrogenation or metathesis (2%) [2]. In general, steam cracking plays a dominant role in olefin production. Global ethylene production in the late 1990s has grown at a very high rate of 7-8% per year [3]. This is largely due to the strong demand growth in East Asia, especially by China, while the current market growth in the US and Europe was rather moderate. The propylene market is growing faster than the ethylene market by (1-3%). Recently, large capacities are being built or planned in the Middle East, but most of them produce ethylene from ethane, which is available at very competitive prices [3]. There are two categories of feedstocks for olefin production: one derived from crude oil (such as naphtha, gas oil, propane, etc.) and another derived from natural gas (ethane, propane, etc.). Their availability depends on the composition of crude oil and natural gas and their production volumes. Generally speaking in terms of weight, ca. 10% of oil refinery output is naphtha while 1-14% of natural gas is ethane and 80-90% is methane. Natural gas from the Middle East and Norway usually has higher ethane content than that from Russia. These regions together have 80-90% of the world's natural gas reserves [4].

Steam crackers consume high energy and produce high CO2 emission worldwide. Reduction of this emission can help meet the emission targets set by Kyoto Protocol [5]. Energy cost is counted ca. 70% of production costs in typical ethane or naphtha based olefin plants [6]. In addition, over 35% of the European crackers are over 25 years old. Therefore, energy management and re-investment are important considerations [2]. From both environmental and economic perspectives, it is therefore of interest to study energy losses in the existing processes as well as energy-saving potentials offered by recent improvements and alternative processes.

Turbine exhaust gas (TEG) effectively provides high-level air preheat, thus lowering the heaters' fuel requirements.

However, unlike air preheat systems, because of the reduced oxygen content of TEG; the total mass flow of flue gas passing through the furnaces is increased. This increases steam production in the convection (heat recovery section of the pyrolysis module.

The power produced by the gas turbine can be used either for mechanical drives or to produce electric power for in-plant use or export.

At an ethylene plant, a heavy-duty industrial gas turbine is used to drive the charge gas compressor while the exhaust provides oxygen for combustion in the cracking furnaces.
With this arrangement, plant operation is dependent on the availability of the gas turbine. Trip of the gas turbine will result in a plant shutdown.

In gas turbine integration systems, the gas turbine is used to drive a generator, producing electric power. The systems are designed to safely switch the cracking heaters from combustion (using hot TEG) to ambient air without shutdown.

II. PROCESS DESCRIPTION

A. Overall Configuration of Cracking Furnace

The original design configuration for the heaters uses 100% ambient air as the combustion air source. In this situation the oxygen in the air is 21 vol%. Gas turbines typically run at a high excess air. Super High Pressure (SHP) steam is produced using integral boiler feed water (BFW) and steam super heater coils in the convection section.

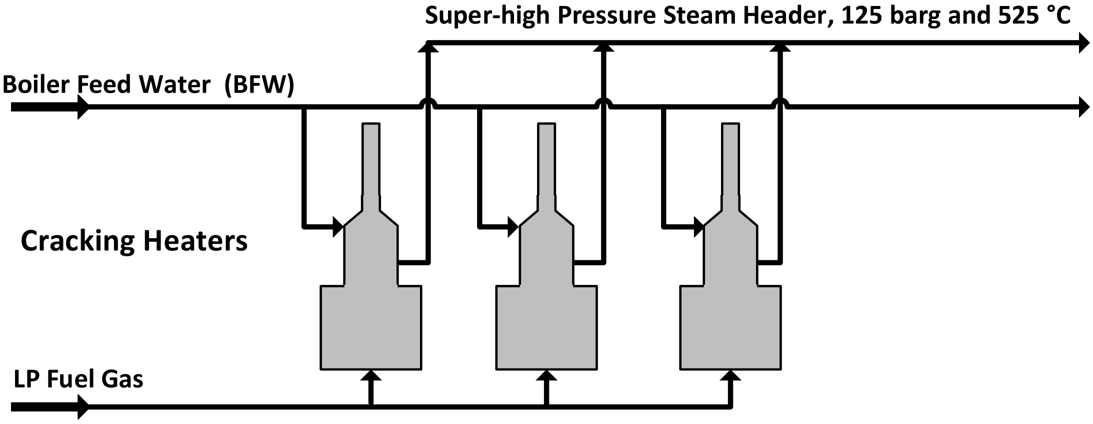


Fig. 1. Overall Configuration of Cracking Furnace with Ambient Air

B. Gas Turbine Integration with Cracking Furnace

When the heaters are integrated with gas turbine exhaust (TEG) as the primary source of combustion air, the oxygen in the preheated air to the heaters is significantly lower, about 14-16 vol%, depending on the turbine model characteristics. Therefore, to maintain the same excess air to the heater burners, a higher total flow of combustion air is required. This effect is translated to the need for higher heat recovery from the higher flue gas flow to maintain overall efficiency (same stack temperature), resulting in increased steam production. The process side (feed preheat and cracking) of the heater operation is essentially unchanged. The fuel fired in the heater is reduced about 10%, due to the high heat content of the TEG which provides heat input **[7]**.

