

APPLICATION OF THERMO-CHEMICAL TECHNOLOGIES FOR CONVERSION OF ASSOCIATED GAS IN DIESEL-GAS TURBINE INSTALLATIONS FOR OIL AND GAS FLOATING UNITS

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ABSTRACT

The paper considers the issue of thermo-chemical recovery of engine's waste heat and its further use for steam conversion of the associated gas for oil and gas floating units. The characteristics of the associated gas are presented, and problems of its application in dual-fuel medium-speed internal combustion engines are discussed. Various variants of combined diesel-gas turbine power plant with thermo-chemical heat recovery are analyzed. The heat of the gas turbine engine exhaust gas is utilized in a thermo-chemical reactor and a steam generator. The engines operate on synthesis gas, which is obtained as a result of steam conversion of the associated gas. Criteria for evaluating the effectiveness of the developed schemes are proposed. The results of mathematical modeling of processes in a 14.1 MW diesel-gas turbine power plant with waste heat recovery are presented. The effect of the steam/associated gas ratio on the efficiency criteria is analyzed. The obtained results indicate relatively high effectiveness of the scheme with separate high and low pressure thermo-chemical reactors for producing fuel gas for both gas turbine and internal combustion engines. The calculated efficiency of such a power plant for considered input parameters is 45.6%.

Keywords: thermo-chemical heat recovery, gas turbine engine, diesel engine, associated gas, steam reforming, efficiency, methane number

INTRODUCTION

The development of the global economy generates growing demand for oil and gas. At the same time, there is a decrease in the number of promising mainland deposits. The vector of fossil hydrocarbon extraction is steadily shifting to the area of the continental shelf. Over 37% of the world oil production and 28% of gas production come from fields located on the shelf [1]. Essentially, these deposits are located in the Middle East, Brazil, the Gulf of Mexico, the North and Caspian seas, and on the Arctic shelf. The recently discovered offshore oil and gas deposits are about 10 times larger than newly discovered land deposits. The development of the continental shelf deposits creates the basis for providing the

world economy with hydrocarbon raw materials for the long perspective.

Oil and gas floating units are located at significant distances from the coast. At the same time, various technologies and technical means are successfully applied and developed for various climatic conditions. An increasing number of oil and gas production facilities are related to deep water (0.4...1.5 km) and ultra deep water (over 1.5 km). The process of oil and gas extraction from the sea shelf is energy intensive, and with the increase of extraction depth the energy costs also grow higher. At the same time, the emissions of greenhouse gases produced by power plants increase as well.

The need to solve the problems of improving fuel efficiency and reducing harmful emissions during power equipment

operation is a paradigm for designing power plants for marine vessels and ocean engineering objects. All this requires defining new promising ways to improve the efficiency of oil and gas production power plants.

IDENTIFICATION OF THE INVESTIGATION OBJECT

Low-speed two-stroke diesel engines (2SDE) are most widespread in the ship power industry. 2SDE have high efficiency and can work on cheap heavy grades of fuel oil. The efficiency of such power plants can be improved due to the recovery of energy resources [2]. Large weight and size indicators of such engines do not allow their use in power plants of oil and gas floating units.

The main thermal engines used in power installations of oil and gas floating units are gas turbine engine (GTE) and medium speed four-stroke diesel engine (4SDE). Despite the fact that the efficiency of internal combustion engines is higher, the advantage is given to GTEs, as they better satisfy the requirements of ensuring high power with small weight and size parameters.

A large number of publications are devoted to solving the problem of increasing the efficiency of gas-turbine engines for oil and gas production facilities. One of the ways to increase this efficiency can be humidification of the air entering the GTE compressor [3]. The most widespread way to increase gas turbine unit efficiency is to use the heat of the waste gas in the combined gas-steam turbine cycle. Combined-cycle power plants of this type have been installed on three Norwegian gas fields [4]. It was revealed that large mass and dimensions of the steam-turbine circuit equipment [5] restrain the use of such technologies at oil and gas production facilities.

