23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

ANALYSIS OF ORC SYSTEM FOR LOW-GRADE WASTE HEAT RECOVERY IN OFFSHORE PLATFORMS

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Abstract. *This present work is a proposal of expansion of power generation in an offshore platform for oil and gas exploration. Increasing energy efficiency these platforms requires a commitment to cost and compactness of the equipment. The Organic Rankine Cycle (ORC) is a promising technology for energy conversion by means of low and average sources temperature. Thus, the cycle is an alternative to expansion of power generation in platforms, in order to maximize energy efficiency as well as reduce environmental impacts by thermal pollution. The aim is to assess the availability of low-grade waste heat from different processes in a FPSO. The study of energy flow in this platform indicated the processes with the greatest potential for energy recovery. A genetic algorithm was developed to optimize the thermodynamic parameters of different working fluids. A multi-objective optimization is carried out to maximize the efficiency of the work cycle and minimize costs by reducing the ORC module area. Thus, it can predict the performance of systems with greater energy use allied to favorable economic factors.*
Keywords: *FPSO, ORC, Energy Efficiency, Power Generation.*

1. INTRODUCTION

Oil and natural gas remain the main source of energy in world, for its final use quite distinguished it is also a key source of supplies. According to studies by IEA 2014 oil demand will continue to increase in the projected period of 2013-2019. Increased demand for oil follows a cyclical pattern that is parallel to the global economic recovery, and is what is observed in the current world scenario, following economic recovery after the end of the last decade.

The use of oil as predicted has a principle of drop especially in developed countries, even though these are the largest consumers. However, this decrease is more than compensated elsewhere in the world mainly by countries in economic and industrial growth. According to the IEA 2014 estimates, within an expectancy of five years, countries in emerging and newly industrialized economy, will overcome for the first time the developed countries in oil consumption, and this trend will remain after the period.

Within these perspectives, offshore platforms have been used to expand exploration and processing of oil and gas in Brazil, as in other regions of the world. The FPSO unit (Floating Production Storage Offloading) became one of the most commercially viable formulations for exploration of oil fields in deep water.

According (KOCAMAN, 2008), offshore production has been an important part of the development of the oil and gas industry over the past two decades. Offshore platforms has provided about 33% of world oil production in 2007, and its contribution should be relatively stable by 2035.

In recent years, the political and industrial organizations went through a ripeness that resulted in modifications of global trends regarding the use of energy. The sustainability of production processes is now subject by a search for improvement energy efficiency, while taking into account economic objectives, energy and environmental security.

In Brazil, the expanded use of FPSO is due to the recent oil discoveries in the pre-salt field. Great efforts are made in the way of technological achievement and development of national engineering, with a view to existing challenges in exploration and production of oil and natural gas in ultra-deep waters and far from the coast.

This study evaluates the potential of using ORC cycles in waste heat recovery of production processes of a Brazilian FPSO platform. The great challenge for power generation to support the demand of this input on a FPSO is mainly due to its restrictions on physical space, weight limitation and security. In this respect, the ORC cycle is a high-potential technology for this application, since it is a compact system, as well an appreciable economic performance due to simplicity of the cycle configuration.

The organic Rankine cycle has emerged as an efficient technology for conversion of low and medium temperature heat into electricity. The working fluids for an ORC cycle presented a low evaporation point and a latent heat of vaporization lower than that of water, allowing evaporation at lower temperatures. These technical features provide better utilization of low quality energy sources, allowing efficient use of energy resources.

2. FPSO'S PROCESS DESCRIPTION

The search and the improvement of energy efficiency in oil mainly advanced enough to overcome the challenges of rising oil and gas demand industry, the necessity of reducing emissions of CO2 and other gases, and increased production costs.

The oil extraction activity involves the removal of various materials such as gas, water, sand and salt together with the well fluid. These impurities must be removed from the crude oil before being processed in refineries or used as fuel. The main objective of FPSO production unit is to separate the fluid from the reservoir exploration in oil, gas and water. Then, each of these streams pass through a series of operations order to satisfy specifications until their end uses, which may be exportation, treatment for use in process, or disposal.

