COLD EXERGY, THE CONCEPT AND APPLICATIONS

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الملخص

يهدف هذا العمل إلى المساهمة في موضوع استعادة الإكسيرجي الباردة من الحالات التي تكون فيها درجات الحرارة أقل من درجة حرارة المحيط الجوي، حيث قد تمتلك هذه المواد مثل الغاز الطبيعي المسال (LNG) كمية كبيرة مما يسمى بالإكسيرجي الباردة، والتي عادة لا يتم تمييزها أو استردادها أثناء عملية إعادة تحويل الغاز المسال إلى غاز (عمليات التغويز). تم اختيار محطة درنة البخارية (شمال شرق ليبيا) لتسليط الضوء على مدى الاستفادة من الإكسيرجي الباردة التي يمتلكها الغاز الطبيعي المسال، حيث تتم عملية التغويز من خلال استخدام الطاقة الحرارية المنبعثة من مكثف محطة الطاقة البخارية المختارة. يتم ضغط الغاز الطبيعي وتسييله لخفض حجم الغاز المعد للشحن في درجات حرارة منخفضة للغاية، حوالي 110 كلفن. الحرارة الكامنة (حرارة التبخر) للميثان (المكون الرئيسي للغاز الطبيعي) عند 0.1 ميجا باسكال هي 512 كيلو جول/كجم. يمكن استرداد الإكسيرجي الباردة عن طريق نقل الحرارة من المحيط الجوي (مثل مياه البحر) إلى محرك حراري وطرد الحرارة إلى مكب حراري، على سبيل المثال إلى الغاز الطبيعي المسال أثناء عملية التغويز. تظهر النتائج أن 40.84٪ من الإكسيرجي الطبيعية للغاز الطبيعي المسال يتم تدميره أثناء عملية التغويز التقليدية. يمكن زيادة صافي إنتاج الطاقة لمحطة الطاقة البخارية المختارة بنسبة 12.1٪ عند توصيلها بدورة التغويز.

ABSTRACT

The purpose of this work is to contribute to the issue of recovering cold exergy from cold states. Material at temperatures less than atmospheric temperature such as liquefied natural gas (LNG), may possess an abundant amount of so called cold exergy, which is usually not recognized nor recovered during the regasification process. Derna power plant is selected to explore this issue, by utilizing the cold exergy which is possessed by the Liquefied Natural Gas (LNG), here, the gasification process takes place by utilizing the heat energy which is rejected by the condenser of the selected steam power station. Natural gas is compressed and liquefied to lower the specific volume for shipping at extremely low temperatures, around 110K. The latent heat (heat of evaporation) of methane (the major component of the natural gas) at 0.1MPa is 512 kJ/kg. Cold exergy could be recovered by transferring heat from the atmosphere (from seawater for instance) to a heat engine, and rejecting heat to a sink, for instance to the LNG during the evaporation process. The results show that 40.84% of the input physical exergy of the LNG is destroyed during the conventional regasification process. The net power output of the selected steam power plant could be raised by 12.1 % when connected with the regasification cycle.

KEYWORDS: Exergy; Cold Exergy; Exergy Destruction; Liquefied Natural Gas; Liquefaction; Regasification;

INTRODUCTION

As it is desired to move toward a clean environment, we are obligated to lessen the emissions and contamination due to population evolution and economic advance, however, this desire is challenged by the growing global energy demand. In addition to this contest, high energy expenses are forcing us on the way to an ecological use of energy resources. Liquefied Natural Gas (LNG) is characterized by its low greenhouse gas emissions compared to coal and oil, by 50 % and 20 % respectively, and plays a key role in the move on the way to becoming an ecological energy resources [1].

It is well known that mechanical power could be generated by transferring heat from a system at a temperature higher than the atmospheric temperature to another system at lower one through a heat engine. However, power could also be generated when heat transfers from the atmosphere (sea water for instance) to a sink which is kept at temperature below the atmospheric temperature through a heat engine, for instance liquefied natural gas (LNG) at temperature around 110 K could be used as a sink to generate power.

