GAS TURBINE DIRECT EXHAUST GAS INTEGRATION IN PROCESS INDUSTRY – REVIEW OF APPLICATIONS AND OPPORTUNITIES FOR POLISH MARKET

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Abstract

The typical combined heat and power plants requires the introduction of additional heating medium. The alternative solution is the direct integration of the exhaust gases from heat engine. The high temperature, surplus oxygen and low water content of the GTs exhaust gases enabled the successful integration at industrial scale as: preheated combustion air for industrial furnaces, heat source for drying and for absorption chillers. The article comprises the reference list for direct exhaust gas integration of GTs produced by GE, the processes overview, GTs selection criteria, as well as the review of documented GTs applications in process industry focusing on technical and economic considerations. The described solutions allowed to reduce the specific energy consumption in the range from 7 to 20% or the costs of energy consumption by 15-30%. The overall efficiency of cogeneration plant above 90% was achieved. The preliminary assessment of potential applications for GTs produced by GE with TEG integration in Polish process industry is done.

Key words: turbine exhaust gases, gas turbines, utilization, direct drying, cooling, heating

1. INTRODUCTION

Raising electricity and fuel costs, combined with environmental norms being more rigorous, stimulates the efforts to enhance the efficiency and reduce emissions in process industry. One of the solutions for these needs is given by combined heat and power (CHP) plants. Typically, the CHP plants are indirectly integrated with process, by the means of heat recovery from exhaust gas to produce steam or hot water, according to process demand. Alternative solution in which the additional heating medium becomes optional is the direct integration of exhaust gases with process. The direct integration allows to enhance the overall effectiveness of heat exchange between engine and process. When the significant heating or drying of feedstock is required compering to the plant power demand, the GT engines, with favorable exhaust energy to power ratio are attractive for direct exhaust gas utilization. Turbine exhaust gases (TEG) from the GT with shaft power level less than 35 MW have been successfully integrated at industrial scale applications as:

- Preheated combustion air for industrial furnaces
- Heat source for direct drying
- Heat source for absorption chillers

The main attributes of GT that enabled mentioned applications are: surplus oxygen content, high temperature and low water content of TEG as well as high exhaust energy to power ratio. The comparison with reciprocating engines that are also commonly selected for CHP applications is reported in Table 1.

Table 1 Comparison of the GT engines with power less than 35 MW with reciprocating engines.

Heat Engine	**Power**	**Efficiency (LHV)**	**Exhaust Gas**				
			Temp.	**Mass Flow**	**Oxygen**	**Water**	**Energy to Power Ratio (3)**
	MW	%	°C	ton/hr	% by vol.	% by vol.	-
Gas Turbine (1)	5.6-33.6	29-41%	480-570	70-510	13-15	6-8	1.0-1.9
Reciprocating (2)	1-17.7	41-51%	390-430	6-110	9-11	9-12	0.4-0.7

Notes: 1. Gas Turbines offered by Baker Hughes. Performance data at ISO conditions in accordance with ISO 2314:2009 (15°C)
2.Performance data at ISO conditions in accordance with ISO 15550:2002 (25°C), based on [1] and leading OEM's technical specifications.
3. Exhaust Energy referred to 120°C

GT selection for specific application requires an in-depth knowledge about process and the TEG properties. Technical constrains of industrial process and the performance of GTs available in the market, as well as economic aspects are determining the feasibility of the integration. Successful application requires matching of the TEG properties for GTs available on the market with the process requirements, thus during GT selection the multiple tradeoffs need to be addressed. In case the revamping of existing plant with TEG integration is considered, the modification of process equipment may be required e.g. extending the heat transfer area required to utilize the increased mass flow of TEG comparing to pre-modification system. The technical indicator of successful TEG integration is the change in the specific energy of industrial process (energy consumed to produce the specified quantity of product).

TEG utilization as the preheated combustion air for the primary reformer furnace in ammonia plants [2] and steam cracker furnace in ethylene plant [3] is recommended by the best available technology (BAT) issued by European Commission. Further TEG integrations are suggested by the BAT for ceramic manufacturing industry in the spray dryers used during tiles production and in the brickworks dryers [4].

The opportunities to enhance the profitability of CHP plant are given by the possibility to burn the by-products of industrial process in GT (process gas in ethylene plant) and utilization of the excess steam that is commonly generated during quenching of high temperature reactions (cracking and ammonia syntheses). The excess steam can be injected to GT for the NOx abatement or power augmentation [5].

According to the GE records the TEG was directly integrated for the 1st time in late 60's in ammonia plant in which the single shaft Frame 5 engine (15000 hp) was installed as driver for PAC. The reference list of the 1st and recent projects for GE gas turbines, in which the TEG has been directly used in the downstream process is reported in Table 2. In mentioned applications the selected engine is typically heavy-duty Frame 5 engine, with the base load shaft efficiency around 30% and significant TEG mass flow rate (450-510 ton/hr at full load and ISO conditions). In the last years the modern gas turbine MS5002E (43000 hp) with efficiency around 36% have been selected. The current GT engines offered by Baker Hughes in the 5-35 MW power range are reported in Table 3, the highlighted GT models were selected in the referenced projects with direct TEG integration.

The main objectives of this article, addressed for 3 various direct TEG integration applications (industrial furnaces, direct drying and absorption chillers) are following:

- Describe the industrial process in which TEG was directly used in the particular applications
- Define the GT selection criteria
- Review of successful applications, with focus on technical and economic considerations
- Review potential opportunities for direct TEG integration in Polish Industry.

Table 2 Reference projects with direct TEG integration in industrial plants for the Baker Hughes GTs (Formerly GE).

