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Natural Gas Fired Power Plant with Tri-Generation of Power, Process Heat and Refrigeration Using Waste Heat Recovery

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Abstract—Tri-generation is one of the most efficient ways for maximizing the utilization of available energy. This system is extremely useful for Energy Intensive Industry like Oleo-Chemical Process Plant. The utilization of waste heat (flue gases) liberated by the gas turbine power plant is analyzed in this research work for simultaneous production of: (a) Power (b)Process Heat in the form of hot thermic fluid and High pressure steam, and (c) Refrigeration using vapor absorption chiller (VAM). The flue gases liberated from the gas turbine power cycle is the prime source of energy for the tri-generation system. The heat recovered from gas turbine exhaust gases is used in combination with Main duct burner (B1) to improve the quality of exhaust gases passed over TFHRU for heating of Thermic fluid which is used for heating distillation column. The TFHRU is designed for supply temperature of 320 Deg. C and return temperature 290 Deg. C, Capacity of 10 Mkcal/hr.

The exhaust gases coming out of TFHRU are again heated to design temperature at by using duct burner (B2) and passed over HRSG designed for capacity of 12 Ton per hour and pressure of 66 kg/cm2 for high pressure steam generation which is used for processing vegetable oil splitting operation. Exhaust gases coming out of HRSG are passed over Economizer for steam generator feed water heating. Balance heat available in the flue gases are utilized for Hot Water Recovery Unit (HWRU). This hot water generated is used for generation of chilled water by operating Vapor Absorption Machine (VAM, Capacity – 275 TR each, Two Nos.). Major part of cooling is used for reducing the inlet air temperature of gas turbine to enhance the capacity of Gas Turbine. Economic and environmental benefits of the tri-generation system in terms of cost savings and reduction in carbon emissions were analyzed. Energy efficiency of about 82%-85% is achieved by the tri-generation system.

Keywords- CCHP - Combined cooling heating and power; GT - Gas Turbine; TFHRU - Thermic fluid heat recovery unit; HRSG - Heat recovery steam generator; HWRU - Hot water recovery unit; VAM - Vapor Absorption Machine; GHG – Greenhouse Gases; TR-Tons of Refrigeration; Mkcal - Million kilocalories

1 INTRODUCTION

The growing need for electric energy, especially for industrial sector has resulted in a greater need for the operation of thermal power plants that increase CO2 emissions significantly. Energy problems are increasing around the world due to population growth and rising living standards. This has put the world to face daunting pressures on the energy market. For instance, the past decade has witnessed a significant increase in electricity demand along with a considerable rise of its consumption as well as retail prices and fuel costs.

Constraints on traditional electricity supply and delivery, global competition, climate change concerns, failing grid infrastructure and security issues are another affecting forms that exert increasing pressure on the energy situation and thereby release additional environmental, human health, and financial consequences. Thus, energy usage must be optimized through improving the efficiency of the applied energy system.

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In this scenario of peak demand of Energy in industrial sector, some industries are energy intensive, for example the oleo-chemical process plants having major energy consumptions. This consumption is mainly split into electricity consumption, process heating, process cooling and hot water usage. Conventionally, these loads are provided by electricity of the national power grid, and/or heat generated separately in boilers/Thermic fluid heaters by burning natural gas or furnace oil. But thermal power Plants (steam/gas turbines) are characterized by a relative low total efficiency; where the average efficiency for electrical generation is less than 40%. For heating loads as well, steam generators/boilers could be of only 70% efficiency.

Furthermore, the use of fossil fuels mainly coal, upon which most conventional power generation systems are based, result in a huge amount of greenhouse gases (GHG) emissions. Meanwhile, the global oil supplies will reach a peak at some point after which they will start to decrease and never rise again and continuous rising trend of natural gas is also alarming. Hence, it is necessary to optimize the usage of the limited fuel resources in industrial sector. Therefore, separate production of electrical and thermal energy would be energetically and environmentally inefficient; it will be more reliable to produce both forms of energy in a single power production process.

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The utilization of the low-grade waste heat from the power generation process for heating and/or cooling/refrigeration will be one of the solutions to save the energy squandering, and thus is the employment of cogeneration or tri-generation technologies. Installing energy efficient technologies like combined cooling, heating, and power (CCHP) in oleo-chemical sector is very effective.