The offshore separation of these three phases is necessary to maximize oil production and minimize its gas content and water, for economic reasons and production process requirements (SVALHEIM et al., 2003). Figure 1 summarizes the operation of an FPSO.

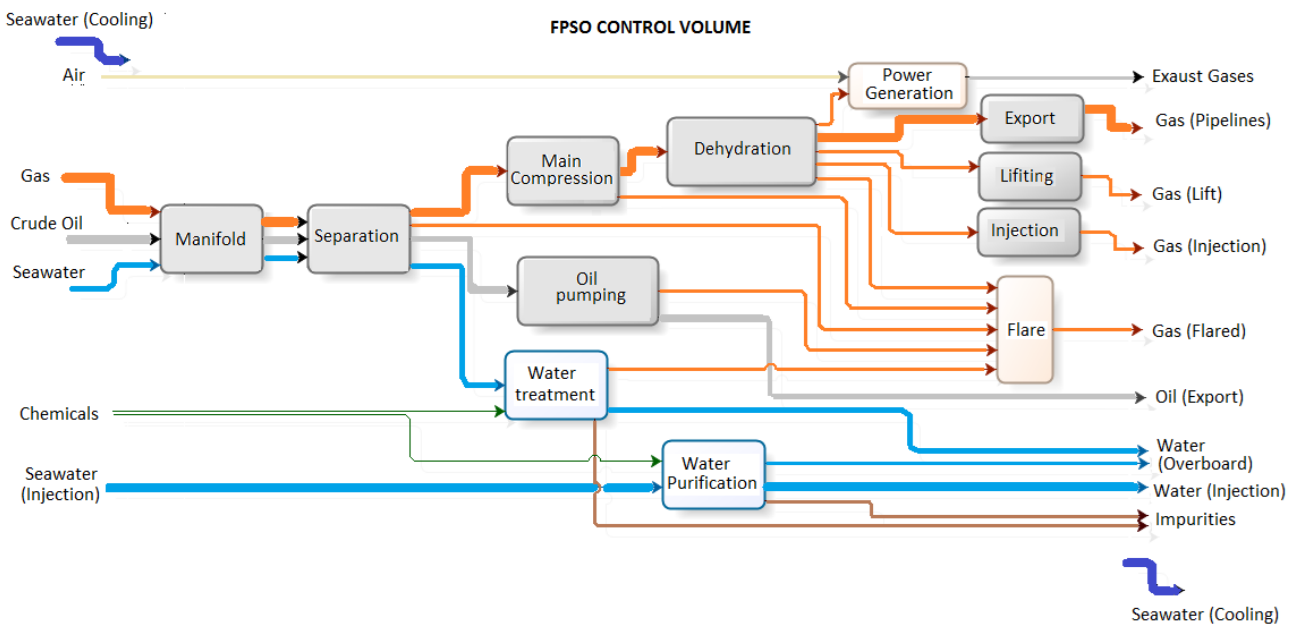

Figure 1. Summary of the FPSO operation

Basically, crude oil is extracted in one or more wells and transferred to the platform via a network of ducts and a system of collectors. In the separation unit, the flow is separated into oil, water and gas. The separated oil passes through an initial treatment process and is sent to the ship's tanks. The FPSO platforms are equipped with storage systems that correspond to large tanks where the oil is stored in the deck until it is sent to oil tankers, or directly for the continent via pipelines.

In the Gas Processing Plant (GPP), the extracted and separate natural gas is initially recompressed in Main Compression Unit (MCU), and then subjected to a series of treatment processes according to its final purpose. The gas can be exported to continent, used for injection in wells, lifting, and used on the platform for generating power.

3. ORC CYCLE

The generation of electricity by means of heat absorption is a well-established form of energy conversion, which the most exploited thermodynamic cycle is the conventional Rankine cycle. However, the use of sources of heat below 400 ° C using conventional Rankine cycle is unfeasible due to their low efficiency under these conditions, considerably increasing the costs of generation. The organic Rankine cycle (ORC) is an alternative efficient technology for conversion of low and medium temperatures for electricity generation small and micro scale. This technology allows the efficient use of energy resources, with smaller systems and high economic performance.

