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Study of waste heat recovery potential and optimization of the power production by an organic Rankine cycle in an FPSO unit

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ABSTRACT

This paper aims to explore the alternatives for waste heat recovery in a floating production storage and offloading (FPSO) platform to meet the demand for heat (from hot water) and to maximize the electric power generation through the organic Rankine cycle (ORC) with purpose to increase the overall thermal efficiency of the process and reduce CO_2 emissions. Two different cycles' configurations are explored (simple and regenerative) using exhaust gases from the gas turbines as the heat sources for the ORC and the cogeneration system. The curves of the GE LM2500 and GE LM2000 turbines are modeled together with the water heating systems and the organic Rankine cycle. The model is solved using a genetic algorithm optimization method, whose objective function is set to meet the electric power demand for the FPSO platform. The purchased equipment costs of the ORC, the reduction in fuel consumption and CO_2 avoided are estimated. Waste heat recovery meets the heat demand and contributes up to 21% of the electric energy demand, which increases the overall efficiency of the system, and improves the utilization factor by up to 10.8% and 19.2%, respectively. There is an average reduction of 22.5% in fuel consumption and CO_2 emissions during the lifetime of the FPSO. The economic analysis based on the NPV shows that a US$12.55 million return on investment is possible, in addition to reducing the initial investment cost by US$14.2 million through the exclusion of the GE LM2500 gas turbine at project implementation.

1. Introduction

One of the world's major concerns today is environmental pollution as well as its consequences. With the growth in industrialization, the problem has worsened, and environmental agencies have become more demanding in relation to CO_2 emission criteria. According to the International Energy Agency (IEA), greenhouse gas emissions and the concentration of these gases in the atmosphere has steadily increased. One of the main causes of this increase is the energy sector, which accounts for approximately two-thirds of all anthropogenic emissions that will cause irreversible impacts to the planet [1].

For the oil and gas industry, methane and carbon dioxide are the two most important greenhouse gases, the former having a greater capacity to capture solar radiation in the atmosphere, which makes it a potential cause of short-term warming. The large expansion in oil and gas exploration due to the discovery of the pre-salt layer in Brazil has seen the increase in the use of offshore platforms [2]. Although Brazil is not obliged to reduce its CO_2 emissions, a commitment to reduce them is assumed for the year 2020. In Brazil, the main sources of CO_2 emissions are changes in land and forest use due to over-burning and deforestation, contrary to other countries where burning fossil fuels is the main source of emissions. However, from the year 2020, it is forecasted that Brazil will reach a situation similar to those of industrialized countries, which requires the adoption of control policies on the burning of fossil fuels [3].

The recovery of residual heat from offshore processes with the organic Rankine cycle (ORC) has been explored by several researchers around the globe for the purpose of generating power without the need for additional burning of fossil fuels. Mondejar et al. [4] conducted a study of an ORC integrated into a passenger vessel of the M/S Birka Stockholm cruise ship. It was evaluated by an off-design model based on optimized design conditions. Using the ORC, 22% energy was obtained in relation to the total demand of energy on board. Suarez et al. [5] studied a practical application of exhaust gas waste heat recovery from the engines of the Aframax tanker. A conventional Rankine cycle was compared to the ORC using benzene, heptane, hexamethyldisiloxane, toluene, and the R245fa. The installation of a waste heat recuperator allows an annual fuel saving of €154 k and a reduction in CO_2 emissions of 705 t. The fuel consumption and CO_2 emissions fall by 17% using the ORC when compared to the conventional Rankine cycle. Song

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Nomenclature

Latin and greek symbols

D	demand (MW)
h	enthalpy (kJ/kg)
i	discount rate (%)
I_{fuel}	income saved fuel consumptions (US$/yr)
I_{CO_2}	income saved CO_2 emissions (US$/yr)
L	workload (%)
LHV	lower heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
mf	mass fraction (%)
M_f	maintenance factor
P	pressure (Bar)
$\dot{Q}$	heat energy (MW)
T	temperature (°C)
$\dot{W}$	power (MW)
ΔT	temperature difference (°C)
ε_u	utilization Factor (%)
$\bar{\eta}$	average efficiency (%)
η	efficiency (%)