Fuel characteristics largely determine the performance indicators of thermal engines, including GTE [6]. 4SDE and GTE are dual-fuel engines, adapted to operate on gaseous and liquid fuels. The associated gas, separated from crude oil, can also be used as a fuel. The composition of the associated gas varies and it can contain a lot of heavier hydrocarbons [7-11].

The use of such a fuel in an internal combustion engine can cause problems associated with significant influence of fuel composition on the engine's working process. The methane number is the measure of resistance of the gas fuel to knock. Leading manufacturers of marine internal combustion engines restrict the lower limit of the fuel methane number (MN). For example, for Wartsila dual-fuel engines, fuels with methane number WMN <46.8 are not recommended for use. Moreover, the molar methane content should not be less than 70%, and H₂ should not be more than 30% [12].

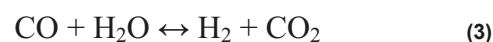
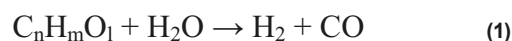
The authors have carried out calculations of the methane number for associated gases with different compositions [7-11]. The calculations were carried out using the Wartsilä Methane number calculator, as well as the method of the Gas Research Institute [13]. The results of the MN and Low Calorific Value (LCV) calculations are presented in Table 1.

Tab. 1. Parameters of associated gas

Parameters	Value				
	A1	A2	A3	A4	A5
Designation of associated gas					
Chemical compound (% mol)					
Reference source	[7]	[8]	[9]	[10]	[11]
Methane (CH ₄)	68.00	62.77	73.7	64.48	67.32
Ethane (C ₂ H ₆)	15.00	15.07	6.70	11.98	17.66
Propane (C ₃ H ₈)	9.00	6.64	6.10	8.75	8.95
Butane (C ₄ H ₁₀)	5.00	2.40	3.89	3.84	4.20
Pentane and Heaver (C ₅ +))	1.00	1.12	3.70	2.02	1.87
Hydrogen Sulfide (H ₂ S)	-	2.80	0.20	0.57	-
Carbon Dioxide (CO ₂)	1.00	9.20	1.34	0.63	-
Nitrogen (N ₂)	1.00	-	4.37	3.73	-
Water vapor (H ₂ O)	-	-	-	4.00	-
Methane Number Calculation					
Wärtsilä Methane Number (WMN)	<46.8	<46.8	<46.8	<46.8	<46.8
GRI methods:					
Linear coefficient relation (GRI LCR MN)	27.5	47.3	42.6	21.5	26.1
Hydrogen/carbon ratio relation (GRI H/C MN)	64.4	53.4	61.2	53.3	67.9
Low Calorific Value Calculation					
LCV, MJ/kg	46.3	38.6	44.0	42.9	47.9

To prepare the associated gas for use as fuel in an internal combustion engine, Wartsila developed the steam reforming based GasReformer Technology. According to this technology, the methane number of the fuel gas is improved by converting heavier hydrocarbons into synthesis gas and methane [14]. The patented Wärtsilä GasReformer executes the conversion of the associated gas with steam reforming on nickel catalysts (Ni/MgAl₂O₄). Since nickel catalysts are very sensitive to sulfur compounds, frequent desulfurization is envisaged. In addition, during the gas reformer operation, intense deactivation of the nickel catalyst takes place due to carbon deposition on the catalyst surface. The installation is designed to work with 4...12 MW 4SDE Wärtsilä engines. The claimed efficiency is 44.5%.

Steam reforming of hydrocarbon fuels is accompanied by endothermic reactions of steam reforming (1) and decomposition (2) requiring external heat supply (+ΔH), as well as exothermic reaction (-ΔH) of water-gas shift (3):



The main components of the synthesis gas that can be obtained as a result of steam reforming are H₂, CO, CO₂,

CH₄ and H₂O. During steam reforming of hydrocarbon fuels, an increase of the process pressure results in the shift of the conversion efficiency region to a high temperature zone. At the same time, the pressure of the gaseous fuel supplied to the gas turbine engine is 1.5...3 MPa, while to the 4SDE, the gaseous fuel is fed at a pressure of 0.5...0.6 MPa. The conversion executed at pressures close to atmospheric can be effective at lower process temperatures, but it requires considerable power inputs to compress the obtained synthesis gas before it enters the engine.