The Organic Rankine cycle is composed of its main components: evaporator, turbine, pump and condenser; and its operating principle is similar to a Conventional Rankine Cycle. The main difference between the two cycles is the working fluid used – the Conventional Rankine Cycle uses water while the Organic Rankine Cycle can use hydrocarbons or coolants (organic fluids), that provides its special characteristics.

The working fluids in an ORC cycle present boiling points and latent heat of vaporization inferior to that of water, allowing evaporation to lower temperatures, which provides better yield of the heat supplied by a hot source, and highlight its use to low and medium temperature sources, (HUNG, 2001)

Furthermore the ORC cycles are not only subject to laboratory studies, according (KANG, 2012) over a hundred ORC plants are in operation to generate electricity commercially. Investigations about the ORC is based on the aspects of:

- Working fluid selection;
- Thermodynamic analysis;
- Performance analysis and integration of the main components.

The working fluid selection is largely evaluated in several scientific publications and is considered one of the most important criteria analysis in an ORC cycle. The selection of the working fluid is critical to obtain high thermal efficiency and optimum use of the available heat source. In addition, the organic working fluid must be carefully selected based on various indicators such as thermodynamic performance, characteristic of the saturated vapor curve, environmental restrictions, health and safety restrictions, as well the commercial availability and cost.

4. ORC INTEGRATION

In this study was conducted an analysis of the production processes of a Brazilian FPSO based on real data operation provided by plant operators, BG18. The processes of the major FPSOs production units evaluated were simulated by commercial software Hysys and GateCycle. In this assessment, it was estimated the operating parameters of the process flows, allowing thermodynamic modeling of process and of residual heat sources platform.

From this analysis, it was possible identify preliminarily the main sources of waste heat from the platform. According this analysis, the greatest amount of waste heat generated in the platform is due to the heat generated in compression of gas in the Gas Processing Plant (PPG), and the waste heat from exhaust gases from gas turbines in Power Generation Unit (PGU).

The exhaust gases from the gas turbines can be considered sources with great potential for energy recovery, and their utilization for electricity generation in offshore platforms is discussed in the study (NGUYEN et al., 2013; NORD; BOLLAND, 2013).

However, in accordance with (NGUYEN et al., 2014), the current FPSO platform systems do not allow the recovery and efficient utilization of low-grade waste heat in the process, such as the sources in PPG evaluated in this study. The low potential energy sources are waste heat sources of low temperatures, in which the harnessing of the potential of these is restricted. Because of this limitation, this study aims to optimize the ORC cycle operating parameters, to better use of these sources.

The residual heat is a considerable amount of the total energy contained in the primary sources of useful energy. Due to inefficient exploitation of low quality sources by conventional methods, this residual heat is usually discarded into the environment becoming a problem because of thermal pollution. According to Hung (HUNG et al., 1997), the residual heat is about 50% or more of all heat generated in industrial processes.

Each of the gas compression process PPG is followed by an intermediate heat exchanger to reduce the compressed gases temperature to 40 °C. The integration of ORC cycle aims to recovery this waste heat as a source for the cycle, as shown in Fig. 2.

The development of thermodynamic model of the heat recovery in the production PPG stages was determined by characterization of each waste heat source in these processes. For this was taken into account the chemical composition of the gases, temperature, pressure, and molar flow in the compression stage.