GT Model	COD	Country	Industry	NOx abatement	Primary Fuel	Driven Equip.
MS5002B(R)	1983	UK	Petrochemical	None	Process Gas	CGC
MS5002C(R)	2004	UK	Petrochemical	None	Process Gas	CGC
MS5001LA	1971	USA	Inorg. Chemicals	None	Natural Gas	Generator
MS5001LA	1971	USA	Inorg. Chemicals	None	Natural Gas	Generator
MS5001LA	1971	USA	Inorg. Chemicals	None	Natural Gas	Generator
MS5001PA	Install	USA	Inorg. Chemicals	DLN 1	Natural Gas	Generator
PGT2	1995	Italy	Pulp & Paper	Water	Natural Gas	Generator
MS5001L	1967	USA	Fertilizer	None	Natural Gas	PAC
MS5001L	1968	Netherland	Fertilizer	None	Natural Gas	PAC
GE10-2	2000	Netherland	Fertilizer	Steam	Natural Gas	PAC
MS5002C	2000	Saudi Arabia	Fertilizer	Water	Natural Gas	PAC
MS5002C	2003	China	Fertilizer	None	Process Gas	PAC
MS5002C	2010	China	Fertilizer	LHE	Natural Gas	PAC
MS5002E	2015	India	Fertilizer	DLN 2.5	Natural Gas	Generator
MS5002E	2015	Bangladesh	Fertilizer	DLN 2.5	Natural Gas	PAC
MS5002D	2016	India	Fertilizer	Steam	Natural Gas	PAC
MS5002E	2017	Bolivia	Fertilizer	DLN 2.5	Natural Gas	PAC
MS5002D	2019	India	Fertilizer	Steam	Natural Gas	PAC
MS5002C	2019	Egypt	Fertilizer	Steam	Natural Gas	PAC
MS5002D	Install	Brazil	Fertilizer	Steam	Natural Gas	PAC
MS5001PA	Install	Canada	Fertilizer	Steam	Natural Gas	PAC
MS5002D	Install	India	Fertilizer	Steam	Natural Gas	PAC

Table 3 Base load performance at ISO conditions for Baker Hughes GTs with DLN/DLE combustion system and power level below 35 MW. Exhaust Energy referred to 120 °C.

GT Type	GT Model	Shaft Power	Efficiency (LHV)	Exh. Temp.	Exh. Flow	Exh. Energy	Exh. O_2	Exh. O_2
		MW	%	°C	ton/hr	MW	% vol.	ton/hr
Small Industrial	LT5-1	5.9	31.9%	574	71	9.9	13.6	11
	LT5-2	5.6	31.5%	556	72	9.7	13.8	11
	GE10-1	11.6	32.3%	482	173	18.9	14.8	29
	GE10-2	11.8	32.7%	486	168	18.7	14.7	28
	LT12	12.6	36.5%	488	152	17.0	14.2	24
	LT16	16.8	37.3%	482	197	21.6	14.3	32
Heavy Duty	MS5001PA	27.8	29.9%	483	451	49.4	14.8	75
	MS5002C	28.4	29.0%	517	447	54.0	14.6	73
	MS5002D	32.5	29.6%	510	509	60.2	14.7	83
	MS5002E	32.1	36.5%	496	370	42.4	14.0	58
Aeroderivative	PGT25	23.3	37.5%	529	245	28.6	13.6	38
	PGT25+	31.1	40.5%	501	302	32.3	13.7	46
	PGT25+G4	33.7	40.5%	513	324	35.8	13.5	49

1. INDUSTRIAL FURNACES AND HEATERS

1.1. Process Overview

High temperature reaction is one of the initial steps applied in the production of large volume chemicals, in which the feedstock is converted to intermediate product. Typical examples are: the steam cracking in ethylene plant, that is used to broke down the long-chain hydrocarbons into ethylene and steam reforming in ammonia plant, that is used to produce hydrogen for ammonia synthesis. To achieve the high yield of desired product and to allow further processing, the steam cracking and reforming are followed by quenching process, that gives opportunity to recover heat and generate steam. Produced steam is mainly used as the reactant, for feedstock preheating and feeding the steam turbines that are driving the process compressors. The feedstock is heated by furnaces to 750–900 °C in the steam cracking [6] and to 400–600 °C in primary reformer [2]. Most common feedstock for reforming process in ammonia plant is Natural Gas, while in the ethylene plants the various hydrocarbons are cracked, starting from ethane, through propane, LPG, naphtha up to heavy gas oils. Crackers can be designed to be fed by single component as well as the combination of gas and liquid streams. In both processes the GT integration have been successfully applied with the specific energy consumption reduced by 7-20% [2] [6]. The typical integration diagram is shown on Figure 1.

Another example of processes requiring significant heating of feedstock are the atmospheric and vacuum distillation units in refineries, as well as heating of intermediate products in further processing steps. Utilizing TEG as combustion air for feedstock furnace and as a replacement of heaters have been analyzed [7] [8], however no industrial application have been reported so far.

