ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

EXERGY ANALYSIS AND STRATEGIES FOR THE WASTE HEAT RECOVERY IN OFFSHORE PLATFORMS

Julian Esteban Barrera
André Almeida Sahlit
Federal University of Santa Catarina, Florianópolis-SC, Brazil, ZIP 88.040-900
julian@labcet.ufsc.br
andre.sahlit@gmail.com

Edson Bazzo
Federal University of Santa Catarina, Florianópolis-SC, Brazil, ZIP 88.040-900
ebazzo@emc.ufsc.br

Abstract. *This paper focuses on the analysis of the main sources of waste heat and the advantages taken of its recovery in offshore platforms. Initially, based on a typical plant configuration, the equipment associated with waste heat generation is listed, and then energetic and exergetic balances are done with the purpose of identifying the possible use of the recovered energy. Derived from the information about the type and the quantity of demand, as well as the availability of the recuperated energy, three scenarios are proposed for the integration of a heat recovery system in a platform: auxiliary power generation, cold generation and both power and cold generation. New balances are performed to quantify the energy efficiency enhancement in each scenario with the aim of determining the best alternative. Finally, the results of the application of this methodology in an existing platform are presented. A simple procedure, based in energetic and exergetic balances, is suggested to get a first approach to the most suitable strategy for the waste heat recovery, as well as to identify the best opportunities for the recovered energy utilization in offshore platforms.*

Keywords: *natural gas, offshore platform, waste heat recovery, exergy analysis*

1. INTRODUCTION

The improvement of the energetic efficiency in the oil production processes has been the subject of various studies, mainly justified by the necessity of reduction of CO_2 emissions and compliance with related legislation (van Nguyen *et al.*, 2011; Voldsund *et al.*, 2010), as well as the energy forecasts and their implication on the oil industry competitiveness (Bourji *et al.*, 2010). Particularly, the growing energy demand in last decades has promoted the offshore oil production at further and deeper locations (Barton, 2009).

Considering the current growth of offshore exploration and production and its technical and economical challenges, the energetic efficiency of this kind of installations will become a key variable for its development, and the technical efforts to increase its productivity and mitigate its impact are justified.

The implementation of waste heat recovery (WHR) for power and/or cold generation in situ, has demonstrated to be a suitable method for the energy use enhancement in this industry segment (Voldsund *et al.*, 2010; Pierobon and van Nguyen, 2012; de Oliveira and van Hombeeck, 1997), however one of the difficulties for its adoption is the fact that there is not enough power/cold demand in situ to use all the potential of the recovered energy (BCS, 2008); consequently, before any recovery system integration, it is necessary to analyze the whole plant, quantifying the available heat to be recovered, identifying its potential for power/cold generation, and establishing the actual demands of heat, power and cold.

A useful tool for this type of analysis is the exergetic balance, that quantifies the maximum reversible work obtainable from an energy source; since this balance is not necessarily conserved, the destroyed exergy can be determined for each operation in order to identify where are the greatest energetic inefficiencies.

This study presents the results of the energetic and exergetic balances of the process operations of a Brazilian offshore installation; according to this information and based on previous results concerning power and cold generation from waste heat (Popli *et al.*, 2013; Pierobon and van Nguyen, 2012), three schemes are examined here for the WHR system integration.

The scope of this study covers the analysis of main separation plant, excluding the gas lift operation, seawater injection, production water treatment system, auxiliary systems such as control, air distribution, flare, gas dehydration, seawater desalinization, commodity services, crane, illumination, and ship screw.

The main reason to exclude the gas lift and water injection system is that these systems require too much electric power to be supplied by a WHR system; moreover these systems generally are considered as essential to plant working and its continuous operation must be guaranteed. On the other hand, the energy demands associated with control system, air distribution, flare, seawater desalinization, illumination and commodity services are considerably smaller than the separation plant consumption (Arnold and Stewart, 2008). In the case of ship screw and crane, its operation is seldom

ISSN 2176-5480

and generally its power supply is exclusive. In addition, All above mentioned demands can be considered approximately constant.

2. Process description

The type of installation corresponds to a floating production, storage and offloading (FPSO) unit designed to process 12800 m^3/day of fluid. In addition, the unit is equipped with facilities for the treatment and injection of seawater and gas lift.