Makeup ambient air supplements the TEG, via a common trim fan (TF) connected to the main duct. The use of the TF enables the system to control duct pressure at a fixed level, thereby maximizing utilization of hot TEG to the heaters without causing combustion flow maldistribution or “starving” oxygen from any particular heater. This is important because each heater may have different cracking conditions. There is typically no venting of TEG under normal cracking conditions with all heaters in operation. Some plants have successfully used TEG during High Steam Standby and decoking operations **[7]**.

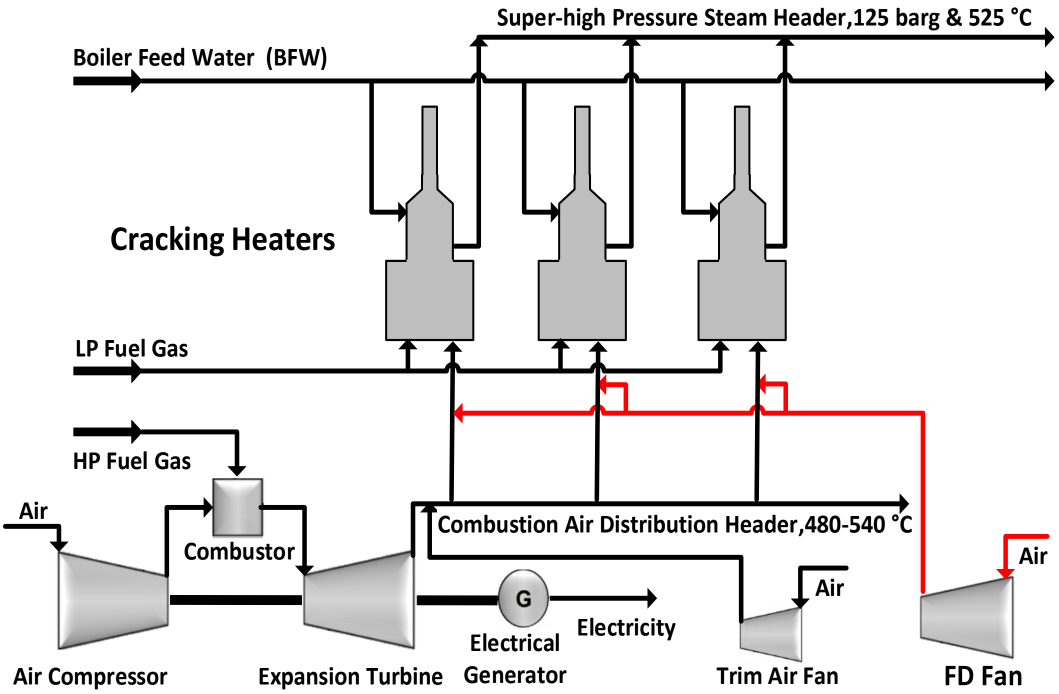


Fig. 2. Configuration of Gas Turbine Integration with Cracking Furnace

III. GAS TURBINE INTEGRATION IN ETHYLENE PLANT

A. Utility Balance for World Class Ethylene Plant

For the GT integration scheme applied to a plant capacity of 1000 kTA naphtha cracker, an industrial-type gas turbine at an optimized TEG flowrate and electrical output to best fit the heater operation has been selected. The GT size selected utilizes all the TEG as combustion air to the heaters, with approximately 85% of the oxygen for combustion from TEG, and the balance from ambient trim air (TF) and wall burner firing, in order to achieve the required 10% excess air level for safe burner firing. It is assumed that all the TEG is used in the heaters, with no venting to atmosphere.

In Table I the utility balance for gas turbine integration is compared to the base 100% ambient air configuration for design. The evaluation assumes that the same crossover temperatures and thermal efficiency are applied to the GT and Ambient heater designs. This means that the heating surface in the convection section would be adjusted as necessary for the gas turbine design.