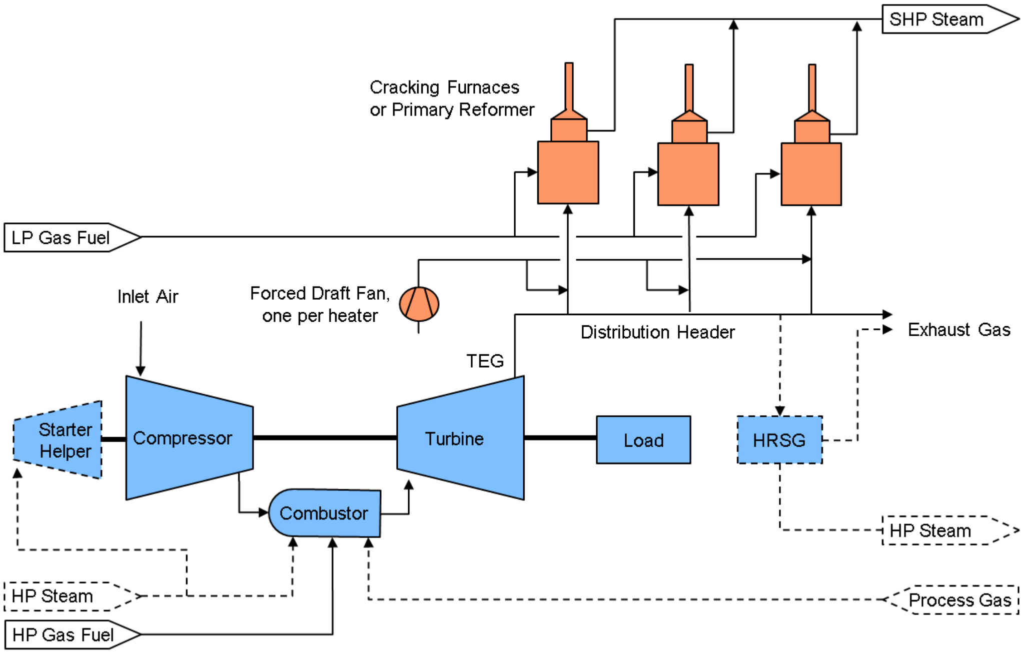

Fig. 1 Gas turbine integrated with Ethylene Furnace or Primary Reformer in Ammonia plant [2] [5] [6]. Optional streams and equipment are marked with dotted lines.

1.1.1. Application Review

Ammonia Production

The 1st application of TEG as a preheated combustion air for primary reformer was implemented in late 60s for ammonia plant in USA, in which the single shaft GT was used to drive the PAC. Since then at least 18 Baker Hughes GTs (Formerly GE) have been integrated, from which the majority are the 2-shaft heavy-duty engines applied as a driver for PAC. The design capacity of plant with TEG integration is from 1100 to 2600 MTPD of ammonia. In the last years the modern heavy-duty GT (MS5002E) was selected for generator drive application. When the GT is applied as generator driver, the ammonia production process can be operated independently of GT availability. Safe transition from operation on TEG to forced ambient air is critical during GT emergency shutdown, because the TEG flow decline more rapidly comparing to normal shutdown.

The example of grassroots project is the ammonia plant in Canada [12] in which the design based on GT driven PAC and TEG integration, was one of the technological features that allowed to achieve low energy demand (30.2 MJ/kg NH_3). In 2015 GE Oil&Gas (currently Baker Hughes) replaced the original 2-shaft GT installed in this plant with single shaft heavy-duty GT (MS5001PA) equipped with steam injection for NOx abatement, manual inlet guide vanes (IGV) control and manual control of inlet bleed heating (IBH) system. The manual IGV control allows to regulate the air flow thorough the GT axial compressor, while the manual IBH control enables the regulation of the GT inlet temperature. The combination of both systems made possible to manually control the TEG temperature and flow at the constant power required by specific PAC operating point.

The ammonia plant in Netherland is example of plant revamping by extensive preheating of the feedstock and the installation of modern small industrial 2-shaft GT (GE10-2), that drives the PAC and provides TEG with amount of oxygen nearly matching the requirements of primary reformer furnace [2]. The excess steam from the process is utilized in GT for NOx abatement purpose and power augmentation (Fig.1). The furnace burners were modified, to achieve uniform distribution of the TEG over the burners. As a result of this plant revamping, the specific energy was reduced from 36 to 31.1 MJ/kg NH_3, however the 50% of reduction was achieved by maintenance activities. Thanks to the lower oxygen surplus the plant NOx emission was reduced <200 mg/Nm3. The expected payback period was less than 1 year.

Ethylene Production

The specific energy of ethylene production has been successfully reduced by the TEG integration with cracking furnaces. This solution is highly attractive for locations with high electricity cost and possibility to export the excess steam and power. The integration of GT saves between 10 to 20 % of total energy requirement for an ethylene plant [6]. In 2005 11 plants were operating successfully with the TEG integration concept designed by Lummus.

The 1st design in ethylene production application was placed in service in the mid-80s in Scotland featuring the 2-shaft Frame 5 GT driving the gas compressor train [5]. Originally installed GT was MS5002B with regenerator, in 2004 the unit was replaced by MS5002C. GT is heavily integrated with the plant, the GT uses the plant by-product gas as fuel, the excess steam is injected to augment GT power and utilized in 6MW helper/starter steam turbine (Fig.1).

Most recent designs include the turbo-generator train rather than turbo-compressor, because the excess steam from the process is utilized mainly on steam turbine driving compressor train. In the ethylene plants in Japan and Korea for the 1st time the aeroderivative GTs were integrated with cracking furnace [10]. Another 3 plants, designed with heavy-duty GTs, started-up at the beginning of 90’s. All systems are designed with generator drive GTs to allow safely switch the ethylene cracker heaters from TEG to forced ambient air, without shutdown that is common for designs based on mechanical drive units. Sufficient redundancy of oxygen source allows to operate the plant independently of GT availability. The original design of integration system with aeroderivative engine required temporary reduction in cracking furnace firing during GT emergency shutdown, due to rapid decay of TEG flow. In the improved designs, firing reduction was avoided by installing air fans close to each heater and running them continuously. During GT emergency shutdown system performed as expected with furnace operating continuously through the transient. Additionally, operation on TEG decreased the cracking heaters NOx emission from 95 ppm to 70 ppm on dry basis and 0% O2 content.

The heat balance and economic modeling have been conducted for GT TEG integration in ethylene plants designed for 750 kTPY [10] and 1000 kTPY [11] capacities with naphtha feedstock. In the first case the two Frame 5 single shaft units are proposed (42.8 MWe), while in the second case the 83.2 MWe turbo-generator is proposed. The specific energy is reduced respectively by 13.5% to 20.6 MJ/kg and by 19.7% to 18.0 MJ/kg. In both analyzed cases the electric power produced by turbo-generator and additional steam generated in the heat recovery compensate the higher total fuel consumption. The simple payout rate for proposed solution is 2.2 years.