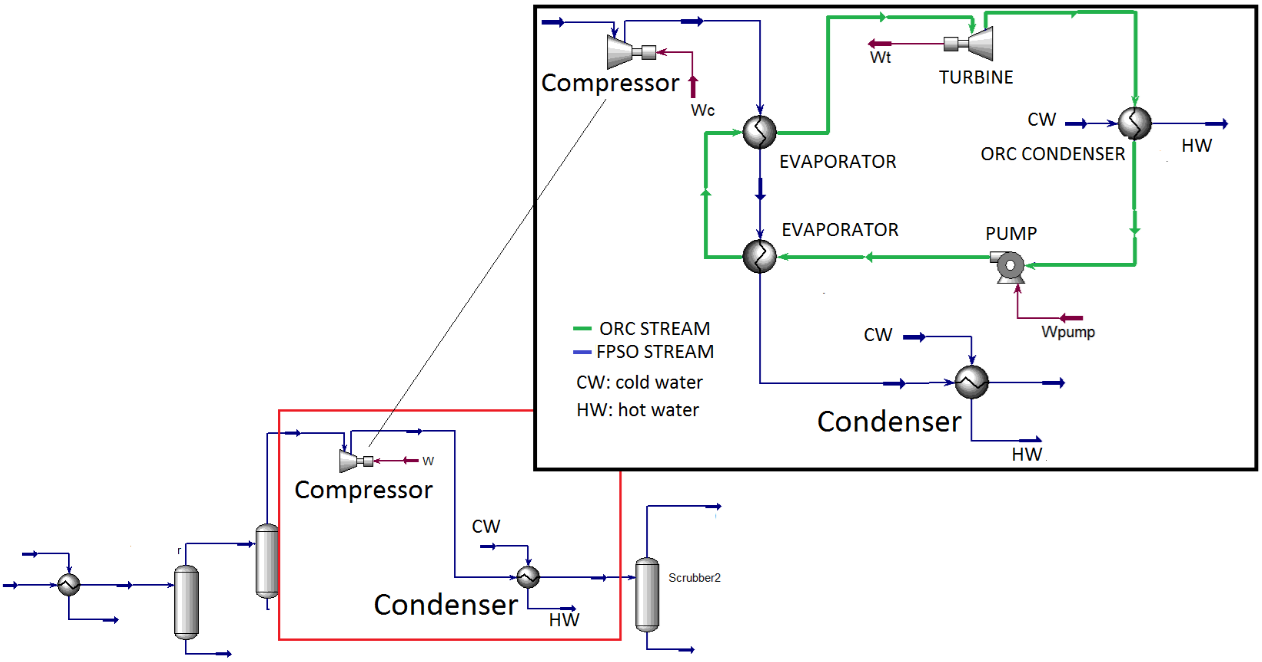

Figure 2. ORC system integration

The greatest potential for integration of ORC cycle, among the sources of low quality, was the fourth compression stage of CO2 Compression Unit (CCU) and the compression of gases in the Main Compression Unit (MCU). The characteristics of these sources are shown in the Tab.1.

Table 1 Flow gas characteristics

Source	Temperature [°C]	Pressure [kPa]	Mass Flow [kg/s]	Waste Heat [kW]
4° Stage CCU	135	25109,9	55,54	10918,8
MCU	158	8196,1	61,78	19531,18

5. METHODOLOGY

Initially a model of the physical system of interest was developed using software Hysys to simulate the processes according to actual operation data, based on measurements supplied by the plant operators. From this simulation, allowed the calculation of energy flows and materials.

5.1 Thermodynamics Evaluation

A computer programming in MATLAB was developed based on cubic equations of state, in addiction to mass and energy balance. This simulation aims to evaluate the thermodynamic properties of the system and analyze the ORC performance. The production processes of the evaluated platform in this work were simulated using the ASPEN-HYSYS® v.8.6 software. The model PRSV state equations was used for calculate the physical and thermodynamic properties according to compositional data for hydrocarbon streams.

The thermodynamic properties are used to determine the energy demands in transformation processes, both to assess variations in reversible processes and to determine the irreversibility in real processes.

The mass balance and energy is applied to each component of the cycle. For a volume control in steady state the situation of mass inside it's, and in its borders does not change with time. The formulation of energy and mass balance (BEJAN et al., 1996):

$$\dot{Q}_{vc} - \dot{W}_{vc} + \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right) - \sum_s \dot{m}_s \left(h_s + \frac{V_s^2}{2} + gz_s \right) = 0 \quad (1)$$

In thermodynamic modeling of the cycle the following simplifications were made:

- Operation in steady-state;
- Kinetic energy, potential energy and heat losses are not considered;;
- Detailed pressure loss calculations and heat transfer in the evaporator, condenser and internal heat recovery are ignored since they rely heavily on materials and design details of the heat exchangers (adiabatic process);
- Heat exchangers operate with countercurrent flow;
- The isentropic efficiency of the turbine and pump are constant (ηb = ηt = 80%);
- The working fluid in the condenser outlet is as saturated liquid.