The table also shows the improvement in plant energy efficiency, i.e., decrease in specific energy, for GT integration compared to 100% ambient air. This is because the electric power generated by the gas turbine and the additional steam produced in the heaters compensate for the higher total fuel fired (heaters plus gas turbine).

TABLE I. HEAT BALANCE COMPARISON BETWEEN AMBIENT AIR DESIGN AND GAS TURBINE INTEGRATION

TABLE II.

	Air Design	Turbine Integration	Credit (+)/ Debit (-)
Fuel Fired , MMkcal/h			
Cracking Furnaces	631	583	
Gas Turbine Fuel Fired	0	224	
Total Fuel Fired	631	807	- 176
SHP Steam Production, t/h	438	576	+ 138
Net Electricity Production , MW	0	83.2	
Energy Improvement, MMkcal/h			
Specific Energy, kcal/kg Ethylene	5367	4311	
Ethylene Production Rate, t/h	125	125	
Efficiency Electricity Generation, %	-	60	

The decrease in specific energy is 1056 kcal/kg ethylene with GT integration. The value of fuel equivalence for electricity (2675 kcal/kW) may vary but that effect should result in the same order of magnitude savings in specific energy.

The energy savings comes from the electricity generated, the reduced heater firing, and the additional super high pressure steam produced in the cracking heaters. The specific energy savings is summarized below:

Integration of the gas turbine increases the SHP steam production by138 t/h. This can have an impact on the plant steam balance, e.g., it can reduce import of SHP or lower level steam. However, if the plant cannot utilize the additional steam, then an outside user for the export must be found.

The extra SHP steam production can also reduce firing requirements in the utility area (boilers), where energy efficiency is typically much lower than heat recovery in the ethylene heaters.

Another consideration for GT integration is the fuel needed to fire the GT. Since the plant offgas may not satisfy the total fuel requirements when including the GT firing, sufficient fuel shall be imported.

Another important consideration is where to export any surplus electricity which is above the requirements for the ethylene plant and neighboring facilities in the complex. This can have a major impact on the economics to justify the GTI-integration design option.
Table II below shows preliminary cost information for the following basis:

- 1000 kTA Ethylene Plant
- Utilities and gas turbine data are from Table I

TABLE III. COST INFORMATION FOR GAS TURBINE INTEGRATION OF HEATERS

Design	Unit	Gas Turbine/Heater Integration
Fuel Cost	US $/MMkcal	25
Electricity Cost	US $/kWh	0.063
Net Energy Saving	MMkcal/h	132
Operating Cost Saving	Million US$/year	26.4
Total Investment Cost *	Million US$	58
Payment Time	Year	2.2

* Equipment-only price for one simple cycle power unit, consisting of a skid-mounted single fuel gas turbine, electric generator, air intake with basic filter and silencer, exhaust stack, basic starter and controls, conventional combustion system, quoted FOB the factory in 2012 US dollars.
(Source: Gas Turbine World 2012 GTW Handbook, Volume 29)

Based on this table, the gas turbine system should pay for itself in two years.

Modifications to the ambient air-only heater design include more convection surface area for SHP steam production, larger ID fan/motor, upgraded burner materials, new trim/forced draft fans, and new ducting.

The implementation of the gas turbine integration scheme does not affect once-through yields, radiant coil size, or process conditions (hydrocarbon feedrate, dilution steam ratio, and severity). Run length is maintained for the GTI-heater operation by designing to the same crossover temperature as an AMB-heater.

IV. FACTORS TO CONSIDER IN GTI

There are several factors to consider when designing the heaters for gas turbine integration (GTI) instead of the base 100% ambient air (AMB) configuration:

1. The ID fan size is increased for a GTI-heater, due to the higher flue gas flowrate associated with lower oxygen content in the combustion air, and the requirement to maintain the same excess air to the burners as the AMB-heater;

2. Convection section heating surface is increased for a GTI-heater in order to recover the heat in the flue gas as SHP steam and maintain the same thermal efficiency as the AMB-heater;

3. There should be a steam balance evaluation to ensure all the additional SHP steam is used in the plant or exported;

4. Fuel gas to the turbine is typically high-methane content, compressed to about 20 kscg at the GT burners, while the heater fuel gas can remain at typical composition for a liquid/gas cracking plant at about 2.5 kscg at the burners;

5. Plot plan must allow for adequate room to install gas turbine, emergency GT vent stack, TEG/Trim Air mixer, combustion air ducting to the heaters, standby forced-draft fans, combustion air manifolds underneath the heater, etc.;

6. The run length of a GTI-heater operating on 100% ambient air will be lower than that same heater operating on TEG, due to the lower crossover temperature which is the result of the fixed convection section surface.