Refinery

For bitumen refinery (300 kbpd bitumen mixed with 100 kbpd naphtha) in North America with 540 MW electric power requirement, authors propose to replace 2 furnaces used for heating feedstock for atmospheric and vacuum distillation and superheat the steam by TEG from three PG9351 (FA) gas turbines [7]. At Natural Gas price of 20 $/MWh gas turbine are more economical and the price limit is at NG price of $ 30 /MWh.

The linear programming to address multiple tradeoffs simultaneously, was used to propose the optimal GT for integration in the system of furnaces (340 MWth) and boilers (360 MWth) in the oil refinery [8]. Assuming the site maximum consumption of 30 MWe, the screening step indicated the optimal size is around 25÷30 MW and the payback time is between 1.3 to 1.9 years. For integration with HRSG, the best performance is achieved with aeroderivative GT, while for the integration with furnaces with Heavy Duty GTs.

1.2. GT Selection Criteria

Following criteria were considered to select the GT for integration with reforming and cracking furnaces [5] [9] [10] [11] :

- Significant oxygen concentration in TEG
- High temperature of TEG
- 10% excess in available Oxygen mass flow comparing to the furnace demand
- Low NOx emission
- Possibility to utilize the excess steam and operate on process gases.

The stable combustion in the reformer and cracker furnace requires the sufficient temperature and oxygen content of TEG. Figure 2 shows an example of the stability limit defined by burner manufacturer and the estimated fuel saving in steam cracking furnace relative to operation on ambient air [5]. Even though the savings shown are for average furnace and will vary depending on feedstock and furnace design, the 0% estimated fuel saving line can be used as a threshold for the profitability of TEG integration. The values of exhaust temperature and oxygen content at ISO conditions and Full Load for the GTs currently offered by Baker Hughes in the 5-35 MW power range from Table 3 are plotted. As shown the estimated fuel saving is within 5-15%, thus all offered GTs can be considered potentially profitable for this application. The TEG properties and consequently fuel saving is affected by ambient conditions, less fuel will be consumed during hot days and more fuel is needed in cold days.

The next criterion is that the O_2 mass flow rate of TEG needs to match the furnace demand with 10% margin. GTs being constant volume flow engines are affected by changes in air density, thus the selection needs to be based on the max temperature during summer days, in which the O_2 mass flow rate in TEG will be lowest. This approach leads to surplus TEG flow in ISO and low ambient temperatures, that can be utilized in the plant heat recovery system.

In case of limited fuel availability or plant demand for power, the selected GT may not satisfy the furnace O2 demand and the partial integration can be considered supplemented by fan blowers. Nevertheless, fuel savings are decreased when the TEG is mixed with ambient air.

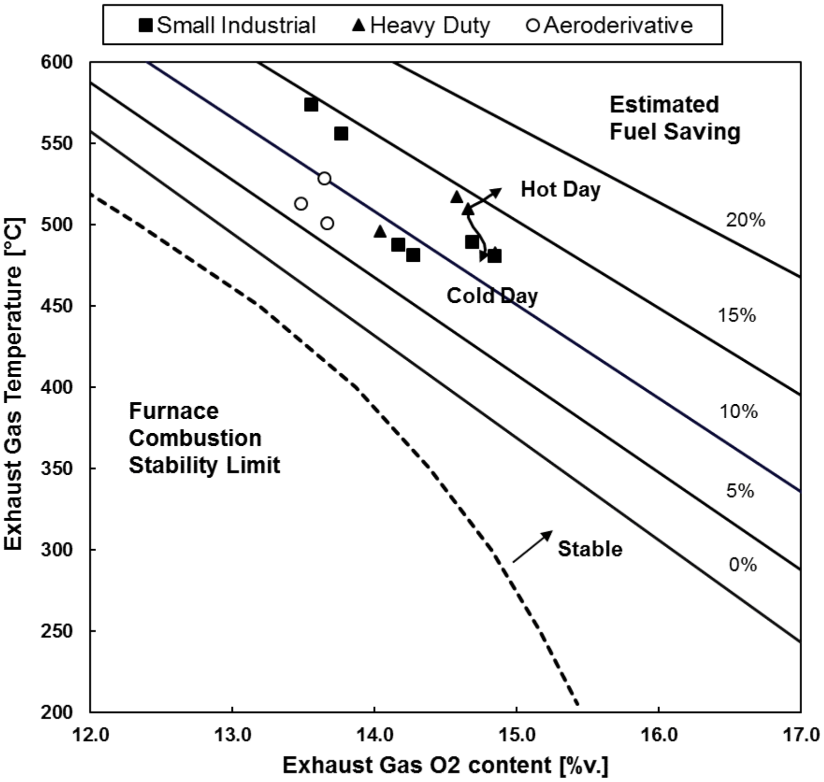

Fig. 2 Estimated Fuel Saving vs Exhaust Gas Temperature and O_2 content in steam cracking furnace *[5]*

1.3. Opportunities for Polish Industry

Several potential opportunities to integrate the TEG with process furnace are identified in the Polish process industry. The most promising are the ethylene plant in Płock with design capacity of 700 KTPY based on Lummus technology and the ammonia plant in Puławy, that consist of 2 trains, each designed for 1500 MTPD capacity. Other applications of TEG integration could be considered for ammonia plants in Włocławek and Kędzierzyn-Koźle, each one has design capacity of 1500 MTPD. The ammonia plants in Poland are designed with conventional steam reforming and partial oxidation processes, that consumes more energy comparing to reduced primary reformer with GT integration [2].