The concept of exergy of cold is defined when heat transfer occurs at temperatures below the atmospheric temperature, however, the cold exergy is less recognized and understandable than the exergy of heat. Exergy is defined as the maximum useful reversible work that can be obtained from a given state in a given environment. Heat denotes the transfer of energy between two systems as a result of the existing temperature gradient. This phenomenon occurs for conditions above or below the atmospheric temperature. Below the atmospheric temperature the expression transfer of cold sometimes replaces the transfer of heat. The exergy flow associated with heat (or cold) transfer is expressed as [2]:

$$\dot{\Psi}_Q = \dot{Q}\left(1 - \frac{T_o}{T}\right) \tag{1}$$

Equation (1) indicates that the direction of exergy flow, $\left(\dot{\Psi}_Q\right)$ depends on the direction of heat, $\left(\dot{Q}\right)$ and on the temperature, (T) if it is above or below the atmospheric temperature, (T_o). For temperatures above the atmospheric temperature, both heat and exergy flow in the same direction, however this is not the case for temperatures below the atmospheric temperature, where heat and exergy flow in the opposite directions.

Natural gas (NG) is liquefied and transported in the liquid form, however, the process of liquefaction is an extremely energy demanding process, an amount of this energy is reserved in the LNG in the form of so called cold exergy. The process of regasification is required to introduce the NG to the network, the traditional way for regasified the LNG is by exchanging heat directly with the environment, however, an amount of around 370 kJ/kg of cold exergy is lost during the heat exchange process [3].

The production of natural gas has been grown up and reached $3{,}613 \times 10^9 m^3$ in 2016 as a result of the 2009 crisis. Liquefied natural gas is the most efficient way for large-distance transportation. As the gas volume compressed about 600 times, LNG could be transported by ships, especially for distances larger than 1550 km [4].

Many authors have suggested the recovery of the cold exergy. A new method is employed to recover cold exergy from the liquefied natural gas [3]. The main feature of the approach is the utilization of the natural gas as the working fluid for a combined Rankine-Brayton cycles. The proposed system is optimized based on the economic and thermodynamic aspects. The optimization process revealed that an exergatic efficiency of 60% could be reached and a first law efficiency of 65% may be obtained.

The possibility of recovering cold exergy from LNG was investigated [5]. Four different systems to produce electrical power employed LNG as the sink were investigated. The analysis indicated that an exergatic efficiency in the range of 20% to 36% could be achieved.

The option of recovering the cold exergy of LNG by cooling the working fluid before compression in Brayton cycle was analyzed [6]. Aspen Hysys software was used to model and simulate the processes. Different working fluids were tested for best exergatic efficiency. It was found an improvement in the exergatic efficiency in the range of 35 to 135% could be achieved.

A combined cycle consists of an Organic Rankine (ORC) cycle and a Liquefied Natural Gas (LNG) Rankine cycle was analyzed [7]. The effects of the maximum pressure and the critical temperature of the working fluid were investigated. The results revealed that the exergatic efficiency had a maximum value at a certain turbine inlet pressure.

In the first part of this work, the gasification processes are modelled and simulated, the results are validated against the reported results in the literature. The second part aims to alter the thermodynamic performance of Derna power station. The task is to utilize the rejected heat from the condenser of the power station to gasify the LNG, and hence extra power will be gained.

MATERIALS AND METHODS

LNG possesses cold energy which is dissipated into the evaporating media (such as seawater) during the regasification process. **The first part of this work** is devoted to validating the regasification model. The LNG is modeled as 100% methane. The process of regasification is depicted in Figure (1) [1].