Abbreviations

Ar	argon
API	American petroleum institute
C1, C2, C3	compressor 1, 2 and 3
CC1, CC2, CC3	combustion chamber 1, 2 and 3
CO_2	carbon dioxide
DC	direct costs
EES	engineering equation solver
FPSO	floating production storage and offloading
FCI	fixed-capital investment
GWP	global warming potential
GT	gas turbine
GA	genetic algorithm
GE	general electric
H_2O	water
IEA	international energy agency
IC	indirect costs
N_2	nitrogen
O_2	oxygen
ORC	organic Rankine cycle
ODP	ozone depletion potential
OF	objective function
PEC	purchased-equipment costs
R ORC	regenerative ORC
S ORC	simple ORC
TC	turbo-compressor
TCI	total capital investment

Subscripts and superscripts

1–24	refers to locations of GTs – ORC
A–H	refers to locations of ORC
atm	atmosphere
co	condenser
eco	economizer
eva	evaporator
sup	superheater
elect.	electric
fuel	fuel
gen	electric generator
in	input
mix	mixture
max	maximum
ml	logarithmic mean
n	mixture components
ORC	organic Rankine cycle
ove	overall
OTB	once-through boiler
p	pump
pp	pinch point
r	real
rc	heat recovery
re	regenerator
s	isentropic
sL	saturated liquid
sv	saturated vapour
t	turbine
up	upper
water	water

et al. [6] studied the waste heat recovery of a marine diesel engine. There was an efficiency increase of 10.2% for the marine diesel engine, and the system proved to be economically attractive. Larsen et al. [7] compared the conventional Rankine, the Kalina, and the ORC cycle for combined cycle application in conjunction with a large two-stroke marine diesel engine. The maximum power was obtained using the ORC cycle whereas the conventional Rankine cycle and the Kalina cycle produced ~75.0% of the ORC power. The thermal efficiency of the plant of the cycle combined with the ORC was 52.0%, whereas the Kalina and Rankine cycles resulted in 51.0% and 51.1%, respectively, making a possible increase in the overall efficiency of the plant of up to 2.6%. Pierobon et al. [8] conducted a study to determine which heat recovery technology is the most suitable for offshore installations. The results showed that the ORC presents better performance with respect to the Rankine steam, whereas the air-bottoming cycle modules are not interesting from the economic and environmental standpoints. Despite the high cost of the ORC equipment, the ORC turbogenerators are the solution to reduce CO_2 emissions in offshore installations. Girgin and Ezgi [9] conducted a thermodynamic study of an ORC to recover the waste exhaust gases from a diesel generator on a naval ship. In an ideal case, it was possible to produce 92 kW of power using toluene as the working fluid, in addition to saving 25,500 liters of diesel fuel and reducing 67.2 tons of CO_2 emission at the end of 1000 operating hours.

Several other studies related to ORC for waste heat recovery were performed. Soffiato et al. [10] evaluated the heat recovery from an ORC of three engines of a driven liquefied natural gas. Three ORCs were compared: simple, regenerative and two-stage ORCs. The results showed that the two-stage cycle reaches maximum net power corresponding to almost double the simple and regenerative ORC. Imran et al. [11] carried out a thermo-economical optimization study of a simple and regenerative ORC for waste heat recovery for a constant heat source. Thermal efficiency and specific investment cost was optimized to different working fluids. The results showed that the R245fa is the best working fluid and the simple ORC presents lower specific cost. Song and Gu [12] studied a dual-loop ORC for waste heat recovery of the engine exhaust gas and the jacket cooling water. Cyclohexane, benzene and toluene were evaluated in the high temperature loop whereas R123, R236fa, and R245fa were chosen for the low temperature loop. The results showed that the combination of cyclohexane and R245fa presents the maximum net power and the additional power generated correspond to 11.2% of the original power output of the engine. Cao et al. [13] proposed the ORC as a bottoming cycle for the