Thermo-chemical conversion of heavy hydrocarbons into synthesis gas can be carried out using plasma-chemical methods [15, 16, 17]. The plasma-chemical technologies are used to intensify the process of burning the synthesis gas of various composition, including low LCV [18, 19, 20].

One of the promising ways to improve the power plant efficiency is the use of engine's exhaust energy to support endothermic reactions of steam reforming of hydrocarbon fuels with different compositions.

The previously conducted researches have shown that the thermal potential of the secondary energy resources in the internal combustion engine does not provide opportunities for efficient conversion of associated gas components. On the other hand, the temperature range of the exhaust gases in modern commercial GTEs enables efficient conversion of heavy hydrocarbons being part of the associated gas.

The diagram of the combined diesel-gas turbine power plant with thermo-chemical heat recovery (COGED+TCR) is considered in [21]. This diagram presents steam reforming of natural gas or cargo vapor products on LNG gas carriers. The heat source for conversion is the heat of GTE off-gases.

The COGED+TCR installation can be applied on oil and gas floating units which utilize the associated gas with different composition as a fuel.

CHARACTERISTICS OF POWER PLANTS WITH CONVERSION OF ASSOCIATED GAS FOR OIL AND GAS FLOATING UNITS

Figure 1 shows two variants of the combined COGED+TCR installation. The plant consists of a gas turbine unit based on a simple cycle gas turbine engine and two dual-fuel 4SDEs. All engines run on products of associated gas reforming. The heat of the GTE exhaust gas is utilized in a thermo-chemical reactor and a steam generator.

In the diagram with single reactor (Fig. 1A), the conversion of the associated gas is carried out at the pressure corresponding to the feed pressure in the internal combustion engine (0.6 MPa). This moderate process pressure implies a shift in the effective conversion range to a region of relatively low temperatures corresponding to the GTE exhaust gas temperature. The synthesis gas obtained in the reactor is passed to the dehydrator. The drained synthesis gas has a significantly lower content of non-combustible components, which significantly simplifies the processes of mixture formation and combustion. The disadvantage with respect

to gas turbine engines is that dehydration of the synthesis gas results in the loss of thermal potential of the steam-and-gas mixture. Further, the dried synthesis gas is divided into two streams. The first stream is passed to the internal combustion engine, while the second stream is compressed in the compressor to the feed pressure in the GTE (1.5 MPa). The water obtained in the dehydration process returns to the cycle.

In the second case (Fig. 1B), two reactors are provided – with high pressure of 1.5 MPa and low pressure of 0.6 MPa. From the high-pressure reactor, which has a sufficiently high temperature, the steam-and-gas mixture flows into the combustion chamber, like in the STIG cycle. After leaving the low-pressure reactor, the synthesis gas undergoes the dehydration process and is further fed to the internal combustion engine.