Based on comparison with reviewed applications, the oxygen demand of cracking furnace in 700 kTPY ethylene plant is expected to be satisfied by two modern heavy-duty GTs – MS5002E. The steam cracker in Płock is designed for variable feedstock from C2+, LPG up to heavy gas oil, therefore the variability in actual duty and oxygen demand of furnaces needs to be considered to verify the GT selection. The demand of oxygen in primary reformer furnace of 1500 MTPD ammonia plant, could be satisfied by two aeroderivative GTs – PGT25. Further opportunity is the reduction of NOx emission and potential CO2 tax reduction, by using less carbon intensity fuel, as well as funding programs for electricity production in high efficiency cogeneration. The detailed technical and economic analysis are required for mentioned plants to estimate the reduction in specific energy and profitability of TEG integration.

2. DIRECT DRYING

2.1. Process Overview

Drying is commonly applied in process industry to remove water from raw material prior to further processing. High amount of heat required for drying is typically produced by the duct burners, in which the hot gasses are generated at temperature from 170 °C to 850 °C. The maximum temperature of hot gases is limited by thermal stability of dried material and safety requirements associated with risk of fire. Depending on the considered fuel and product quality requirements, hot gases can be directly supplied to the dryer (Fig.3) or the heat can be exchanged indirectly by means of steam, thermal oil or ambient air. The direct drying is allowable for gas fuels that produce clean hot gases, while the liquid and solid fuels requires indirect drying system. As an exception the direct drying is not applied in the food industry, even with gas fuels, because of rigorous product purity requirements. High drying requirements are associated with production of: inorganic and construction chemicals, ceramic tiles, wood derivatives, food and pulp & paper.

The power generated by GT is significantly enhancing the global efficiency of fuel usage from 40-50 % for duct burners to 65-90% for CHP with direct drying. The gas consumption for drying system based on GT will increase, however the generated electricity is reducing the overall energy consumption cost by 15-30% [13] [14] [15]. Successful applications of TEG for direct drying have been reported in ceramic, wood derivative, pulp & paper and inorganic chemicals industries. Up to now there are at least 120 GTs directly integrated worldwide with various type of dryers: spray (Fig.3), flash and drum, as well as paper machine.

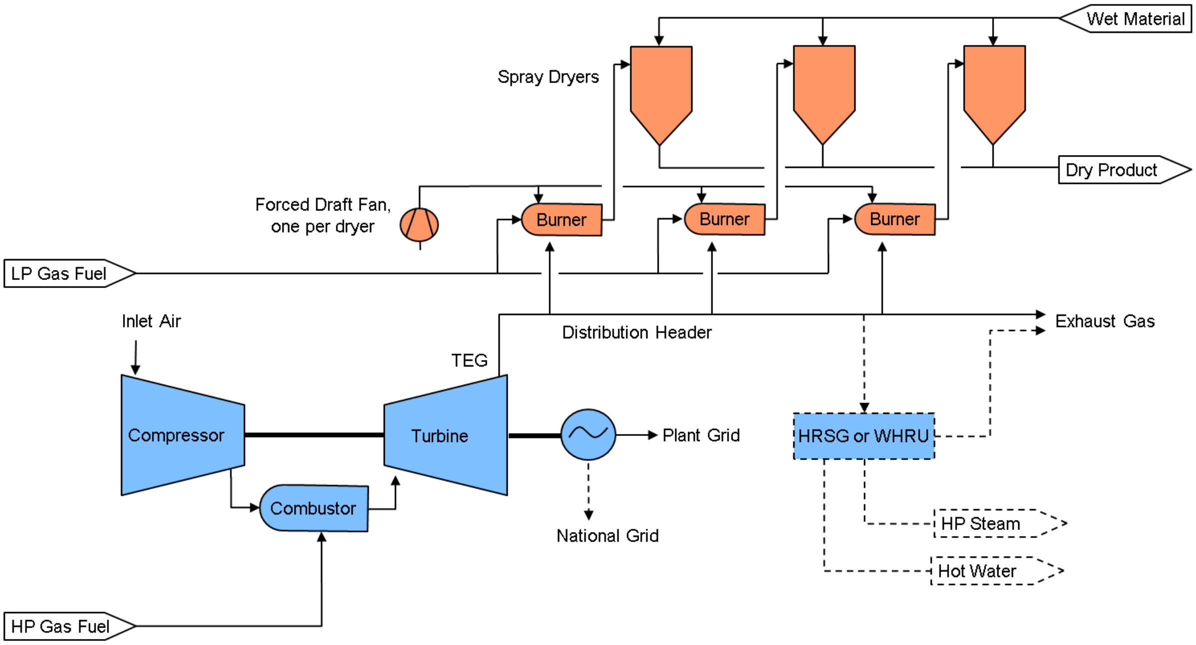

Fig. 3 Gas turbine integrated with Spray Dryers [14] [16]. Optional streams and equipment are marked with dotted lines.

2.1.1. Application Review

Inorganic Chemicals

The first application of TEG for direct drying was installed at the beginning of 70s in the magnesium production plant in USA. Three single shaft GTs are producing power and hot gases that are utilized in spray dryer and HRSG. The ISO rating of installed GTs was 55 MWe and is the largest reported CHP plant with TEG applied for direct drying. Recently the plant is under revamping process to increase production capacity from 63.5 kTPY to 76.5 kTPY of magnesium and to install new MS5001PA GT with TEG applied for direct drying. Eventually, the total ISO power of CHP plant will be 82.2 MWe.

Ceramic Industry

The most energy consuming equipment in ceramic industry is the spray dryer, in which the hot flue gas at 550÷600°C is used to dry raw material from 35÷40% to 5÷6% moisture [14]. Numerous CHP plants with TEG application for direct drying are operating in ceramic factories in Brazil, Italy and Turkey [13] [17]. The turbo-generator power level is from 1.1 MWe to 7.5 MWe. The largest CHP direct drying plant in ceramic industry has total power of 22.5 MWe and consists of three GTs with TEG ducted to nine spray dryers.