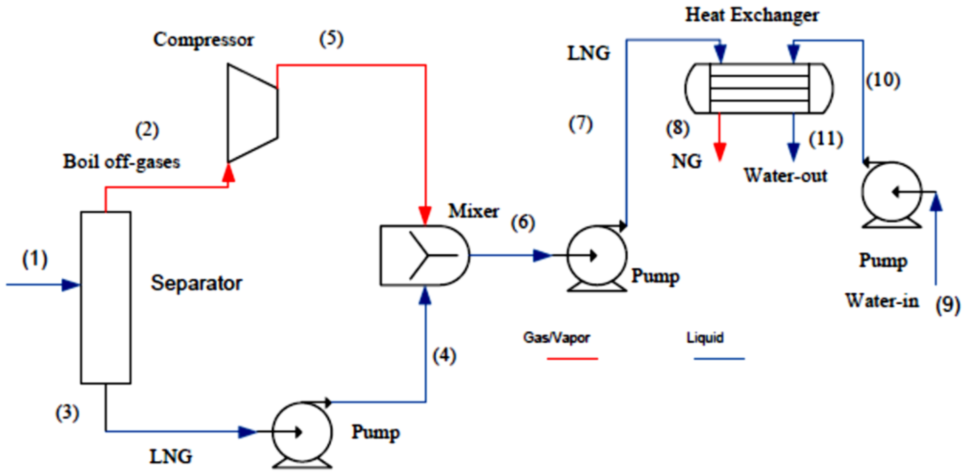


Figure 1: The gasification process of LNG

The LNG enters the separator at 1.26 bar and -162°C with flow rate of 90.43 kg/s. Some of the liquid boils-off to what so called boil off gas (BOG) at -130°C, and then compressed to 10 bars in the compressor. The rest of the LNG leaves the separator from the bottom, pumped to 10 bars and then mixed with the BOG in the mixer. The LNG is pumped to 60 bars before exchanging heat with water in the heat exchanger. Water at 20°C and 1 bar is pumped to 3 bars and then enters the heat exchanger as a hot fluid. In the heat exchanger, LNG is converted to NG at high pressure (60 bars) for further transportation. Water is rejected into the atmosphere at a temperature of 17°C.

Through energy and exergy analysis, the amount of energy and exergy dissipated in the heating fluid is analyzed. LNG, inlet water, and electricity to run the pumps and compressor contribute to the input energy and exergy. NG, and discharged seawater contribute to the output energy and exergy of the system. There are energy losses and exergy destructions from different components of the system.

In the second part of this work, the regasification process is modeled by utilizing the rejected heat from the condenser of Derna electrical power station. It is located 5 km West of Derna (Libya-North Africa). Location coordinates are: Latitude = 32.781, Longitude = 22.5874. The power plant has a total rated capacity of 65 MW [8]. The first unit was commissioned in 1976 and the last in 1985. It is operated by General Electricity Company of Libya (GECOL).

The schematic diagram of the Derna steam power plant is shown in Figure (2). The plant consists of High pressure, intermediate pressure and low pressure turbines; condensate pump, feed pump, condenser, two closed feed water heaters and deaerator. The mass flow rate of fuel (n-Decane) is 4.5 kg/s with lower heating value of 44620 kJ/kg. The mass flow rate of steam leaving the steam generator is 68 kg/s with temperature of 520°C and pressure of 87 bars. The bleeding pressures in bars are 21.8, 6.02, 1.15 and 0.62 for the high pressure heater, deaerator and low pressure heater, respectively. The isentropic efficiencies for the expansion processes are taken as 83% from state 1 to 2, 89% from state 2 to 3, 88% form state 3 to 4 and 71% from state 4 to 5. The isentropic efficiencies for both pumps are taken as 85% [8].