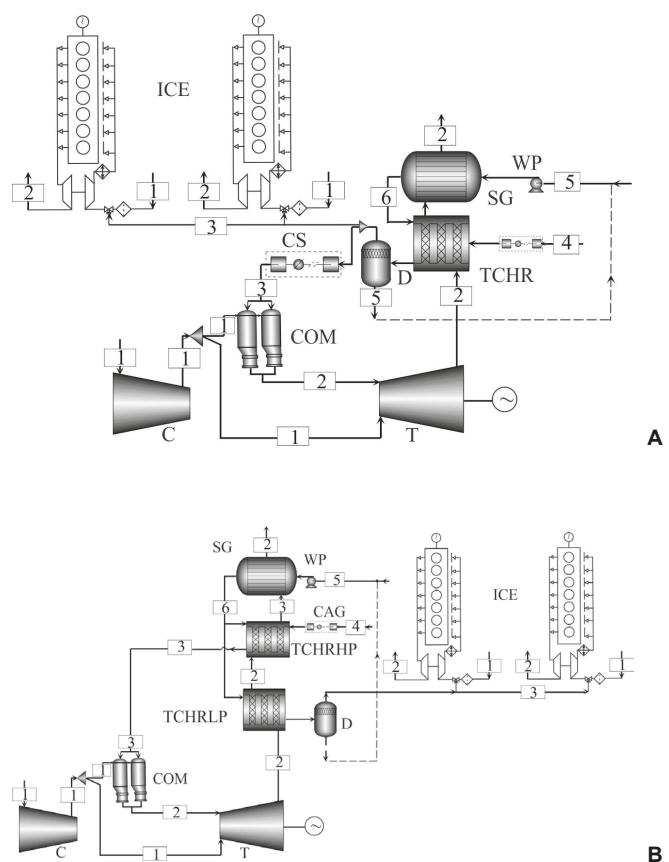


Fig. 1. Simplified calculation schemes of a COGED+TCR plant. A – scheme with single unit reactor, B – scheme with double unit reactor. Designations: 1 – air, 2 – gas, 3 – syngas, 4 – associated gas, 5 – water (steam), C – compressor; CAG – associated gas compressor; COM – combustor; CS – syngas compressor; D – degasifier; SG – steam generator; T – gas turbine; TCHR, TCHRLP, TCHRHP – thermo-chemical reactor; WP – water pump

The applicability range of the developed COGED+TCR diagrams was evaluated using mathematical modelling of processes. In this modeling, the power plant was structurally considered as a system of three functionally interconnected subsystems:

- energy subsystem, in which the chemical energy of the fuel is converted into mechanical and thermal energy;

- recovery subsystem, designed to convert the waste heat of the energy subsystem into mechanical and thermal forms of energy;
- associated gas conversion subsystem.

The range of applicability of the proposed diagrams can be comprehensively evaluated based on the efficiency of use of the chemical energy of the associated gas and the efficiency of the thermo-chemical conversion of heavy hydrocarbons being part of the associated gas.

As the criterion of the fuel energy efficiency, the efficiency of the installation was provided:

$$\eta = \frac{N_{combi}}{m_{\Sigma f} \cdot LCV} \quad (4)$$

where N_{combi} is the power output of the combined plant, and $m_{\Sigma f}$ is the fuel mass flux.

$$N_{combi} = i \cdot N_{GTE} + j \cdot N_{4SDE} \quad (5)$$

$$m_{\Sigma f} = m_{\Sigma GTE} + m_{\Sigma 4SDE} \quad (6)$$

In Eqs. 5 and 6, i and j are the numbers of gas turbine and diesel engines, N_{GTE} , N_{4SDE} are the power outputs of the gas turbine and diesel engines, and $m_{\Sigma GTE}$, $m_{\Sigma 4SDE}$ are the fuel mass fluxes of the gas turbine and diesel engines, respectively.

The plant power and the associated gas LCV are considered as constants. In this case, the efficiency criterion is the function of change of fuel consumption rate

$$\eta = f(\Delta m_{\Sigma f}) \quad (7)$$

where $\Delta m_{\Sigma f}$ is the change of consumption rate of the associated gas fed to the gas turbine engine, or to the internal combustion engine.

As criteria of the efficiency of thermo-chemical conversion of heavy hydrocarbons contained in the associated gas, two parameters were taken:

- the rate of conversion of the corresponding hydrocarbon (ethane, propane, butane, pentane);
- the methane number, defined as WMN and GRI Linear Coefficient Relation MN.

The conversion rate is defined as

$$\xi = \frac{(q_{in}^m - q_{out}^m)}{q_{in}^m} \quad (8)$$

where q_{in}^m is the mole fraction of the corresponding hydrocarbon in the associated gas, and q_{out}^m is the mole fraction of the corresponding hydrocarbon in the fuel gas fed to the internal combustion engine.

