

## Peak Load Electricity Production with Cryogenic Fuels\*

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### Abstract

Natural Gas is often liquefied (LNG) for its transport by ships over long distances. In order to prepare it for further transport by pipelines it has to be reduced again to a gaseous state, normally by heating it with sea water. A similar technology is envisaged for long-distance transport of Hydrogen as an energy carrier. The scope of this article is the thermodynamic investigation of two power plants for peak load energy production. These two power plants use as fuel the fluids obtained by the re-gasification of the cryogenic fluids. The first proposal is a Hydrogen-fired steam power plant, while the second considers the use of LNG in an oxy-combustion arrangement with subsequent CO<sub>2</sub> separation, which is obtained by a three-stage intercooled compression train. The power cycle performance was verified in both cases by exergy analysis. Since the size of these power plants is relatively small (10 MWe), they can be easily built inside the area of LNG gasifiers, or inside the area of the plant producing liquid Hydrogen; the cryogenic fuel and oxidizer are thus considered available, and the purpose of the power plant is peak load energy production rather than obtaining high values of conversion efficiency.

**Keywords:** LNG, Hydrogen, exergy, industrial applications, cryogenic technology, peak load energy production.

### 1. Introduction

Liquefied Natural Gas is becoming increasingly important as an energy carrier. It is transported in cryogenic conditions by ships over long distances; after this it has to be reduced again to the gaseous state for further transport by pipeline, for example to a power plant. The overall transport and utilization process is economically attractive. However, a high amount of energy has to be spent for reducing the natural gas to cryogenic liquid conditions.

In the future, hydrogen will also be used as an energy carrier. Hydrogen can be produced by nuclear power stations or by renewable energy sources, or also by gas reforming or coal gasification. In case of large-scale production, it will be necessary to store and transport it under cryogenic conditions as well. Hydrogen is attractive for energy storage and transport, but it is also relevant for power plant utilization (Jin et al., 2000; Cicconardi et al., 2004; Malysenko et al., 2004), with special reference to peak load energy production. Cryogenic H<sub>2</sub> can be an effective way of storing energy when the production cost of electricity is low (e.g., at night), while large amounts of power can be available in short times when the cost of electricity is higher (that is, in peak load hours).

The future will thus very likely see an increasing market penetration of cryogenic fuels, which are attractive both for transport and as energy storage systems.

The basic idea of this paper is to propose new ways of using the cryogenic fluids in small sized power plants for energy production during peak load electricity demand. Two simple reactive steam power cycles are

proposed using the cryogenic fuel and a cryogenic oxidant, e.g., pure oxygen. In a large power plant, an ASU, operating under constant conditions, would be included. The O<sub>2</sub> would then be stored in cryogenic conditions for usage during peak load hours.

Due to their small size, these power plants can be easily built inside the area of the LNG or H<sub>2</sub> gasifiers, also in the case that the gasifier is placed on an offshore platform. In the case of use of Hydrogen, an alternative would be locating the peak load power plant island within the Hydrogen production plant.

The present proposals, intended for peak load power production, are a simple alternative to developing more complex non-reactive power cycles allowing the exploitation of the cryogenic exergy of the fuel (Szargut and Szczygiel, 2007), which would be justified in larger-scale applications. Other interesting possible ways of using this exergy have been proposed through integration with low-temperature industrial processes (Xu et al., 2007), but in this case process integration is not always possible.

### 2. Cryogenic H<sub>2</sub>/O<sub>2</sub> cycle

The H<sub>2</sub>/O<sub>2</sub> cycle is described first, as its layout is simpler. The power plant is designed for a size of about 10 MWe. This is close to what was tested at the DLR (Deutsches Zentrum für Luft- und Raumfahrt) around 1995 (Sternfeld and Heinrich, 1989) as a peak load shaving addition to a large lignite power plant. A schematic diagram of the basic system is shown in Figure 1.

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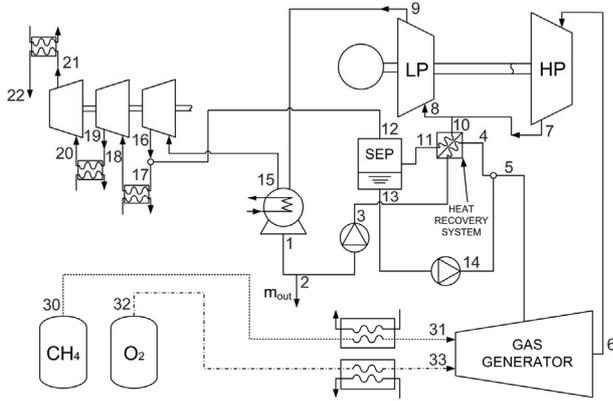


Figure 3. Schematic diagram for basic LNG/O<sub>2</sub> cycle with CO<sub>2</sub> Separation.