2 Principle of Separate Generation versus Multi-generation Technology

Cogeneration or combined heat and power (CHP) production is the use of a heat engine or power station to simultaneously generate electricity and useful heat. In this sequential energy production, both heat and power requirements are satisfied from a single fuel source.

The heat, that would otherwise be wasted in the power production process (into natural environment through cooling towers, flue gases, or other means) is recuperated to provide process heat requirements, else being delivered with a separate fuel source, and thus providing significant fuel savings and pollution reductions. So, cogeneration is a thermodynamically efficient use of fuel. Recovered heat can be used for heating processes, such as hot water for VAM operation and subsequently used for chilled water generation.

Tri-generation (or CCHP) is one step ahead of cogeneration, referring to the simultaneous generation of electricity, useful heating, and cooling from a single fuel source. Relative to CHP, the otherwise lost heat is captured and used to generate, in addition to power and heat, a cold effect. The latter can be produced with help of VAM; can attain higher overall efficiencies than traditional power plants or cogeneration. Heating and cooling outputs may operate concurrently or alternately depending on needs and system construction.

The general concept of cogeneration and tri-generation systems is presented in Figure No. 1. First, fuel and excess air are mixed and burned in order to drive a prime mover (GT) which in turn drives an electrical generator that produces electricity for final use. In addition to this the hot gases exhausted from gas turbine contains waste heat which is used for process heating in term of thermic fluid heater, steam generator and process cooling by chilled water generation with help of Vapor Absorption Machine.

For separate electrical power generation, input process plant has to purchase power from state electricity board which contributes to inefficient generation and distribution losses by the Thermal power plant and GHG emissions are the major drawback. Also, process plant has to run individual thermic fluid heaters, steam boilers, and Vapor compression refrigeration plant. On the other hand, Multi-generation input is the tri-generation technology which gives electrical power, process heat and cooling simultaneously with single energy source that is Natural Gas in case of Gas Turbine Power Plant.

At the present time, one of the most appealing and available energy efficiency measures is the CCHP technology. Overall energy demand drop, fuel independency, increased business competitiveness, GHG emissions cut, and electrical grid improvements are some of many benefits this technology can offer.

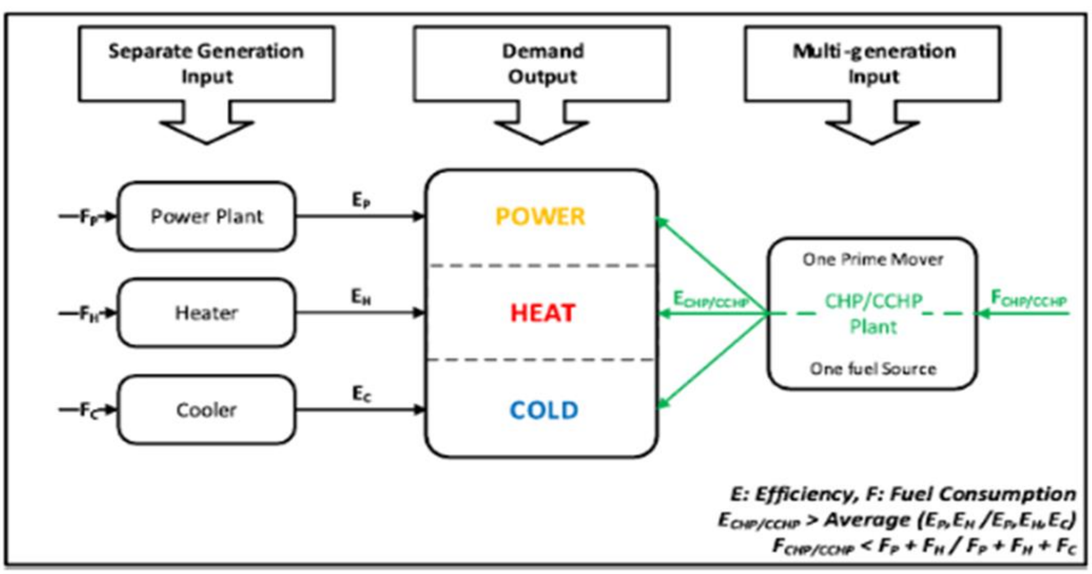

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Figure No. 1: Comparison between separate generation and multi-generation technology.

3 Oleo-chemical Plant Processes and Utilities

For illustration, the energy intensive oleo-chemical plant having key manufacturing process is given in Table No. 1.