The methane number defined as WMN and GRI LCR MN was used as the criterion of energy efficiency of the

thermo-chemical conversion of heavy hydrocarbons contained in the fuel gas fed to the internal combustion engine.

The WMN was determined using the on-line Wäertsilä Methane number calculator program. To calculate the GRI LCR MN, the following dependency was considered [13]:

$$\begin{aligned} \text{GRI LCR MN} = & \\ = & 1.445 \cdot (137.78 \cdot x_1 + 29.948 \cdot x_2 - 18.193 \cdot x_3 - \\ & - 167.062 \cdot x_4 + 181.233 \cdot x_5 + 26.994 \cdot x_6) - 103.42 \end{aligned} \quad (9)$$

In Eq. 9, x represents the mole fraction of an individual component: $\text{CH}_4 = x_1$; $\text{C}_2\text{H}_4 = x_2$; $\text{C}_3\text{H}_8 = x_3$; $\text{C}_4\text{H}_{10} = x_4$; $\text{CO}_2 = x_5$; $\text{N}_2 = x_6$.

The basis for the mathematical model of the gas turbine block is the extended GTE calculation which takes into consideration total pressure losses. The combustion chamber model is based on combined chemical and phase equilibrium, while to determine the composition of the components, the Gibbs free energy for reaction products is minimized. Note that the obtained synthesis gas has a low calorific value and high content of non-combustible impurities, therefore it is advisable to use a plasma-chemical intensification system to initiate the burning process in the gas turbine combustion chamber [22, 23].

The rate of the waste gas heat required for fuel conversion was determined from the thermo-chemical reactor heat balance.

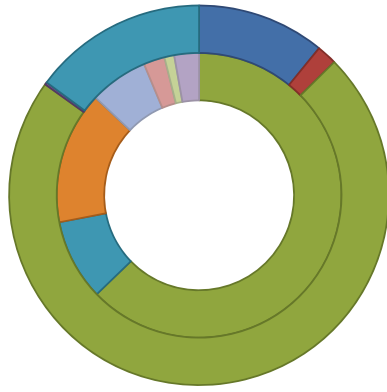
The modeling of the power plants was based on the gas turbine engine UGT 2500 and two medium-speed 4SDE engines Wäertsilä 6L50DF. The total plant power was 14.1 MW.

The simulation of the GTE processes was carried out for the parameters of the basic turbo-compressor unit, with the following restrictions:

- fixed GTE power (2.7 MW);
- fixed gas turbine inlet temperature ($T_3 = 1223$ K);
- environmental parameters according to ISO 3046-1:2002.

With regard to the 4SDE engine Wäertsilä 6L50DF with fixed power (5.7 MW) and total energy consumption at 100% load (7.41 MJ/kWh), the change in fuel consumption in terms of LCV associated gas supplied to the power plant was determined.

Mathematical modelling of the processes in the plant has revealed that the diagram shown in Fig. 1A has low fuel energy efficiency. The energy consumed for compressing the dried synthesis gas to the GTE feed pressure is larger than the increase in energy efficiency due to steam reforming of the associated gas. As a result, the efficiency of the installation shown in the diagram in Fig. 1A is comparable to or lower than the baseline plant efficiency without TCR. The efficiency calculation of thermo-chemical conversion parameters showed complete conversion of heavy hydrocarbons (Fig. 2).



■ H2 ■ H2O ■ METHANE ■ CO ■ CO2
 ■ ETHANE ■ PROPANE ■ N-BUT-01 ■ N-PEN-01 ■ H2S

Fig. 2. Comparing chemical compounds (% mol) of the associated gas (inner ring) with the resulting synthesis gas conversion products (outer ring)

The results of modelling of the processes in the power plant shown in Fig. 1B have demonstrated good effectiveness of this scheme. Due to the steam reforming of the associated gas and the use of the potential of the steam-gas mixture, the mass flow rate of the associated gas used as GTE fuel decreased by 19...20% (Fig. 3), which resulted in the increase of the gas turbine unit efficiency by 6.8%.