The main operating parameters are collected in Table 2, and the calculated performance parameters are shown in Table 3.

The overall efficiency of the cycle (32.8%) was evaluated using Eqn (1) and Eqn (2), substituting H<sub>2</sub> with LNG, and establishing the bounds of the control surface at points 31 for LNG and 33 for O<sub>2</sub> (Figure 3). In Table 3 the vaporization heat rates for LNG and O<sub>2</sub> are also reported, only for the purpose of sizing the heat exchangers.

#### 4. Exergy analysis of the proposed cycles

The two cycles were the objects of an exergy analysis in order to assess the exergy efficiency of the two power plants proposed. Different from the thermodynamic analysis previously presented, in the exergy analysis the borders of the control surface are shifted to the exit of the cryogenic fuel/oxidant storage, i.e. 20 and 22 in Figure 1 or 30 and 32 in Figure 3. In this way, the exergy destructions that take place in the heat exchange of Hydrogen, Oxygen and LNG with the environment are taken under consideration, giving a broader description of the cycle from the exergy point of view. The classical definition of exergy (including reactive terms) (Kotas, 1995) is used

$$\varepsilon = (h - h_0) - T_0 \cdot (s - s_0) + \varepsilon_{0M} \quad (3)$$

where  $h_0$  and  $s_0$  are the specific enthalpy and entropy of the mixture at the reference state (101325 Pa and 25 °C). The chemical exergy of the mixture is given by:

$$\varepsilon_{0M} = \sum n_i \cdot \varepsilon_{0i} + RT_0 \sum_i n_i \cdot \ln \left( \frac{n_i}{\sum n_i} \right) \quad (4)$$

where  $n_i$  is the number of moles and  $\varepsilon_{0i}$  the standard chemical exergy of the  $i^{\text{th}}$  component in the mixture. Table 4 states the standard chemical exergies for the substances of interest.

The exergy destruction or loss was calculated separately for each plant component by the exergy balance:

$$E_{in} + E_{in}^Q = E_{out} + E_{out}^Q + W_{net} + EXDL \quad (5)$$

Table 2. Main parameters, LNG/O<sub>2</sub> cycle.

LNG mass flow rate ( $m_{30}$ )	0.54 kg/s
Oxygen mass flow rate ( $m_{32}$ )	2.16 kg/s
LNG storage temperature ( $T_{30}$ )	-163 °C
Oxygen storage temperature ( $T_{32}$ )	-193 °C
Storage pressure LNG/O <sub>2</sub> ( $p_{30}, p_{32}$ )	6 MPa
Combustor inlet temperature (LNG, O <sub>2</sub> ) ( $T_{31}, T_{33}$ )	15 °C
Combustor pressure ( $p_6, p_{31}, p_{33}$ )	6 MPa
Combustor exit temperature ( $T_6$ )	540 °C
Extraction pressure ( $p_{10}$ )	254 kPa
Condenser pressure ( $p_1$ )	10 kPa
CO <sub>2</sub> temperature at condenser exit ( $T_{15}$ )	30 °C
Intermediate/final pressures for CO <sub>2</sub> compressor train ( $p_{17}, p_{19}, p_{21}$ )	0.254/24/80 MPa
Turbine isentropic efficiency (HP/LP)	0.88/0.90
Pump isentropic efficiency	0.8
Compressor isentropic efficiencies	0.90

Table 3. Power plant performance - LNG/O<sub>2</sub> cycle.

Extraction mass flow rate ( $m_{10}$ )	0.54 kg/s
I Intercooler flow rate of H <sub>2</sub> O removed	0.4 kg/s
Gas generator cooling water mass flow rate ( $m_5$ )	7.7 kg/s
Flow rate of CO <sub>2</sub> removed ( $m_{22}$ )	2.7 kg/s
Turbine $m_{H_2O}/m_{CO_2}$	6.04
Compressors power inputs	0.66/0.28/0.11 MWe
Turbines power outputs	6.97/4.11 MWe
Net power output $W_{net}$	10.0 MWe
Condenser heat rate $Q_{Cond}$	17.81 MWt
Input heat rate $Q_{IR}$	30.5 MWt
Total compressor intercooler heat rates	1.6 / 0.3 / 0.3 MWt
Cycle efficiency	32.8 %
LNG vaporization heat rate $Q_{LNG}$	-0.44 MWt
Oxygen vaporization heat rate $Q_{O_2}$	-0.85 MWt

Table 4. Standard chemical exergy (Kotas, 1995).