In the vitrified tiles plant in India with design capacity of 3.6 mill. m^2/year, GT with power level of 3.5 MWe is selected and operated at partial load (80%) aligned with plant electrical load [14]. TEG is ducted to the spray dryer and no supplementary firing is required for most of the time. Product quality is the same as in the present process. NG consumption will increase, but the overall energy consumption cost will be reduced by 23%. Simply payback period is 3.6 year.

The CHP plant in a ceramic factory, located in Izmir, Turkey, utilizes TEG for direct drying of ceramic muddy to produce ceramic sand [18]. System consists of two 4.2 MWe and one 4.6 MWe GTs, six spray dryers and two WHRUs. Mean efficiency for cogeneration system is estimated to be 82.3% based on the hourly data trends. The exhaust temp. from spray dryers is 70÷90°C and the dried product humidity is 3%. The payback period for investment was found to be 2 years. [16]

Wood Derivatives

CHP plants with TEG direct drying are operating in wooden boards production facilities in Turkey (MDF) and France (particulate boards/OSB) [13]. Both plants consist of one 7.5 MWe and two 5.5 MWe GTs with the design overall efficiency exceeding 80%. In Turkish plant the TEG are ducted to the flash dryers, while in French plant to the drum dryers.

In the wood chips dryer in Turkey with capacity around 50 TPH, the TEG from 5 MWe GT are utilized in drum dryer [19]. The temperature and flow of hot gases are boosted by heating system. The estimated efficiency of the drying system referred to heat of hot gases is 34%, the drying efficiency with reference to consumed fuel is about 40% and the overall efficiency of CHP plant is approx. 65%.

Pulp & Paper

CHP plants with TEG direct drying are operating in tissue production factories in Chile and Italy [13]. Plant in Italy is designed with 7.5 MWe GT, while the plant in Chile with 22 MWe GT. In both cases the excess TEG energy is recovered in HRSG and the saving on energy costs is 15-20% compering to non-integrated system.

Example of deep TEG utilization is the paper production plant in Italy designed for 100 MTPD, in which the CHP plant is based on PGT2 GT with TEG ducted to HRSG [15]. Downstream HRSG, the TEG at 160°C are directly used for drying of paper machine product and are further utilized for water preheat. This highly integrated cogeneration system allowed to achieve the overall fuel efficiency exceeding 90%. The 2 MWe GT has sufficient margin to the plant power demand of 1.6 MWe even during hot days. NOx emission is reduced to 100 mg/Nm^3 (dry, 15% O_2) by water injection. Economic analysis showed the discounted payback time of 3.1 years and energy cost saving of 29.7%.

CHP plant in Spain, operated by the company involved in the manufacture of molded containers and cushions, using paper stock as raw material, utilizes the exhaust heat from two 1MWe aeroderivative GTs in four dryers and hot water boiler [20]. Existing duct-burners (174 kW rated power) are operating continuously supplementing the GT exhaust gas to meet the required process conditions and to keep the process in operation in case the GTGs are not available (Fig.3). The max temperature of gases at the inlet of each dryer must be limited, to prevent any risk of fire. The temperature of gases supplied to the dryers is 170°C to 260°C. The flow-rate of gases supplied to the dryers (turbine exhaust gases plus recirculation gases) must be maintained at a virtual constant, preventing any sudden change. Overall efficiency is 74%, the primary energy saved is almost 50%.

Food Industry

The research done at the end of 80's [21], reveled the direct drying by means of TEG may cause the pollution of food products by the nitrogen oxides or formation of carcinogen compounds (nitrosamines). At that time the diffusive combustors were available, characterized by the NOx emission 5-40 times higher comparing to currently offered lean premixed combustors in GT, that allow to achieve the single digit NOx emission. Despite the significant development in NOx abatement technology, prior to commercialization of direct drying by means of TEG the test combined with food product quality analysis must be performed.

2.2. GT Selection Criteria

The GT selection for utilization of TEG as heat source for direct drying is conducted with following criteria:

- High exhaust energy to power ratio (at least 1.5)
- Recoverable TEG energy at least with 10% margin to the dryer energy demand
- Low H_2O content in TEG (6-7% by vol.)
- High temperature of TEG
- TEG flow rate kept constant

The ratio of exhaust energy to the power for GTs selected for direct drying is from 1.5 to 2.6, typically allowing to satisfy both heat and power demand of the plant. Recoverable TEG energy has to be evaluated at reference temperature corresponding to the exhaust gas at dryer outlet. Typical temperature of the exhaust gases after drying is within 70-100 °C. Selected GTs are designed with high excess air that corresponds to low overall fuel to air ratio (FAR) in the range of 1.5-1.9%. Consequently, to the low FAR, the H2O content in TEG is low (6-7% by vol.) that is beneficial for the mass transfer process in dryer.

High TEG temperature allows to reduce or even eliminate the need for supplementary burners, however in case the TEG temperature exceeds the thermal stability limit of dried material or causes the safety risk, mixing with forced ambient air (Fig.3) or dryer exhaust can be considered.

In the plants with only one spray dryer installed, TEG integration may require the back-up dryer to allow the continuous system operation because the dryers may be shut down frequently for cleaning. Solution based on multiple engines is more reasonable in the sites with limited availability of dryers and variable production quantity.

2.3. Opportunities for Polish Industry

Most attractive opportunity to apply TEG for direct drying is in the ceramic tiles industry in Poland. Based on the production capacity Poland is the 3rd tiles producer in EU. The largest facilities are in Opoczno where the three trains are designed for total capacity of 28 mill. m^2/year and in Wałbrzych with design capacity of 19 mill. m^2/year. Furthermore, there are 7 plants with design capacity from 6 to 9 mill. m^2/year.