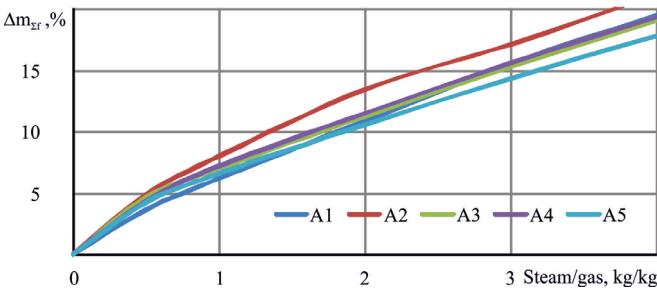


Fig. 3. Decrease in mass flow rates of associated gases with different compositions depending on the water/gas ratio (mass)

As a result of the use of thermo-chemical heat recovery of the waste gas, the calculated efficiency of the COGED+TCR unit (45.6%) increased by 3% compared with the basic COGED power plant. This result is comparable to the declared Wärtsilä GasReformer data.

The performed simulation made it possible to determine the composition of the synthesis gas obtained as a result of conversion of associated gases with different compositions (Table 2).

Tab. 2. Parameters of fuel gases fed to internal combustion engines

Parameter	Value				
	A1	A2	A3	A4	A5
Designation of base associated gas (Tab. 1)	A1	A2	A3	A4	A5
Chemical compound of fuel gas fed to internal combustion engine, (% mol)					
Hydrogen (H ₂)	12.7	10.7	11.7	11.4	12.9
Water vapor (H ₂ O)	1.7	1.7	1.7	1.7	1.7
Methane (CH ₄)	74.0	71.3	73.4	73.7	74.6

Parameter	Value				
Carbon Oxide (CO)	0.2	0.2	0.1	0.2	0.1
Carbon Dioxide (CO ₂)	10.6	14.6	10.3	10.4	10.7
Nitrogen (N ₂)	0.8	1.5	2.8	2.6	
Calculated Wärtsilä methane number	78	82	77	78	87
Calculated GRI LCR methane number, Eq. (6)	78	84	76.7	77.6	79.3
LCV, MJ/kg	35.7	28.1	30.5	34.7	36.2

The efficiency calculations of the thermo-chemical conversion of heavy hydrocarbons in associated gases with different compositions have shown that the obtained values correspond to the Wärtsilä requirements for the methane number and chemical composition of the fuel gas.

The main characteristics of the COGED+TCR unit with separate high and low pressure thermo-chemical reactors are given in Table 3.

Tab. 3. Design product specification of COGED+TCR unit with separate high and low pressure thermo-chemical reactors (total power 14.1 MW)

Parameter	Unit	Value
Pressure:		
high pressure reactor	MPa	1,4
low pressure reactor		0,6
Temperature of synthesis gas:		
high pressure reactor – in/out	K	714/680
low pressure reactor – in/out		675-660
Specific mass flow rate per 1 MW shaft power:		
feed gas mass flow rate		165-170
total steam demand:	kg/(MW·h)	300-350
of which recycled boiler water		120-140
of which fresh water		180-210
Energy consumption for compressors and pumps	kW	25-30

FINAL CONCLUSIONS

The use of thermo-chemical conversion to recover the heat from the engine's exhaust gas and further utilization of this heat for steam reforming of heavy hydrocarbons expand the possibilities of using the associated gas as fuel in power plants for oil and gas floating units.

It is rational to carry out thermo-chemical conversion of the associated gas in a COGED+TCR unit with separate high and low pressure thermo-chemical reactors to produce fuel gas for both gas turbine engines and internal combustion engines.

COGED+TCR power plants make it possible to combine attractive advantages of low weight and size of a marine gas turbine engine without reducing the energy efficiency.

In this work, only the thermodynamic analysis of the COGED+TCR power plant is presented. An additional feasibility study is needed to fully assess the application range of such an installation for oil and gas floating units.

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