Each and every process requires energy/utility in different forms. To cater these process requirements, plant requires different utility process units like Thermic fluid heaters, steam boilers, hot water generators, refrigeration and air-conditioning.

Table No.1: Oleo-chemical plant processes and utilities.

Sr. No.	Oleo-Chemical Plant Processes and Utilities Required		
	Oleo-Chemical Plant Process	**Utilities**	**Energy Form**
1.	Process plant equipment operation and lighting	Electricity and power distribution	Electrical Power
2.	Vegetable Oil Splitting process	High pressure steam	Process Heating
3.	Fatty acid vacuum column distillation process	Thermic fluid heating and medium pressure steam	Process Heating
4.	Raw material /Finished good tank storage, loading and unloading operation	Low pressure steam	Process Heating
5.	Solid production with Pastillator, flakers and beads process plant	Refrigeration and chilled water	Process Cooling

All above process requirements can be fulfilled using tri-generation (or CCHP) as Gas Turbine power plant with waste heat recovery system. This technical paper gives sample calculations and efficiency monitoring sheet along with the schematic arrangement of Tri-generation system for oleo-chemical process plant.

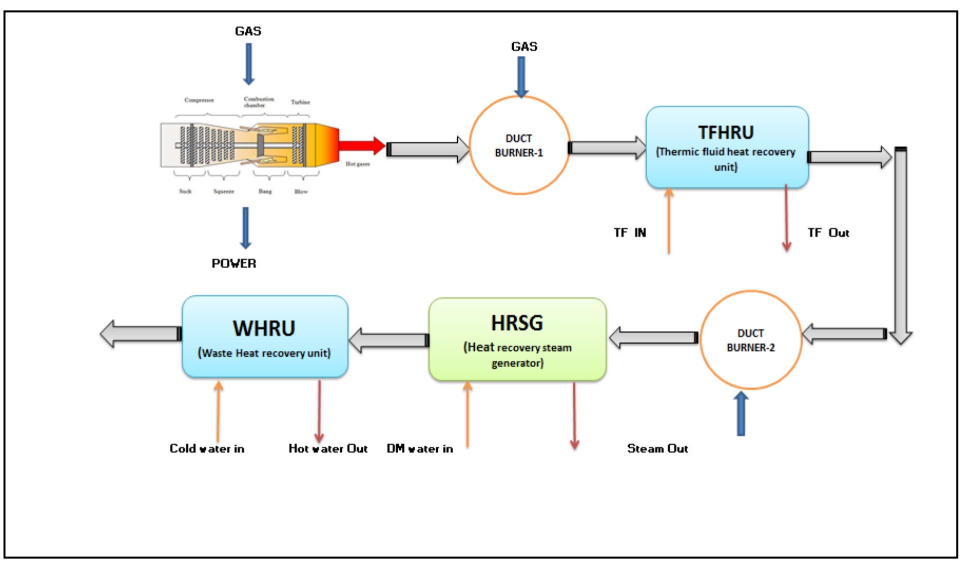

Figure No.2: Schematic arrangement of waste recovery system.

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4 Typical Design Data and Calculations

A typical sample sheet showing the design data and calculations for the energy intensive oleo-chemical plant is shown in Table No. 2.

Table No.2: A typical sample sheet of design data calculations for an oleo-chemical plant.

Sr. No.	Description	Unit	Design Data (calculated)
Section A	**Gas Turbine**		
1	Heat Input	kW	21293.49
2	Heat Input	kcal/hr	18312404.00
3	Fuel consumption for Gas Turbine	kg/hr	1584.34
4	Fuel consumption	sm3/hr	2233.22
5	Inlet air temperature	Deg. C	15.00
6	Natural gas NCV	kcal/sm3	8200.00
7	Fuel Specific gravity - as per report value		0.59
8	Density of air - considering 30 Deg C temperature	kg/sm3	1.20
9	Density of natural gas - calculated at 30 deg temperature	kg/sm3	0.71
10	Heat output in terms of Power	kW	7062.00
11	Heat output in terms of Power	kcal/hr	6073320.00
12	Efficiency of the Gas turbine	%	33.165
13	Heat available at inlet to Waste heat recovery Unit	kcal/hr	12239084.00
14	Flue gas inlet temperature to TFHRU	Deg. C	486.00
15	Specific heat of flue gas - at exit flue gas temperature	kcal/kg Deg. C	0.27
16	Calculated Flue gas flow rate	kg/hr	96630.63
17	Heat content of exhaust gas from Turbine	kcal/hr	12581250.68
18	Heat content of air at turbine inlet	kcal/hr	342166.68
Section B	**Burner 1**		
1	Fuel consumption	sm3/hr	659.00
2	Fuel consumption	kg/hr	467.52
3	Natural gas NCV	kcal/sm3	8200.00
4	Heat Input	kcal/hr	5403800.00
Section C	**TFHRU**		
1	Heat input to TFHRU	kcal/hr	17985050.68
2	Heat Extracted by TFHRU considering Thermic Fluid outlet temperature measured by TI 1-03	kcal/hr	9841570.30
3	Heat Extracted by TFHRU considering Thermic Fluid outlet temperature measured by TI 1-02	kcal/hr	9841570.30
4	Thermic Fluid inlet temperature	Deg. C	288.00
5	Thermic Fluid outlet temperature	Deg. C	320.00
6	Thermic Fluid outlet temperature	Deg. C	320.00