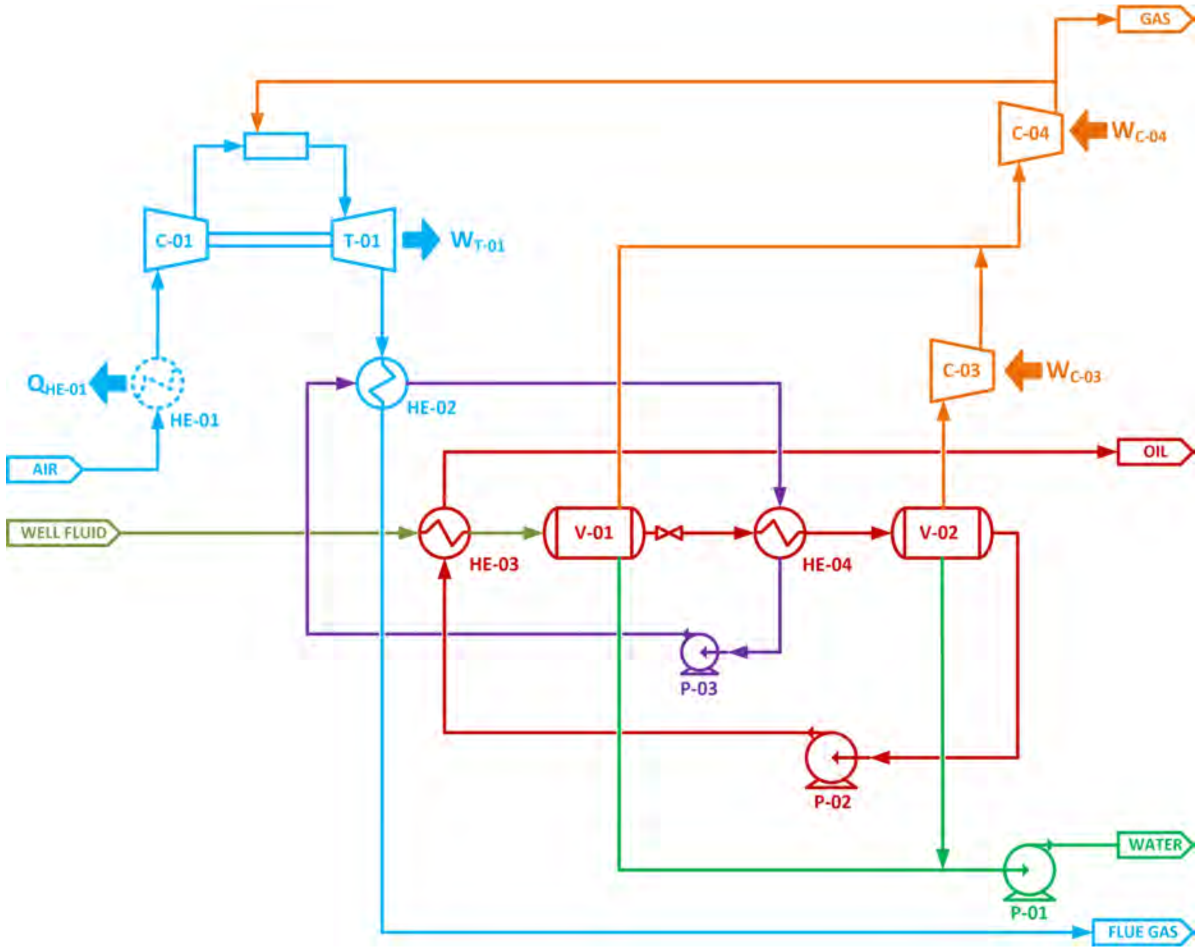

Figure 1. Offshore process scheme

Table 1. Inlet process conditions of offshore platform

Parameter	Value	Units
Inlet std. fluid volume flow (1)	12800	m^3/day
Std. gas volume flow (1)	2	Mm^3/d
Bottom sediments and water - BSW%	40	%
Specific gravity	30	^{o}API
Inlet temperature	55	^{o}C
Inlet pressure	1500	kPa

(1) Standard conditions: 15^{o}C and 101.32 kPa

The main purpose of the process is to separate the well fluid into oil, gas and water meeting the specifications for their export/further treatment. The scheme of operation is shown in Fig. 1, including the power generation plant. The main operation inlet parameters are shown in Tab. 1.

The well fluid is preheated in the heat exchanger HE-03 with the exported oil stream before enters to the 1st stage separator V-01, where the primary separation of the oil, gas and water streams occurs.