Chemical element	Chemical symbol	Standard chemical exergy [kJ/kmol]
C	CO <sub>2</sub>	20170
H	H <sub>2</sub> O	11760
O	O <sub>2</sub>	3970

where

$$E_{in} = \sum m \cdot \varepsilon_{in} \quad (6)$$

$$E_{out} = \sum m \cdot \varepsilon_{out} \quad (7)$$

and

$$E_{in}^Q = \sum_i \left[ Q_{in} \frac{T_i - T_0}{T_i} \right] \quad (8)$$

$$E_{out}^Q = \sum_e \left[ Q_{out} \frac{T_e - T_0}{T_e} \right] \quad (9)$$

For the calculation of the exergy destruction of the gas generator, the exergy of the chemical reaction, evaluated by the Gibbs function of the reaction, was included in the term  $E_{in}$  on the left side of Eqn (5).

On the basis of this definition, the overall exergy efficiency of the cycle is:

$$\eta_{ex,tot} = 1 - \frac{\sum_i EXDL_i}{Exergy_{input}} = \frac{W_{net}}{E_{in} + E_{in}^Q} \quad (10)$$

Here, the exergy input to the system is given by the sum of the fuel exergy, the exergy of chemical reaction and the exergy introduced with the vaporization of  $H_2/O_2$  or  $LNG/O_2$ .

Tables 5 and 6 give the exergy destructions/losses for all the components of the  $H_2/O_2$  cycle and the  $LNG/O_2$  cycle. The values of the exergy efficiency are 36.7% for the  $H_2/O_2$  cycle and 32.5% for  $LNG/O_2$  cycle. These values are quite similar to the efficiency obtained using Eqn (2). This result can be justified by observing Eqn (10), where the dominating value at the denominator is  $E_{in}$ . In fact, the heat exergy provided by the heat exchangers is negligible, consequently the most important part of the denominator of Eqn (10) is  $E_{in}$ . This last value is mainly composed of the chemical exergy of the cryogenic fluid at points 20-22 (Figure 1) or 30-32 (Figure 3), and this chemical exergy is mostly transformed in the heat of reaction in the gas generator. For this reason, the results in terms of energy (Eqn (2)) or exergy (Eqn (10)) efficiency are quite similar.

## 5. Conclusions

Two simple reactive power cycles, using a cryogenic fuel (Liquid Hydrogen or LNG) and a cryogenic oxidant (Liquid Oxygen) have been analysed.

The purpose was to propose simple power cycle layouts, which could be easily integrated within the gasifier or the hydrogen production plant, and should operate only to generate electricity during the peak load demand period.

Both power plants have a reference size of 10 MWe.

The first power plant is operated with  $H_2/O_2$ , and it scores a thermal efficiency of 36.9%; the net power output of 10 MWe is obtained with a hydrogen mass flow rate of 0.19 kg/s.

The second power plant option is operating with  $LNG/O_2$ , including  $CO_2$  separation, with an overall

Table 5. Exergy destructions/losses for  $H_2/O_2$  cycle (Figure 1;  $W_{net} = 10$  MWe).

Component	EXDL [kW]
Condenser	1100
Condensate Extraction Pump	1
Feedwater Pump	7
MFH	400
Gas Generator	11981
HP turbine	368
LP turbine	545
$H_2$ gasifier	1160
$O_2$ gasifier	534
<b>Exergy input [kW]</b>	
Hydrogen	2151
Oxygen	1218
Chemical reaction	23880
<b>Exergy output [kW]</b>	
$H_2$ gasifier	24
$O_2$ gasifier	20
Net work $W_{net}$	10000
Condenser Water Extraction flow rate ( $m_{out}$ )	1118

efficiency of 32.8%. This no-GHG power plant requires 0.54 kg/s of LNG to generate 10 MWe.

The two cycles have been the object of an exergy analysis, which confirmed that the largest exergy destruction takes place at the combustor.

On the whole, the two cycles proposed have a performance lower in comparison to the state of the art, even if it can be attractive for the reference size and considering the simple layout. It should also be considered that the plants discussed in this paper typically have a transient operation, as their scope is to provide energy during the peak load period, using for power production the fluids stored in cryogenic conditions and normally used for other purposes. Furthermore, due to their small size, these power plants can be easily located inside the industrial area where the cryogenic fluids are produced or transformed.

In conclusion, the two power plants appear to have some potential for becoming attractive in the future for the specific application of peak load power generation.

Table 6. Exergy destructions/losses for LNG/O<sub>2</sub> cycle.