Comparing mentioned plants with reviewed applications, the power and heat demand could be satisfied by multiple LT5-1 engines that have the favorable exhaust energy to power ratio (1.9) and substantial exhaust temperature (570 °C).

Poland is the 2nd producer of particle board, 3rd producer of cement and 8th producer of pulp & paper in Europe. The wood derivative industry frequently utilizes the by-products of production to meet the plant heat demand, while in the cement factories the RDF fuel is commonly used. Most of the plants producing pulp & paper in Poland generate heat and power in the distributed CHP plants based on biomass and coal fuels. The exception is the paper plant in Kostrzyń, where the low LHV Natural Gas is utilized in CHP plant (40 MWe and 169 MWth) consisting of two GTs, two HRSG units with supplementary firing and steam turbine generator [13]. As the biomass and RDF fuels are less expensive and are favorable in terms of CO_2 emission comparing to NG, the TEG integration could be considered for the new CHP plants with limited availability of mentioned fuels.

3. TRIGENERATION – ABSORPTION CHILLERS

3.1. Process Overview

Absorption Chiller is the cooling machine, driven mainly by heat and based on the combination of absorption and desorption processes with evaporation at low pressure. One can distinguish the single stage absorption chillers than can operate on low grade heat source (hot water or low-pressure steam) and the double stage configuration, that requires higher grade heat (TEG or high-pressure steam). The coefficient of performance (COP) for single stage absorption chiller is from 0.7 to 0.9, while for more expensive double stage units COP is from 1.05 to 1.4 [22]. The most common absorbents are water solution of LiBr and for application with temperature requirement below 0 °C water-ammonia mixture.

Absorption Chillers are commonly applied for heat recovery in the Combined Cooling, Heating and Power (CCHP) plants. Most of the absorption chillers are indirectly linked with cogeneration plant by means of steam or hot water with typical overall efficiency of 65-75% [23]. In 2004 the first absorption chiller directly driven by TEG, started operation in Texas (USA). The measured total efficiency was 88.8 % [24], proving the advantage of direct heating. The chilled water is produced for district cooling system and for GT inlet air cooling to enhance the performance and efficiency (Fig.4).

The main interest in CCHP based on absorption chillers are in the district cooling and heating systems in the large agglomerations, university campus, hospitals and office buildings [23] [24] [25] [26] [27]. Further examples, can be found in food industry [28] and in several researches for NG treatment plants [29] [30], in which the absorption and desorption processes that require significant heat and cooling are used to remove impurities from NG. High electricity prices, opportunity to recover heat and benefit from high efficiency cogeneration funding programs are the factors that make CCHP plants based on absorption chiller a favorable solution comparing to traditional electricity driven cooling devices.

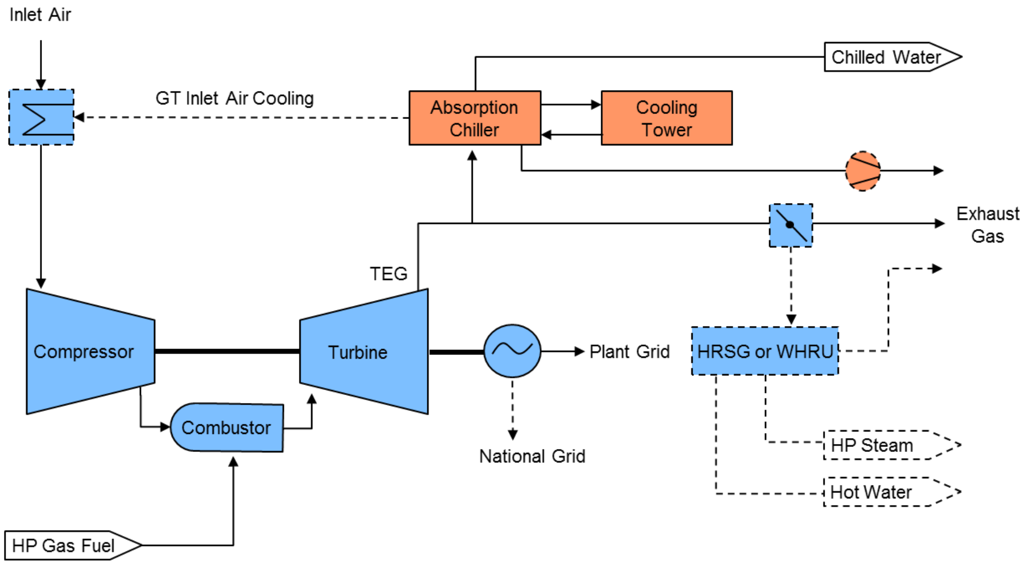

Fig. 4. Trigeneration with absorption chiller driven directly by TEG [25]. Optional streams and equipment are marked with dotted lines.

3.1.1. Application Review

District Cooling and Heating System

In the demonstration project developed through DOE's program in USA (2004), the TEG from 4.6 MWe GT was for the 1st time directly integrated with double-effect absorption chiller (2500 chilling tones) and integrated to district energy system in Austin (Texas) [24]. GT inlet air is cooled to improve power output and electric efficiency using 200-260 tons of chilling capacity during hot days. Absorption chiller is controlled by the outlet temperature of cooling water and the exhaust dampers are closing (less TEG to stack) when the outlet temperature increases. At base load the net plant efficiency is 88.8% (LHV) and the chiller COP is 1.35. The recovered heat can be added to electric power output and cut the NOx emission rate from 0.66 lb NOx/MWh to 0.23 lb NOx/MWh [24] [25]. Plant is economically feasible at baseload for at least 4500 h/year and the estimated payback time is 7 years [26].