The separated oil is then routed to the stabilization heater HE-04 for a further separation in the 2nd stage separator

ISSN 2176-5480

V-02, where additional amounts of water and gas are separated; this step is generally accomplished with an electrostatic separator for meeting the final specifications of oil stream (not shown). Finally the oil is pumped through the heat exchanger HE-03 to the tankers (on board), previous cooling with seawater (not shown).

The gas stream from V-01 is directed to the main compression system C-04, that consist in three stages, each one accomplished with gas cooling and condensate separation (not shown) . The compressed gas is then dehydrated and used for exportation onshore trough piping or injected back to the reservoir by an additional compression train (not shown). A small fraction of the produced gas is used in the power generation system.

The gas stream from V-02 is routed to the booster compression system C-03 that consist in two stages, each one accomplished with gas cooling and condensate separation (not shown). The compressed gas is then directed to the main compression system C-04.

The separated water is routed to the water treatment system (not shown) by pump P-01 for its subsequent disposal on board, previous cooling with seawater (not shown).

The power generation system consist in a conventional Brayton power cycle feed with fuel gas derived from main gas stream (about 3.5% of total mass flow of produced gas) and supplies the electricity necessary for the main process system (pumps, compressors, air coolers, etc.) as well as other on board power demands like FPSO utilities, control systems, air conditioning, etc. The equipment considered in this study corresponds to a SGT-400 (Siemens AG, 2009) gas turbine. The performance curves of this system are presented in Fig. 2, where the operation conditions defined in each proposed scenario are shown.

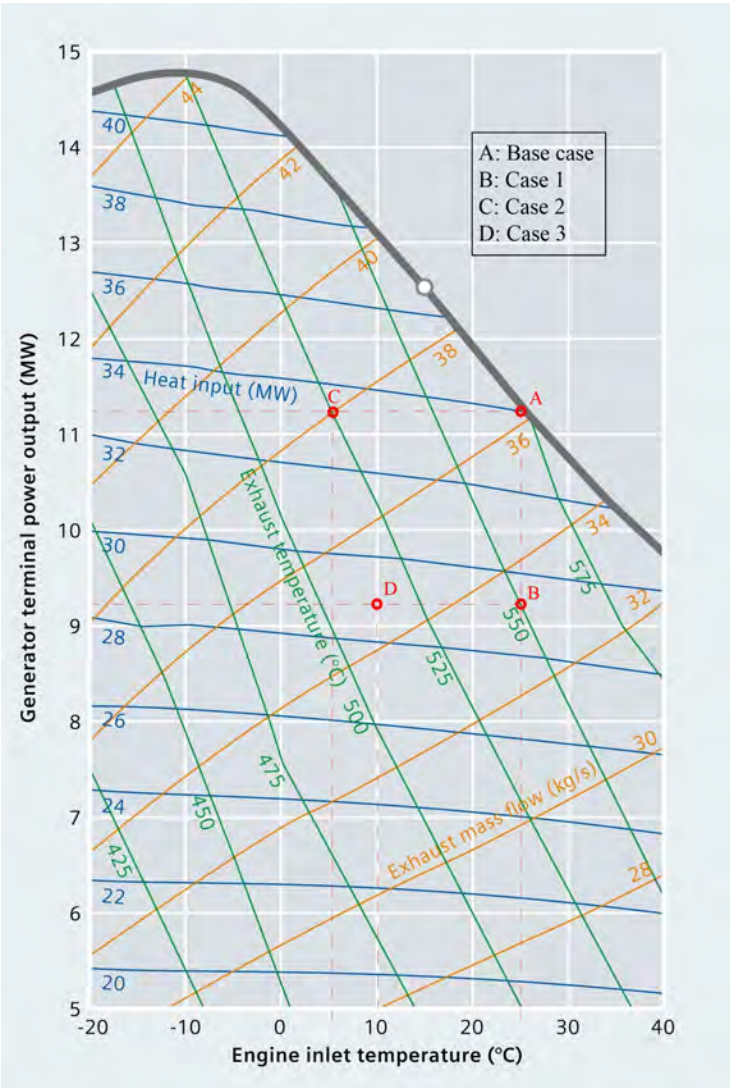

Figure 2. Power cycle performance curves

The waste heat recuperation system is coupled to the exhaust gases stream of power generation system, and provides the energy needed for oil heating by the circulation of a thermal oil through HE-02 and HE-04.