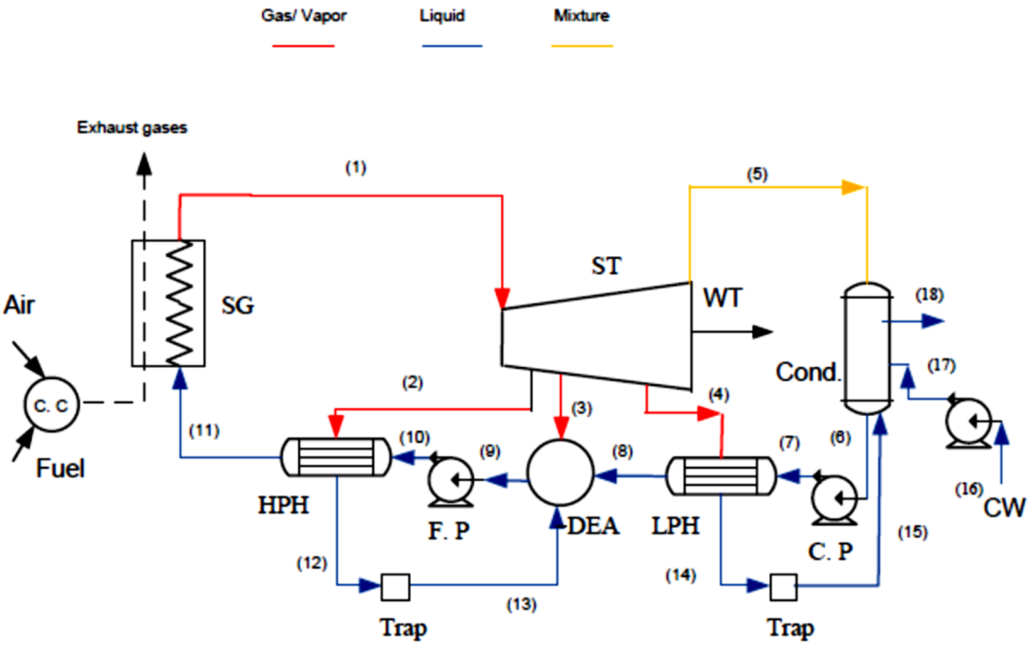


Figure 2: Schematic diagram of Derna power plant

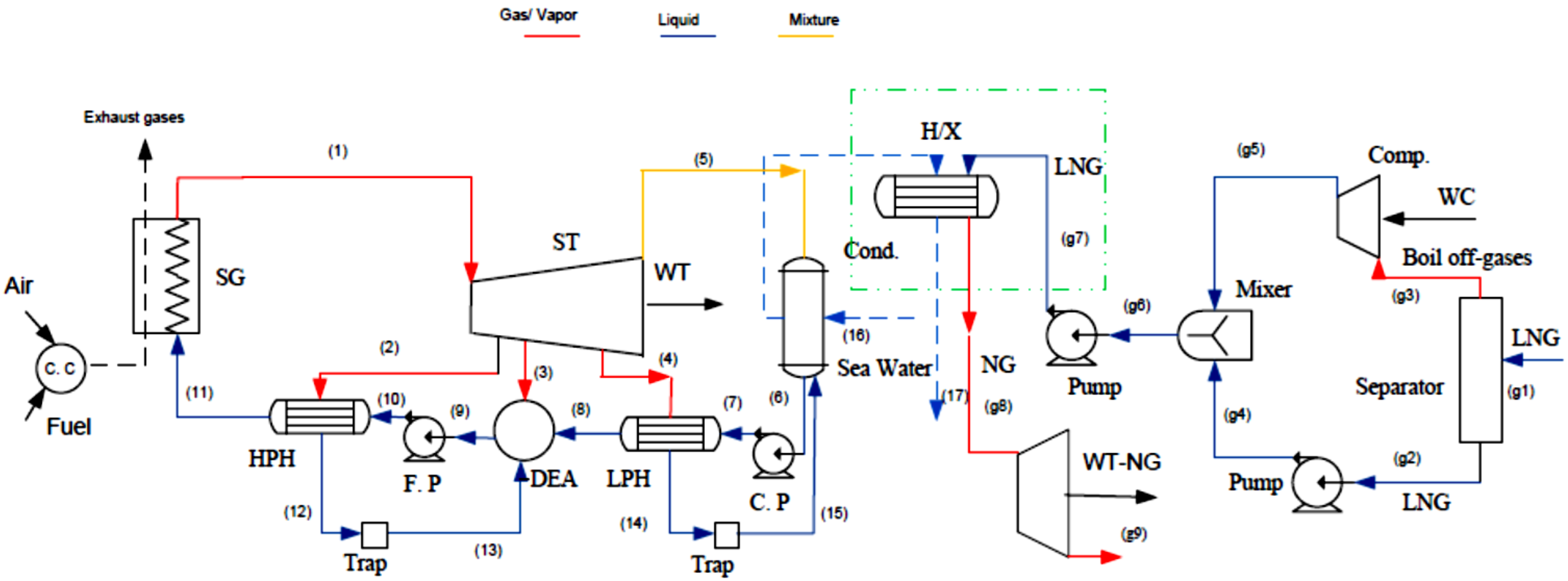


Figure 3: Derna power station with the gasification unit

To improve the efficiency of Derna power station, the power station is connected with the gasification cycle as shown in Figure (3), where the heat is rejected from the condenser employed to gasify the LNG. Liquefied natural gas (Methane) enters the separator at 1.26 bar and -162°C, a small fraction of the LNG Boils-off at -130°C (BOG) due to possible heat transfer from the surroundings. The BOG is compressed by the compressor to 20 bars. The LNG leave the bottom of the separator and then pumped to 20 bar. Both streams enter the mixer and leaves as a compressed liquid at 20 bars. The pressure of the LNG increases to 120 bar by the second pump before entering the heat exchanger (heater) for regasification. The regasified natural gas enters the NG turbine and is rejected at 60 bars for further transportation.

For the analysis, steady-state, steady flow processes are assumed. Pressure drop due to friction, heat exchange with surroundings, the change in kinetic and potential energies are neglected.