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7	TFHRU flow rate	m3/hr	629.00
8	Density of Thermic Fluid - at average temperature	kg/m3	791.18
9	TFHRU flow rate	kg/hr	497652.22
10	Specific heat of Thermic Fluid - at average temperature	kcal/kg Deg. C	0.62
11	Flue gas exit temperature at outlet of TFHRU	Deg C	300.00
12	Flue gas flow available	kg/hr	97098.16
13	Specific heat of flue gas - at TFHRU exit temperature	kcal/kg Deg. C	0.26
14	Heat available at outlet of TFHRU unit	kcal/hr	7684348.05
15	Heat Energy not recovered	kcal/Hr	459132.32
17	Efficiency of TFHRU	%	95.54
Section D	**Burner B2**		
1	Fuel consumption	sm3/hr	574.00
2	Fuel consumption	kg/hr	407.22
3	Natural gas NCV	kcal/sm3	8200.00
4	Heat Input	kcal/hr	4706800.00
Section E	**HRSG = Evaporator + Economizer**		
1	Heat input to HRSG	kcal/hr	12391148.05
2	Heat Extracted by HRSG	kcal/hr	6766118.55
3	Steam pressure at steam drum	kg/cm2 g	66.00
4	Steam pressure at steam drum	kg/cm2 a	67.01
5	Steam pressure at steam drum	bar	65.72
6	Enthalpy of steam	kcal/kg	663.84
7	Eco Inlet water temperature	Deg. C	100.00
8	Enthalpy of inlet water	kcal/kg	100.00
9	Steam flow rate	kg/hr	12000.00
10	Flue gas exit temperature at outlet of Economizer	Deg. C	197.00
11	Specific heat of flue gas at HRSG exit temperature	kcal/kg Deg. C	0.26
12	Flue gas flow available	kg/hr	97505.37
13	Heat available at outlet of HRSG	kcal/hr	4976937.57
14	Heat energy not recovered	kcal/hr	648091.93
15	Efficiency of HRSG unit	%	91.26
Section F	**HWHRU**		
1	Heat input to HWHRU	kcal/hr	4976937.57
2	Heat extracted by HWHRU	kcal/hr	2404700.00
3	Hot water inlet temperature to HWHRU	Deg. C	90.00
4	Hot water outlet temperature from HWHRU	Deg. C	115.00
5	Specific heat of water at average temperature	kcal/kg Deg. C	1.01
6	Hot water flow rate	m3/hr	100.00
7	Density of water - at average temperature	kg/m3	961.88
8	Hot water flow rate	kg/hr	96188.00
9	Flue gas exit temperature at outlet of HWHRU	Deg. C	97.00
10	Specific heat of flue gas - at HRSG exit temperature	kcal/kg Deg. C	0.25

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11	Flue gas flow available	kg/hr	97505.37
12	Heat available at outlet of Waste Heat Recovery Unit	kcal/hr	2387204.58
13	Heat energy not recovered	kcal/hr	185032.99
14	Efficiency of HWHRU unit	%	92.86
Section G	**Overall system - Waste heat recovery system + Supplementary firing**		
1	Heat input to Waste Heat Recovery Unit	kcal/hr	22691850.68
2	Total heat utilized	kcal/hr	19012388.85
3	Heat lost in chimney	kcal/hr	2387204.58
4	Total system efficiency without considering chimney losses	%	93.64
5	Total system efficiency considering chimney losses	%	83.79

5 Results and Discussions

The energy needs of energy intensive industry like oleo-chemical industry which has been elaborated in Table No.1 shows different plant processes and utilities as well as the various energy forms required. For fulfilling these requirements the Combined Cooling, Heating and Power (CCHP) is the only energy efficient option available.