ISSN 2176-5480

3. METHODOLOGY

To obtain the energetic balance of the plant, a process simulation was modeled based on available information, using the software *Engineering Equation Solver-EES*® to establish the plant operating conditions. Some data was assumed according to common operation settings for this type of installations (Maxwell, 1968; Arnold and Stewart, 2008). The most important assumptions are presented in the next subsection.

From the obtained data, energy demands (power, cold and heat) and rejected heat sources are established; according to their magnitudes, the opportunities of use of the recovered energy are identified. This energetic evaluation is followed by an exergetic balance, where the most inefficient operations are identified to determine where a coupled WHR system would have a greater impact.

Finally, the implementation of a hypothetical WHR system are studied in three scenarios: First, only power will be generated from waste heat resource; in the second scenario, only cold will be supplied to plant and the last scenario corresponds to the simultaneous generation of power and cold. The results will be compared based on the degree of perfection, η_P that relates the exergy of the products of interest, B_P and that one associated with the inlet streams, B_{in} (Szargut *et al.*, 1988):

$$\eta_P = \frac{B_P}{B_{in}} \tag{1}$$

In addition, a complementary indicator is proposed in order to link the energy efficiency to measurable parameters in the plant:

$$\xi_v = \frac{\dot{m}_F}{\dot{v}_{in}} \tag{2}$$

where ξ_v is the fuel-based performance, that represents the mass of consumed fuel, m_F for each standard volumetric unit (measured at 15 ^{o}C and 101.325 kPa) of processed fluid, v_{in}. A relation scheme of these indicators are shown in Fig. 3.

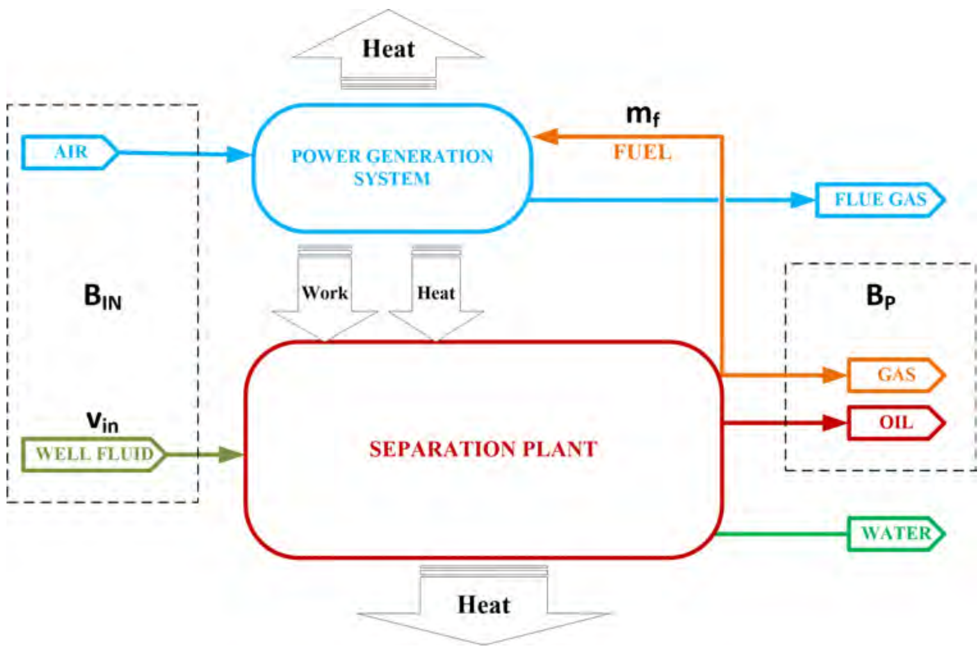

Figure 3. Relation scheme for plant analysis

3.1 Simulation input data and assumptions

Table 2 presents the relevant data assumed in the process simulation. Most data are estimated according to typical operation conditions. For simplicity the simulation is carried out considering the following assumptions:

- Continuous operation, with constant conditions (steady state regime).
- Constant composition of the associated gas trough whole the process, implying that the saturation of associated gas with water is ignored, and the process of gas dehydration is not included within the process.

ISSN 2176-5480

- Constant thermophysical properties of oil during the separation process.
- There are no interfacial or chemical interactions among the fluid phases (i.e. oil, gas and water).
- The nominal power generated by turbine is distributed among the process plant, the seawater injection system and the gas lift system in all cases. The power consumption of the last two systems is considered approximately constant.

Table 2. Inlet data in process model.