Component	EXDL [kW]
Condenser	755
Condenser Pump	11
Coolant mixing (point 5)	9
Combustor	15263
HP turbine	677
LP turbine	448
Heat recovery system	166
Coolant to CC Pump	0.5
I Compressor	4
Mixing Pure CO <sub>2</sub> -CO <sub>2</sub> /H <sub>2</sub> O (point 16)	7
I Intercooler	292
II Compressor	14
II Intercooler	86
III Compressor	2
III Intercooler	45
CH <sub>4</sub> gasifier	253
O <sub>2</sub> gasifier	761
<b>Exergy input [kW]</b>	
LNG	600
Oxygen	1734
Chemical reaction	28243
<b>Exergy output [kW]</b>	
LNG gasifier	15
O <sub>2</sub> gasifier	29
Net work W <sub>net</sub>	10000
Condenser Water Extraction flow rate (m <sub>out</sub> )	515
Flow rate of CO <sub>2</sub> removed (m <sub>22</sub> )	1021
I Intercooler flow rate of H <sub>2</sub> O removed	262

**Nomenclature**

ASU air separation unit  
 GHG Greenhouse gases  
 HP high pressure  
 LP low pressure  
 LNG liquefied natural gas  
 MFH mixing feed water heater  
 SEP incondensable gas separator

$E_{in}$  physical exergy input, kJ  
 $E_{in}^Q$  thermal exergy input, kJ  
 $E_{out}$  physical exergy output, kJ

$E_{out}^Q$  thermal exergy output, kJ  
 $EXDL$  exergy destruction and losses, kJ  
 $h$  enthalpy of the element or mixture, kJ/kg  
 $h_0$  specific enthalpy of the element or mixture at the reference state, kJ/kg  
 $m_{CO_2}$  CO<sub>2</sub> flow rate at turbine inlet, kg/s  
 $m_{H_2O}$  steam flow rate at turbine inlet, kg/s  
 $m_{out}$  water flow rate extracted from the condenser, kg/s  
 $m_5$  combustor cooling water flow rate, kg/s  
 $m_{10}$  mass flow rate extracted to heat recovery system, kg/s  
 $m_{20}$  hydrogen mass flow rate, kg/s  
 $m_{22}; m_{32}$  oxygen mass flow rate, kg/s  
 $m_{30}$  LNG mass flow rate, kg/s  
 $n_i$  number of moles of the i-th component in the mixture  
 $p_1$  condenser pressure, kPa  
 $p_6$  output combustor pressure, kPa  
 $p_{10}$  input MFH pressure, kPa  
 $p_{20}$  hydrogen storage pressure, kPa  
 $p_{21}$  hydrogen input combustor pressure, kPa  
 $p_{30}$  LNG storage pressure, kPa  
 $p_{31}$  LNG input combustor pressure, kPa  
 $p_{22}; p_{32}$  oxygen storage pressure, kPa  
 $p_{23}; p_{33}$  oxygen input combustor pressure, kPa  
 $Q_{1R}$  input heat rate, MW  
 $Q_{Cond}$  condenser heat rate, MW  
 $Q_{H_2}$  hydrogen vaporization heat load, MW  
 $Q_{LNG}$  LNG vaporization heat load, MW  
 $Q_{O_2}$  oxygen vaporization heat load, MW  
 $R$  ideal gas constant, J/(K·mol)  
 $s$  entropy of the element or mixture, kJ/(kg·K)  
 $s_0$  specific entropy of the element or mixture at the reference state, kJ/(kg·K)  
 $T_0$  temperature at the reference state, K  
 $T_6$  combustor exit temperature, °C  
 $T_{20}$  hydrogen storage temperature, °C  
 $T_{21}$  hydrogen Gas generator inlet temperature, °C  
 $T_{30}$  LNG storage temperature, °C  
 $T_{31}$  LNG combustor inlet temperature, °C  
 $T_{22}; T_{32}$  oxygen storage temperature, °C  
 $T_{23}; T_{33}$  oxygen combustor inlet temperature, °C  
 $\Delta H_R$  heat of reaction, MW  
 $W_{net}$  net power output, MW

**Greek**

$\epsilon$  exergy of the mixture, kJ  
 $\epsilon_0$  chemical exergy of the element  
 $\epsilon_{0i}$  chemical exergy of the i-th component in the mixture, kJ/kmol  
 $\epsilon_{0M}$  chemical exergy of the mixture, kJ/kmol  
 $\epsilon_{in}$  specific exergy input, kJ/kmol  
 $\epsilon_{out}$  specific exergy output, kJ/kmol  
 $\eta$  plant thermal efficiency  
 $\eta_{ex;tot}$  plant exergy efficiency

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