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Thermodynamic analysis of an upstream petroleum plant operated on a mature field

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ABSTRACT

Oil and gas processing on offshore platforms operates under changing boundary conditions over a field lifespan, as the hydrocarbon production declines and the water extraction increases. In this paper, the processing plant of the Draugen platform is evaluated by performing an energy and exergy analysis. This facility exploits an end-life oilfield and runs at conditions deviating significantly from its optimal operating specifications. Two different operating modes were assessed, and process models were developed using the simulation tools Aspen Plus® and Aspen HYSYS®, based on measured and reconciliated process data. The total energy demand is moderately sensitive to daily and monthly variations: it ranges between 22 and 30 MW, of which 18–26 MW and about 3–4 MW are in electrical and thermal energy forms. The greatest exergy destruction takes place in the gas treatment (51%), recompression (12%) and production manifold (10%) modules. The separation work performed on this platform is greater than in similar facilities because of higher propane and water fractions of the well-streams. These findings emphasise the differences between *peak* and *end-life* productions: they suggest (i) to set focus on processes including gas expansion and compression, (ii) to investigate possibilities for an improved energy integration, and (iii) to consider and evaluate alternative system designs.

1. Introduction

Reservoir fluids from oil and gas fields are complex multiphase mixtures, containing a large range of chemical compounds, from light to heavy hydrocarbons, contaminants such as carbon dioxide, and subsurface water. The hydrocarbon fraction must be separated and purified to be further transported, while the impurities must be removed and the water phase cleaned. The processing plant of an offshore platform should meet these criteria, and the design phase should consider parameters such as the reservoir fluid composition, flow rate, pressure and temperature [1–4]. The on-site processes are generally designed for near-peak hydrocarbon production and have a lower performance at the end-life of an oilfield, when the oil and gas production decreases and the water production rises. The specific environmental impact and energy intensity of the processing facility will increase, because large amounts of power are consumed to enhance oil recovery by water injection, gas injection and/or gas lift [5–7].

Nowadays, the performance of an offshore platform is measured by indicators related to the energy demand and environmental impact of the processing plant. Svalheim and King [8] mentioned: (i) the *energy efficiency* of the platform, defined as the ratio of the energy exported to the shore to the energy entering the processing plant, (ii) the *energy intensity*, defined as the ratio of the energy used on-site to the energy exported onshore, (iii) the *specific power consumption* and (iv) the *specific* CO_2*-emissions*. The authors emphasised the limitations of these indicators: a comparison of different plants with these metrics may be misleading, since different oilfields present different characteristics [9]. These metrics are based on conventional energy analyses, which yield information on the energy inputs needed to produce a given product [10]. As stated by the 1st Law of Thermodynamics, energy is

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Nomenclature

Symbols

T: Temperature, K
$\bar{e}$: specific exergy, J/mol
$\dot{E}$: Exergy rate, W
e: specific exergy, J/kg
i: chemical compound
j: stream
k: component
p: pressure, Pa
s: specific entropy, J/(kg K)
w: specific power consumption, W
y: component/sub-system exergy ratio

Abbreviations

API: American Petroleum Institute
EOS: equation of state
PP: processing plant
TEG: triethylene glycol
UT: utility plant

Greek letters

Δ: difference
δ: uncertainty (95% confidence level)
η: energy efficiency
ι: intensity
ω: waste
σ: standard deviation
ε: exergy efficiency

Superscripts

*: relative
ch: chemical
kn: kinetic
m: mechanical
ph: physical
pt: potential
t: thermal

Subscripts

0: dead state
$\hat{h}$: energy-based
$\hat{x}$: exergy-based
d: destruction
f: fuel
l: loss
p: product
cool: cooling medium
feed: feed
in: inlet
mix: mixture
o.e: oil equivalent
out: outlet
tot: total

conserved and cannot be destroyed. An energy analysis indicates therefore changes from one form of energy to another and allows the tracing of energy flows throughout a given system.

Unlike energy, exergy is destroyed via conversion technologies and losses in real processes because of entropy generation. An exergy accounting reveals the locations and extents of the thermodynamic irreversibilities of the system under study [11,12], and the amount of exergy destroyed throughout successive processes accounts for the additional fuel use because of system imperfections [13–16]. Rivero [17] argued that the application of an exergy analysis to petrochemical systems would provide valuable insights. Voldsund et al. [18] suggested the use of exergy analysis as a tool for performance benchmarking and evaluation of offshore platforms.

A few studies on energy, exergy and offshore processes exist. Oliveira and Van Hombeeck [19] analysed a Brazilian plant: the gas compression and the separation processes were the main energy users and exergy consumers, and both systems were associated with significant exergy destruction. Voldsund et al. [18,20,21] studied a North Sea oil platform. They showed that the greatest thermodynamic irreversibilities were associated with processes where large changes in pressure took place. Nguyen et al. [22] conducted an analysis of generic North Sea oil platforms. In *most cases*, the gas compression step was the most power-consuming and exergy-destroying process, but one particular case showed different characteristics. Their work indicated that the thermodynamic performance of an oil and gas platform was optimal with low reservoir fluid contents of gas and water.

The literature appears to contain little on the application of energy *and* exergy analyses to offshore *processing plants*, and none with a special focus on their thermodynamic performances when the oilfield is mature. The goal of this study is to help close these gaps. This work aims at (i) quantifying, in terms of energy and exergy, the several transformations taking place within the processing plant of a specific oil and gas platform, (ii) comparing two types of production days, and (iii) investigating the effects of end-life boundary conditions. It is part of a larger research project dealing with the optimisation of electrical energy production and consumption on offshore platforms and builds on earlier work conducted by the same authors [22,23].

The facility investigated in this work is similar to other plants in the North Sea [7,24,25], with two main differences: (i) the oilfield is characterised by a high propane content of the reservoir fluid and a small gas-to-oil ratio, and (ii) oil is not exported continuously via pipelines but in batch operation with shuttle tankers and intermediate storage in on-site tanks. The oil recovery rate is expected to reach 65–75%, which is much higher than the typical rate of 45–50% for Norwegian fields. This has encouraged an extended exploitation of this petroleum field, despite the high water cut of the feed. However, the processing plant is still run within its design range, although far from its optimum conditions. This is the first study on the thermodynamic performance of this particular plant, and on the performance assessment of offshore facilities operated during an extended production life period.

The present work was structured as follows:

- development and calibration of the processing plant model based on measured process data;
- evaluation of the material, energy and exergy flows throughout the processing system;
- analysis of the energy and exergy consumption patterns and of the plant inefficiencies.

The processing plant system and model are described with the methods of analysis in Section 2. Section 3 reports the results obtained, which are discussed and critically reviewed in Section 4. Concluding remarks are outlined in Section 5.

2. Methods

2.1. Case study

2.1.1. System overview

The oilfield investigated in this study (Fig. 1) is located in the Norwegian Continental Shelf region: the construction of the