System	Parameter	Value	
General	Ambient temperature	25	°C
	Atmospheric pressure	101.3	kPa
	Compressor isentropic efficiency	0.95	--
	Turbine isentropic efficiency	0.95	--
	Pump isentropic efficiency	0.75	--
	Gas outlet temperature from aircoolers	40	°C
Power generation	Turbine heat rate	(1)	kJ/kW-h
	Exhaust mass flow	(1)	kg/s
	Outlet exhaust temperature	(1)	°C
	Net power output	(1)	MW
Oil separation	HE-03 pinch point	10	°C
	HE-04 pinch point	15	°C
	HE-04 Oil outlet temperature	81	°C
	Specific mass spec. heat	(2)	kJ/kg-K
	Second stage pressure	389.8	kPa
	Last separation stage pressure	101.3	kPa
	Outlet pressure	175	kPa
	Outlet temperature	55	°C
Gas compression	V-01 outlet std. volume flow	1.66	Mm^3/day
	Outlet pressure	3000	kPa
	Outlet temperature	40	°C
Produced water	Outlet pressure	250	kPa
Heat transfer oil	Maximum working temperature	300	°C
	Specific mass spec. Heat	(3)	
	Heating system pressure	500	kPa

(1) Adjusted according performance curves.
(2) Adjusted according the linear regresion Cp=0,00425T+0,418; T in K (Maxwell, 1968).
(3) Modeled as dowtherm Q.

3.2 Power and cold generation systems

The power and cold generation from rejected heat resources are subject of various studies (Little and Garimella, 2011; Wang and Oliveira, 2005; Pierobon and van Nguyen, 2012). In this paper, these systems are considered as closed packages (i.e. only inlet and outlet energy are accounted), with its capacity and performance referenced in previous papers.

The power generation system consist of an organic Rankine cycle suitable for the generation up to 5 MW. Pierobon and van Nguyen (2012) reported a thermal efficiency of 22% for this type of system using cyclohexane as working fluid.

Respecting the cold generation system, two technologies can be proposed: the absorption refrigeration cycles or adsorption refrigeration cycles. The latter is more convenient for this case, as ships or trains since the adsorbent is solid and its operation is not affected by equipment oscillations; moreover this kind of system can be suitable for the heat recuperation from lower temperature sources. Despite that, its relatively low coefficient of performance (COP) and its low specific cooling power (i.e. cooling power per kilogram of adsorbent)(Wang and Oliveira, 2005), can limit the size of the currently available equipment, therefore this option were dismissed from this analysis. Consequently, the cold

ISSN 2176-5480

generation system is established as a LiBr-H_2O absorption refrigeration cycle (ARC) with a COP of 0.77 and a maximum cold capacity of 12.3 MW (Popli *et al.*, 2013).

4. RESULTS

4.1 Base case

4.1.1 Energetic balance

Table 3 presents the results of the energetic balance of the plant, listing the main heat sources together with the type and amount of energy demanded in current operation. The most important source of rejected heat is the exhaust gas stream from the power generation system. Despite the fact that part of its energy is transferred to heat the oil stream, it represents the 53.7% of the total rejected heat. Sources associated with the oil and production water streams are not negligible, but their relatively low temperature make these sources less interesting and more difficult to be recovered.

Table 3. Main results - base case

Heat Rejected (total)				***25.42***	***MW***
Outlet oil stream		2.02	MW at	69.1	°C
Outlet water stream		4.72	MW at	59.1	°C
Gas air coolers		4.08	MW at	--	°C (1)
Turbine exhaust gases		13.67	MW at	573.2	°C (2)
Combustor		0.93	MW at	719.7	°C (3)
Energy Requirements				***6.49***	***MW***
Oil separation	Oil heating		Heat	3.38	MW
	Oil pumping		Power	0.01	MW
Gas compression	Gas boosting		Power	1.06	MW
	Gas compression		Power	**2.04**	**MW**
Produced water	Water pumping		Power	0.01	MW
Heat Recovered				***3.38***	***MW***
Waste recovery system				3.38	MW
Plant Summary					
Power supplied				11.24	MW
Plant power requirement				3.12	MW
Power available				8.12	MW(4)
Plant heat available				22.04	MW
ξ_v				5.292	
η_P				0.9625	

(1) Heat removed from gas streams in all aircoolers.
(2) Considering 150 °C as minimum temperature of exhaust gases.
(3) Mean temperature.
(4) This value is cosidered as used in other operations as water injection and gas lift.