Another DOE's demonstration project was deployed (2005) in the military base (North Caroline), in which the CCHP plant was designed with 5 MWe GT and TEG directly splitted into the HRSG and 1000 ton absorption chiller (Fig.4). The advanced control system was developed that considers the forecast for heating, cooling and electricity loads and current fuel prices, as well as thermal models of equipment and buildings to optimize the CCHP plant and supplementary firing operation to meet the loads demand and minimize energy cost or maximize efficiency [27].

Numerous CCHP plant based on GTs with TEG ducted to HRSG and portion of steam used to drive the absorption chillers are in operation in USA [23] serving the university campus, hospitals, pharmaceutical R&D facility and high-rise office building. The typical GT power is within 3.5-4.7 MWe range and absorption chillers rating is within 500-3000 chilling tons. The largest plant consists of three GTs with total power 17 MWe, three HRSGs boosted with duct burners producing 135 TPH of steam at 8.6 barg and eight absorption chillers with total capacity of 6900 chilling tons. The payback period is from 4 to 10 years.

Industry:

5 MWe GTG was installed to cover electric and steam demand of margarine factory in Netherland [28]. Ammonia Refrigeration Plant was installed to utilize the excess steam and a shortage of chill (+1400 kW of refrigeration at -23°C). The indirect linkage allows to run the cogeneration plant at constant load, even at varying steam demand.

The technical and economic feasibility of a CCHP system which uses exhaust gases from two single shaft 26.8MW GTs, was investigated for Natural Gas Processing Plant in the Middle East [29]. In addition, three double-effect H2O–LiBr absorption chillers utilize 37.1MW of waste heat to provide 45MW of cooling at a COP of 1.3. Estimated total efficiency is 69%. For NG processing plant operating 300 days/year, the payback period for CCHP system of approx. 1 year.

Trigeneration with GT and compressor chiller was proposed for the NG absorption treatment unit [30]. The estimated required power was 12.2 MWe and 17.3 MWt. 4 GTs with power range 13.7...17.5MWe were analyzed using the pitch pointy technology method. PGT16 (13.7MWe) with supplementary burner was considered as the most reasonable solution because of lowest fuel consumption.

3.2. GT Selection Criteria

The GT selection for utilization of TEG as heat source for absorption chiller is conducted with following criteria:

- High exhaust energy to power ratio (around 2)
- Recoverable TEG energy at least with 10% margin to the absorption chiller demand
- High temperature of TEG

The ratio of exhaust energy to the power for GTs selected for utilization of TEG in absorption chiller is around 2. Recoverable TEG energy has to be evaluated at reference temperature corresponding to the exhaust gas at absorption chiller outlet. Typical temperature of the gases at exhaust of two stage absorption chiller is within 90-120 °C.

High TEG temperature increase the evaporator temperature that is beneficial for the COP of the double effect absorption chiller. However, the high rate of evaporation could cause the risk of the crystallization in the concentrated water-LiBr solution, that lead to the downtime in chiller operation and additional maintenance cost.

Furthermore, in case the GT inlet air cooling is considered the impact of ambient temperature on GT performance should be taken into consideration. The aeroderivative GTs are more sensitive to ambient temperature, comparing to heavy duty GTs, consequently the effect of GT inlet air cooling on engine performance is greater.

3.3. Opportunities for Polish Industry

Even in the warm regions with low fuel price and in applications with continuous heat, chill and power demand the system consisting of GT and TEG ducted to absorption chiller has rather long payback time. Considering the weather climate in Poland, the district cooling system need to be combined with heating system, thus the CCHP plant based on the GT with TEG splitted into absorption chiller and WHRU via diverter valve could be economically substantiated.

The district heating systems in largest cities in Poland are well developed, therefore the CCHP plant could be analyzed for new systems designed mainly for the heat and chill supply to the industrial customers. Nevertheless, the chill demand and consequently the rating of absorption chiller should be high enough to substantiate the additional expense for CCHP plant.

4. CONCLUSION

The direct utilization of TEG in the process industry is well known and field proven technology that allows to enhance the specific energy and reduce the energy costs associated with large volume production in various industries, as well as improve the efficiency of CHP plants. The payback period in TEG applications as preheated combustion air and heat source for direct drying enables to consider the reviewed applications as commercially viable. Driving the TEG with absorption chiller allows to increase the CCHP plant efficiency, however rather long payback period reveals the necessity of cost out efforts.

Selecting the modern GTs offered by Baker Hughes (□ ≥ 36%) for described applications could further enhance the efficiency and energy cost reduction. As the exhaust energy and oxygen flow for modern GT are lower, multi-engine configuration or application of GT with power exceeding the demand and partial load operation might be required. Selection of the most favorable configuration requires a trade-off between the specific energy reduction, energy cost reduction and the cost of investment.

Screening of potential applications and comparison with reviewed publications, reveled the TEG integration as favorable for ethylene, ammonia and ceramic tiles plants in Poland. Further technical and economic analysis are required for investigated applications, considering the technology used, actual production capacity and maintenance plan at specific site.

Nomenclature

□ - Simple cycle efficiency referred to shaft and LHV
BAT – Best available technology
CCHP – Combined cooling, heat and power
CGC – Charge gas compressor
CHP – Combined heat and power
COD – Commercial Operation Day
COP – Coefficient of performance

DLE – Dry Low Emission
DLN – Dry Low NOx
FAR – Fuel to air ratio
IBH – Inlet Bleed Heating
IGV – Inlet Guide Vanes
LHE – Lean head end combustion liners
LHV – Lower Heating Value
kbpd – Kilo barrels per day
kTPY – Kilo tons per year
MTPD – Metric tons per day
NG – Natural gas
OEM – Original equipment manufacturer
PAC – Process air compressor
RDF – Refuse derived fuel
TEG – Turbine exhaust gases

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