The evaluated ORC system is composed of the four primary components: pump evaporator, turbine and condenser, as shown in Figure 5.1. The working fluid is a saturated liquid at the end of the condensation process (9-5), and then compressed in the pump (5-6). The working fluid enters the evaporator where it absorbs heat from the source flow, up to the steam condition; this process is represented by (6-7 and 7-8). Finally, the working fluid is expanded in the turbine to generate work (8-9).

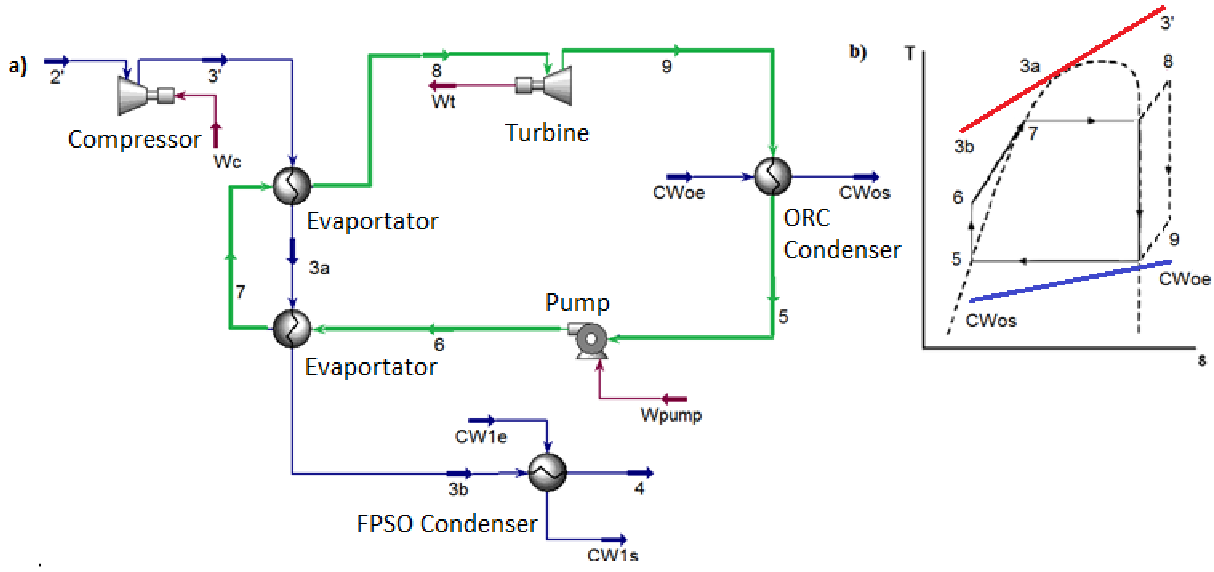

Figure 3 ORC cycle modelling

The rate of destruction of exergy in the interior of a process control volume can be calculated from the energy balance, (KOTAS, 1995; BEJAN et al., 1996). To an open control volume in steady state, the rate of destruction of exergy is defined as the difference between exergy rates entering and leaving the system:

$$\dot{E}_d = \sum_j \left(1 - \frac{T_0}{T_j} \right) \dot{Q}_j - \dot{W} + \sum_e \dot{m}_e e_e - \sum_s \dot{m}_s e_s \quad (2)$$

$$\dot{E}_d = exergy\ destruction\ rate$$

5.2 ORC Integration's Optimization

In this study realized a heat recovery optimization of waste sources evaluated by integrating ORC cycle. The optimization process was performed using the commercial software ModeFrontier®, modeled by the optimization algorithms of the software itself. The objective functions of interest for this study were defined as maximizing net power of ORC cycle, and minimizing the area of the cycle heat exchangers.

The variables pinch point, superheating, vapor pressure and effectiveness, are selected as entry conditions for combination of parameters in the multi-objective optimization. The determination of these variables have a direct influence on the enthalpy change in the turbine, the mass flow of the working fluid in the cycle and the added or rejected heat by the heat exchangers ORC cycle, which determine the cycle performance. These variables were determined for analysis following the assumption of studies as (ROY et al., 2010; SHENGJUN et al., 2011; XI et al., 2013), which the authors present a parametric evaluation to better use of ORC cycle.