On the other hand, the dominant type of energy demand is the power generation. Specifically, the gas compression (boost and main systems), appears with greatest power demand amounting 3.1 MW. By contrast there is not cold demand in the whole process, however the working efficiency of the Brayton cycle in the main power generation system can be improved by cooling of air intake, hence this operation will be allowed as an application for the cold generation in the second and third scenarios. Evidently, the heat demand in separation process is already covered by the existing WHR system.

4.1.2 Exergetic balance

The exergetic balance of the plant is presented in Fig. 4. The more inefficient system in the process corresponds to the gas turbine (indicated in dashed rectangle in Fig. 1) that represents 80% of the total destroyed exergy (15.8 MW).

ISSN 2176-5480

Particularly, the combustion appears as the most inefficient operation; here 31.9% of the fuel exergy is destroyed.

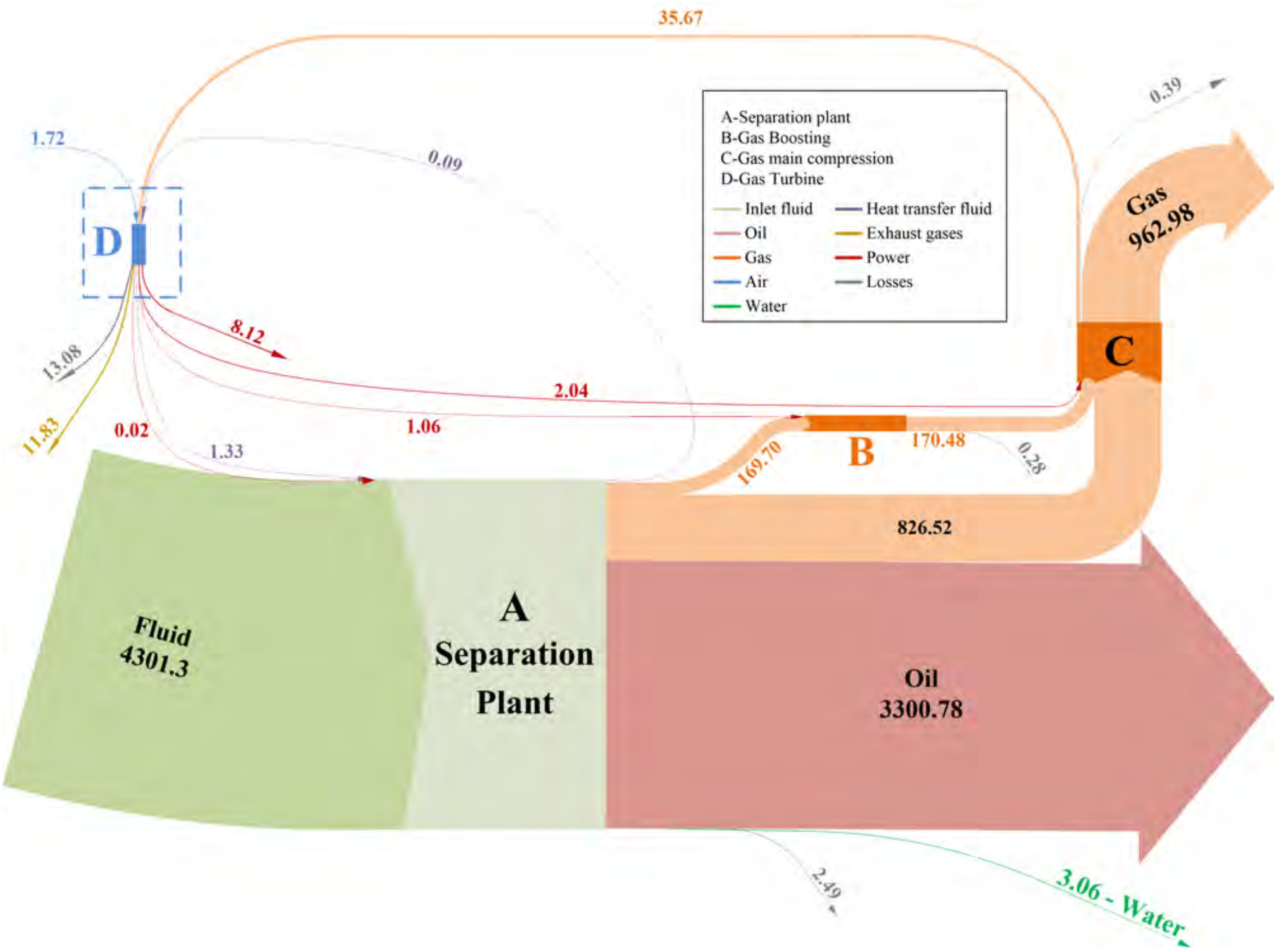

Figure 4. Sankey diagram of base case - exergy flows in MW.