The typical sample sheet showing the design data calculations given in Table No. 2 has been divided into seven sections, named by capital letters A to G. In section A, the total heat input and output in terms of electric power and waste heat in exhaust gas from gas turbine are given. In section B, the fuel consumption and heat output of duct burner B1is illustrated. In section C, , the total heat input and output to the TFHRU, and heat energy output in terms of thermic fluid inlet temperature, outlet temperature and subsequent deltaT and Mkcal heating output are shown.

In section D, fuel consumption and heat input gained by duct burner B2 is given. Subsequently, in section E, that is HRSG with Economizer, the total heat input and output heat of exhaust gases are given along with process heating output in terms of steam flow in kg per hr and heat transfer efficiency of HRSG.

In section F, that is for HWHRU, the heat input and output heat of exhaust gases and process heating and cooling output in terms of heat gained by hot water and subsequently used in generation of chilled water through VAM for process cooling are given. Section G illustrates the overall thermal efficiency of waste heat recovery system including supplementary firing.

This technical paper has elaborated the tri-generation plant utility for oleo-chemical process. The typical sample sheet shows various design calculations results along with the various design parameters that were derived at conception stage of CCHP (combined cooling, heating and power) and it gives the transfer efficiency of all heat recovery equipment. The individual plant's equipment like thermal power plant, thermic fluid heaters, steam generators and vapor compression chillers are having less efficiency in comparison with gas turbine based waste heat recovery plant. The combined cooling heating and power plant has overall efficiency in the range of 80-85%.

For any waste heat recovery project, the efficiency or performance monitoring is very important. The typical data sheet used for the daily efficiency monitoring of the various oleo-chemical plant processes is shown in Table No. 3. The efficiency monitoring sheet shows the efficiency of heat recovery system in the first week of September 2017. Both the heat input and heat output are converted into same unit i.e. kcal per hr. The efficiency monitoring sheet is showing actual heat input that is natural gas consumption in Gas Turbine, B1 burner, B2 burner in terms of SCM per day and the output power and utilities in terms of electric power in kW/day, steam generation in terms of tons per day, thermic fluid heating in terms of Mkcal/day and chilled water output in term of TR/day.

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Table No.3: Typical data sheet format used for efficiency monitoring.

		1-Sep	2-Sep	3-Sep	4-Sep	5-Sep
INPUT						
G.T. N.G. consumed	SCM/day	42068.59	42178.19	40790.38	41712.39	42798.80
TFHRU N.G. Consumed	SCM/day	9499.58	12012.95	11895.50	12922.89	11932.12
HRSG N.G. consumption	SCM/day	8247.36	9860.08	10127.43	9846.94	11810.39
Total N.G. consumed	Kcal/day	568247549.3	608486610	596726473.5	612581109	632142435.5
OUTPUT						
G.T. power generation	KW/day	133776	133472	127200	130960	136672
G.T. power generation	Kcal/day	115027293.6	114765899.2	109372920	112605956	117517419.2
HRSG Steam generation	Tons/day	245.624	244.068	250.633	247.634	276.294
HRSG Steam generation	Kcal/day	161696735.4	160672405.1	164994210.2	163019938.5	181887103.1
Chilled water output	TR/day	7005.64	7068.189484	6990.973325	6519.015653	7139.47
Chilled water output	Kcal/day	21185055.36	21374205	21140703.33	19713503.33	21589757.28
TFHRU Heat load	Mkcal/day	190.1	231.2	228.2	238.1	232.5
TFHRU Heat load	Kcal/day	190100000	231200000	228200000	238100000	232500000
Total	Kcal/day	488009084.4	528012509.3	523707833.6	533439397.9	553494279.6
Efficiency of CPP		85.88	86.77	87.76	87.08	87.56

6 CONCLUSIONS

For fulfilling the energy needs of energy intensive industry like oleo-chemical industry, the tri-generation or CCHP, that is, Combined Cooling, Heating and Power is the only energy efficient option available.

The overall efficiency is dependent upon the heat load requirement in terms of electricity generated in megawatts (MW), thermic fluid heating load in terms of Mkcal/hr, steam generation in terms of tons per hour and refrigeration in terms of tons of refrigeration.

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