A factorial distribution of the optimization variables is performed for verification of different combinations of design parameters. The result of this distribution is the initial population of the genetic algorithm optimization. There were evaluated thirty-one working fluids with different thermodynamic characteristics, with the possibility of using of superheating and use of internal heat recover, when thermodynamically possible.

The multi-objective optimization process maps the variables of decisions aimed at finding a number of ways of how to combine the input conditions such that the values of objective functions are acceptable, or in some way optimal. The optimization of the assessment of the problem leads to the set of optimal solutions in the search space according to the definition of "Pareto-Optimal" presented in (PARETO, 1896). This method determines the set of ideal results at the multiobjective problem in question, constituting the Pareto Frontier, in accordance with the set objective functions. (LEYLAND, 2002)

6. RESULTS

This study identified and evaluated different sources of low quality waste heat in extraction and processing petroleum systems of an FPSO.

In the evaluation of heat recovery of Main Compression Unit (MCU), the combination of parameters, which result in the Pareto front, is ensured by the fluid i-Butane and R-40, providing increased power generation with the smallest area, as shown Fig. 4. The R-40 fluid allows the best setting cycle for power below 1475 [kW]. Above this range, the i-Butane provides the highest power output with smaller areas. The maximum power generated from the ORC cycle in this application is 2175 [kW], with a total area of 7550 m^2 heat exchangers

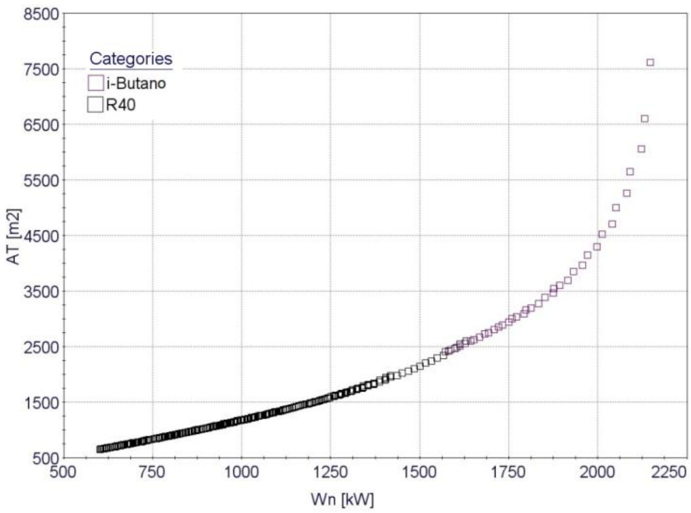

Figure 4 Pareto frontier of heat recovery in MCU.

In the CO2 compression unit (CCU), the gas stream composition is almost entirely CO2. In this step occurring four successive compression stages, the last stage being the one with the greatest potential for heat recovery. At this stage it was possible to generate up to 860 [kW] of net power to the ORC cycle, with a total area of heat exchangers 4000 [m2], as shown Fig. 5.

For integration of ORC cycle in these heat sources, n-pentane fluid would be selectable for low power generation, but minimizing area, at this operating range. Then, the fluid n-Butane, i-butane, R-152a are established as optimal fluid in the intermediate range of power generation. R-134a fluid provides the largest generation of this power source evaluated under the objective of the problem