Specifically, in process plant the lower efficiency is reported for the oil separation stage, principally due to the sequential reduction of stream pressure needed for oil stabilization and storage (Arnold and Stewart, 2008).

The destruction of exergy appears to be necessary in the oil separation stage and unavoidable in combustion operation, moreover these operations are not related with an important power consumption. Therefore the proposed use of the ORC system will be the power supply to the gas main compression system.

4.2 Strategies for recovered energy utilization

As proposed in this work, in order to recover the waste energy in offshore platforms, three scenarios are considered as reliable alternatives to use the power and/or cold generated in place:

- ***Scenario 1:*** Generation of 2.04 MW of power from the rejected heat associated with exhaust gases from T-01, using an ORC to supply the power required W_{C04} in main compression stage C-04 (Fig. 1). This power is withdrawn from the main power system and the conditions of operation of the Brayton cycle are updated according its performance curves.

- ***Scenario 2:*** Reduction of the temperature of the air intake in HE-01 up to 5^{o}C, removing the heat flow Q_{HE-01} (Fig. 1) by means of an ARC supplying the required cold. The conditions of operation of the Brayton cycle are updated according its performance curves.

- ***Scenario 3:*** Generation of 2.04 MW of power from the rejected heat associated with exhaust gases from T-01, using an ORC to supply the power required in main compression stage C-04 with simultaneous reduction of the temperature of the air intake in HE-01 (Fig. 1) up to 10^{o}C, using cold provided by an ARC. The power supplied by ORC is withdrawn from the main power system and the conditions of operation of the Brayton cycle are updated according its performance curves.

ISSN 2176-5480

4.3 Results for proposed scenarios

Table 4 summarizes the obtained results of the studied scenarios. It is evident that the use of rejected energy for power generation has a more significant impact over the system performance and the simultaneous cold generation has the best improvement of the chosen indicators.

Table 4. Main results - Proposed scenarios

	Base case	Case 1	Case 2	Case 3
Heat Recovered (total)	***3.38 MW***	***12.63 MW***	***7.79 MW***	***15.97 MW***
Waste recovery system	3.38 MW	3.38 MW	3.38 MW	3.38 MW
ORC	0.00 MW	9.25 MW	0.00 MW	9.25 MW
ARC	0.00 MW	0.00 MW	4.41 MW	3.34 MW
Plant Summary				
Power supplied	11.24 MW	9.21 MW	11.24 MW	9.21 MW
Power required	3.12 MW	3.12 MW	3.12 MW	3.12 MW
ORC power supply	0.00 MW	2.04 MW	0.00 MW	2.04 MW
ARC cold supply	0.00 MW	0.00 MW	3.40 MW	2.57 MW
Power available	8.12 MW	8.13 MW	8.12 MW	8.13 MW
Plant heat available	25.42 MW	16.17 MW	18.70 MW	11.20 MW
ξ_v	5.292	4.554	5.187	4.493
η_P	0.9625	0.9675	0.9632	0.9679

5. DISCUSSION

In some equipment, the destruction of exergy is unavoidable due to the inherent entropy generation, (e.g. combustion stage in power system). In a similar manner, there are other instances where this destruction cannot be avoided due to process restrictions (e.g. pressure or temperature decrease of main product streams). Nevertheless, the exergy efficiency of the plant can be enhanced taking advantage from the exergy associated with the heat transferred to the surroundings for local power and cold generation.

Comparing both methods, the auxiliary power production appears to be the best method to take advantage from residual heat; although its performance is relatively low, this strategy reduce more significantly the fuel consumption of the power generation system.

Using the proposed methods in combination permits to take more advantage for the waste heat: Depending on the magnitude of power demands of plant equipment, as well as the available heat, the adopted power generation cycle size and performance can be adjusted to fit one of the most predominant power demands, then the remaining heat can be used to cool the power system air intake.

Evidently, the utilization of the generated power/cold from these systems was limited by process constraints such as the magnitude of power demand and rejected heat, as well as the availability of cold generation equipment.

The magnitude of the obtained results is consistent with previous works (van Nguyen *et al.*, 2012), however to improve the precision of the these data, the use of specialized process simulation software is recommended in order to eliminate the use of some assumptions.