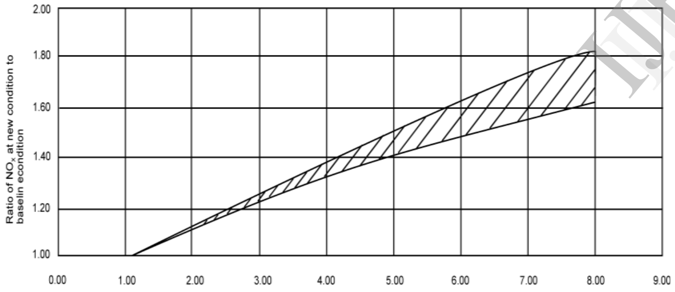
V. NOx FORMATION PARAMETERS

In this section, TEG impact on emissions is reviewed. One of the main NOx formation routes is the thermal NOx mechanism. This mechanism shows that thermal NOx increases exponentially with temperature, making it the dominant mechanism for NOx production in cracking and reforming furnaces [8].

Thermal NOx formation during combustion with air or TEG depends on two main parameters; 1) the temperature of the flame zone and 2) the oxygen concentration.
The temperature of the flame zone is a function of the adiabatic flame temperature and the firebox temperature. The adiabatic flame temperature is that temperature reached by the combustion products when no heat is lost to the surroundings. Its calculation requires taking into account all the energy going into the combustion process, such as air temperature and composition, fuel temperature and composition, excess air, etc.

The firebox temperature plays a role because it is a result of the heat extraction out of the flame zone, and it sets the temperature of the flue gas that is reentrained back into the flame zone. The adiabatic flame temperature itself is determined by fuel composition and temperature, excess air (or in case of TEG it is better to speak of excess oxygen), air/TEG temperature and composition. With increasing the adiabatic flame temperature NOx emissions is increased.

Excess air or excess oxygen is especially important since it determines the oxygen concentration in the flame zone which has a direct impact on NO_x production [9, 10]. The kinetic impact of O2 is more important than the cooling effect of air on the flame temperature, so high excess oxygen typically results in high NOx emissions. For example, Figure 3 from API 535 [11] shows the estimated increase in NOx emissions due to excess oxygen. According to this figure, increasing the excess air from 1% excess oxygen to 5% excess oxygen increases NOx by nearly a factor of 1.5 or 50 percent. Only when the excess air is steadily increased to very high levels (>> 8% O2) the reduction in NOx due to the reduction in flame temperature finally overcomes the increase in NOx due to oxygen concentration. Further increases in excess air then reduce NOx emissions. The presence of water or steam is known to have an impact on NOx formation as well [12]. Besides lowering the flame temperature it is also believed that a portion of the reduction is caused by the increased partial pressure of reducing agents in the primary combustion zone and a subsequent depletion of O radicals. The increased concentration of reducing agents results from the dissociation of steam to hydrogen and oxygen.



Note: This figure is representative only and not intended for design or correction.

Fig. 3. Effect of excess oxygen on NOx formation (API 535) [11]

For Olefin plant described in this paper, gas turbine integration impact on NOx has been summarized in Table III.

TABLE IV. COMPARISON OF COMBUSTION AIR SOURCE CHARACTERISTICS

Combustion Air Source Characteristics	**Ambient Air**	**TEG**
Temperature, °C	25	480-540
Oxygen, vol.%	21	13-17
Inert, vol.%	79	83-87

In the case of TEG stack emissions results are as below:
–22% reduction in NOx concentration (as ppm)
–15% reduction in NOx emissions (as kg/MMkcal)

VI. RESULTS AND DISCUSSION

A standardized scheme was presented to integrate gas turbine power generation into ethylene plants. In addition to generating electric power, the turbines provide oxygen-rich, preheated air as a combustion air source for the cracking heaters. This combination improves the plant's overall energy efficiency, i.e., the specific energy per unit of ethylene production is reduced. Specific Energy reduced from 5367 to 4311 (~ 19.7%).

Firing a cracking furnace on TEG, results in lower firing rates, increased HP steam production and a high overall thermal efficiency.
On a concentration basis, firing with ~540°C TEG containing about 15 vol% O2 (wet) yields about 22% less NOx than the ambient air case (15% reduction in NOx emissions as kg/MMkcal).

The CO_2 product (greenhouse gas) emissions from the heaters are typically reduced by about 5-10%.

This integration scheme enables the ethylene plant to be operated without the gas turbine, in case of a trip or maintenance of the turbine, thus there is no lost ethylene production.

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