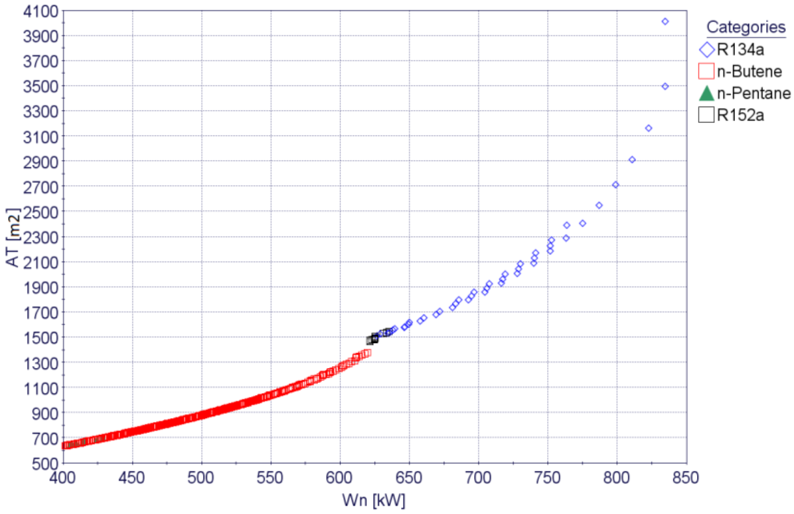

Figure 5 Pareto frontier of heat recovery in CCU

6.1 Thermodinamics Analysis

The compression stages throughout Gas Processing Unit (GPU) are responsible for the greater energy demand across platform. The optimization of the integration of ORC cycle for heat recovery in this unit aims to supply the requested power demand and improve thermodynamic and exergetic efficiency of these processes.

In the Tab.2 are presented some parameters with the purpose of evaluating the relevance of the integration of the ORC cycle in the evaluated sources.

Table 2 Result performance analysis

Source	**W_n [kW]**	**W_n/W_c [%]**	**$\dot{E}_d$ FPSO Compression [kW]**	**$\dot{E}_d$ ORC Integrated [kW]**	**$\dot{E}_d$ Reduction [%]**
4° Stage CCU	860	19,61	1889,86	1546,45	32,7%
MCU	2175	14,49	4509,24	2993,48	35,1%

The ratio Wnwc represents the ratio of net power generated by the ORC cycle and the power consumed at each compression stage. The heat harnessing in the fourth compression stage, provides greater earning at this relationship, allowing recovery of 19.6% of the power consumed by the compressor on its stage.

The exergy destroyed in the conventional process compression of the FPSO was evaluated adopting a volume control which includes each compression stage individually and the subsequent condenser to this, as in modeling the source. Is verified that there is a reduction of exergy destroyed in these sources when using the ORC cycles for recovering the heat generated in these processes. In Compressor Unit (PCU) is the largest reduction of the destroyed exergy, about 35.1%. Thus, it can be seen that the integration of ORC cycle to compression process allows an increase in exergetic efficiency of the operation

7. CONCLUSION

This present study evaluated the potential of using ORC cycles to allow the waste heat recovery at low-quality sources in the production processes of a Brazilian FPSO platform. The great challenge for power generation to support the demand of this input on a FPSO is due mainly to the restrictions on physical space, weight limitation and safety on the platform.

In this perspective, multi-objective optimization methodology presented in this work was essential for verification of better use of the assessed heat source. In this procedure, the optimization cycle of operation parameters for each evaluated working fluid and for the different heat sources investigated, allowed the determination of the set of operating conditions to guarantee best performance of the ORC cycle according to objective functions.

Different fluids composed the Pareto front for maximizing power generation in parallel with the minimization of the total area of the ORC cycle. The R-134a and i-butane were the fluids that favored greater power generation in each valued source.

The heat recovery in the Gas Processing Plant (GPP), wherein the potential of the heat source is greatly reduced, do not achieve a significant generation of electrical power. Electricity generation guaranteed by the integration of ORC cycle allows reducing the use of gas turbines for power generation, resulting in lower consumption of fuel gas, which can be destined to export, as well as reducing CO2 emissions. The reduction in fuel gas consumption provides the economic feasibility of the implementation of ORC cycles on the platform.

Moreover, the integration of ORC cycle PPG ensures a large reduction of exergy destroyed, increasing the efficiency of the compression processes. That exergy destroyed over the processes of an FPSO, due to the low efficiency of the processes, it is crucial to the additional consumption of fuel gas.

8. ACKNOWLEDGEMENTS

The authors want to thanks the Coordination of Improvement of Higher Education (CAPES), The National Council of Technological and Scientific Development (CNPq) and The Foundation for Research Support of Minas Gerais State (FAPEMIG) for their collaboration and financial support in the development of the research work. Also, want to thanks BG E&P Brasil Ltda for funding the Project “Recuperação de Calor Residual em Unidades FPSO Utilizando Ciclos não Convencionais”.

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