A detailed analysis can be performed including the missing systems such as water injection, gas lift, production water treatment, crane, flare, facility services and ship screw, accounting all the available systems to find more energy sources or uses for the generated power/cold.

The focus of the present study was a hypothetical integration of an energy recovery system in an existing plant, nevertheless this type of analysis can be performed in engineering design stages, with the purpose of finding a better energetic performance in new projects.

Further analysis can be done including the process simulation of the proposed cycles with the aim to find the best operating conditions and performance of the integrated system.

Internal modifications in the proposed thermal cycles, as well as an analysis of the form of integration of these systems to the plant can be studied in order to increase the flexibility of these systems and improve their coupling with variable operating conditions.

ISSN 2176-5480

6. CONCLUSION

With the established operation conditions and considering the process constraints, an exergetic balance was used to identify the power supply of gas compression operation and cooling of turbine air intake as two interesting alternatives to improve the energetic efficiency of the plant.

Based on the analysis of three different strategies of power/cold utilization, the best improvement is found integrating simultaneous power and cold generation. In this scenario, the recovered heat amounts 15.97 MW (62% of total rejected in base case), the power generated by ORC 2.04 MW and the heat removed from air intake 2.57 MW. This alternative represents a saving of 15% based in fuel consumption per volumetric unit of fluid processed.

7. REFERENCES

Arnold, K. and Stewart, M., 2008. *Surface Production Operations: Design of Oil Handling Systems and Facilities*. Gulf Professional, Burlington, 3rd edition.

Barton, C.M., 2009. "An overview of offshore concepts". In *Expanding Facilities Knowledge Workshop*. Houston, TX, 195 Slides.

BCS, 2008. *Waste Heat Recovery: Technology and Opportunities in U.S. Industry*. U.S. Department of Energy.

Bourji, A., Barnhart, J., Winningham, J. and Winstead, A., 2010. "Recover waste heat from fluegas". *Chemical Engineering*, Vol. 200, pp. 37–41.

de Oliveira, S. and van Hombeeck, M., 1997. "Exergy analysis of petroleum separation processes in offshore platforms". *Energy Conversion Management*, Vol. 38, No. 15, pp. 1577–1584.

Little, A.B. and Garimella, S., 2011. "Comparative assessment of alternative cycles for waste heat recovery and upgrade". *Energy*, Vol. 36, No. 7, pp. 4492–4504.

Maxwell, J.B., 1968. *Data Book on Hydrocarbons: Application to Process Engineering*. Krieger, Malabar.

Pierobon, L. and van Nguyen, T., 2012. "Waste heat recovery for offshore application". In *1st International Symposium on Advanced Waste Heat Valorisation Technologies*. Kortrijk, Poland, Poster.

Popli, S., Rodgers, P. and Eveloy, V., 2013. "Gas turbine efficiency enhancement using waste heat powered absorption chillers in the oil and gas industry". *Applied Thermal Engineering*, Vol. 50, No. 1, pp. 918–931.

Siemens AG, 2009. "SGT-400 Industrial Gas Turbine". Technical report, Houston, TX. URL `http://www.energy.siemens.com/`.

Szargut, J., Morris, D.R. and Steward, F.R., 1988. "The exergy concept and exergy losses". In *Exergy analysis of thermal, chemical, and metallurgical processes*, Hemisphere, chapter 1, p. 332.

van Nguyen, T., Elmegaard, B., Pierobon, L., Haglind, F. and Breuhaus, P., 2012. "Modelling and analysis of offshore energy systems on North Sea oil and gas platforms". In *Proceedings of the 53rd SIMS conference on Simulation and Modelling*. Reykjavik, p. 16.

van Nguyen, T., Pierobon, L. and Elmegaard, B., 2011. "Towards energy-efficient offshore platforms". In *Energieffektivisering for fremtiden*. Kgs.Lyngby, Poster.

Voldsund, M., Ertesvå g, I.S.l., Rø sjorde, A., He, W. and Kjelstrup, S., 2010. "Exergy analysis of the oil and gas separation processes on a North sea oil platform". In D. Favrat, ed., *Proceedings of the 23rd International Conference on Efficiency, Cost, Optization, Simulation and Enviromental Impact of Energy Systems*. Lausanne, June, pp. 303–310.

Wang, R.Z. and Oliveira, R.G., 2005. "Adsorption refrigeration - An efficient way to make good use of waste heat and solar energy". In *International Sorption Heat Pump Conference*. Denver, CO.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.