The mass balance can be written as:

$$\sum(\dot{m}_i)_k = \sum(\dot{m}_e)_k \tag{2}$$

The first law of thermodynamics can be written as:

$$\sum_k \dot{Q}_k + \sum(\dot{m}_i h_i)_k = \sum(\dot{m}_e h_e)_k + \dot{W}_k \tag{3}$$

The first law efficiency can be written as:

$$\eta^{1st} = \frac{\text{Energy (sought)}}{\text{Energy (cost)}} \tag{4}$$

Where energy (sought) indicates the desired energy of the product and energy (cost) indicates the input energy.

The exergy flow rate can be written as:

$$\dot{\Psi} = \dot{m}[(h - h_0) - T_0(s - s_0)] \tag{5}$$

And the exergy balance for a given component can be written as;

$$\sum_i^N \left(1 - \frac{T_0}{T}\right)\dot{Q}_k + \sum_i^N \dot{\Psi}_{i,k} = \sum_e^N \dot{\Psi}_{e,k} + \dot{W}_k + \dot{I}_k \tag{6}$$

The second law efficiency (effectiveness or exergatic efficiency) is written as:

$$\varepsilon = \frac{\text{Exergy (sought)}}{\text{Exergy (cost)}} \tag{7}$$

Where exergy (sought) indicates the desired exergy of the product, and Exergy (cost) indicates the input exergy.

RESULTS AND DISCUSSION

Referring to Figure (1), the properties and exergy at each state is tabulated in Table (1). The physical exergy of the LNG (state 1) is 96.58 MW, while the physical exergy of the NG (state 8) is 55.50 MW, i. e. only 57.47 % of the LNG physical exergy is recovered, and hence, 42.53% is destroyed during the gasification process.

Table: 1: Properties and exergy for each state

State	$\dot{m}(\frac{kg}{s})$	P (bar)	T °C	ψ(kJ/kg)	$\dot{\Psi}\ MW$
1	90.43	1.26	-159.40	1068	**96.58**
2	1.402	1.26	-130	167.70	0.24
3	89.03	1.26	-162	1083	96.42
4	89.03	10.00	-161.60	1084	96.51
5	1.042	10.00	-8.31	355.3	0.37
6	90.43	10.00	-157.90	1063	96.13
7	90.43	60.00	-155.30	1067	96.49
8	90.43	60.00	10	613.7	**55.50**
9	5544	1.00	20	0.18	0.98
10	5544	3.00	20.01	0.38	2.10
11	5544	3.00	17	0.66	3.64

In the first part of this work, the gasification process is analyzed, and the model is validated by comparing the result with that given by S. Yadav [1]. Table (2) shows the exergy destructions and their percentage in each component. The total exergy destruction is found equal to 41.98 MW. The exergy destruction due to gasification alone is found equal to 39.45 MW and the effectiveness for the whole processes is calculated as 55.56%. compared to 57.4% as given by S. Yadav [1]. The gasification process in the heat exchanger contributes to 93.97% of the total exergy destruction of the whole processes, value of 94% is reported by S. Yadav [1]. The exergy destruction of the heat exchange process in the heat exchanger in percentage relative to the physical input exergy is 40.84% as shown in Figure (4).

Table 2: Exergy destruction

Unit	Exergy destruction [MW]	Exergy destruction [%]
Separator	0.43	1.02
Pump (1)	0.14	0.33
Pump (2)	0.99	2.34
Pump (3)	0.26	0.63
Compressor	0.21	0.49
Heat Exchanger	**39.45**	**93.41**
Mixer	0.75	1.78
Summation	41.80	100.00

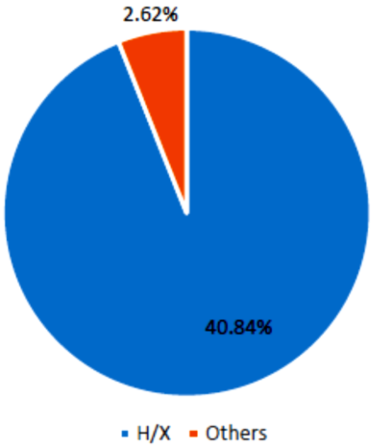


Figure 4: The exergy destruction [%] relative to the input physical exergy

Figure (5) compares the percentage of the exergy destruction of the current work with that reported by S. Yadav [1], good agreement is found as can be shown.

Theoretically the overall effectiveness could be improved by recovering the exergy destruction in the heat exchanger by replacing the heat exchanger by a reversible heat engine (Carnot), the total exergy output would be 94.94 MW and hence the overall effectiveness raises to 98.31%.

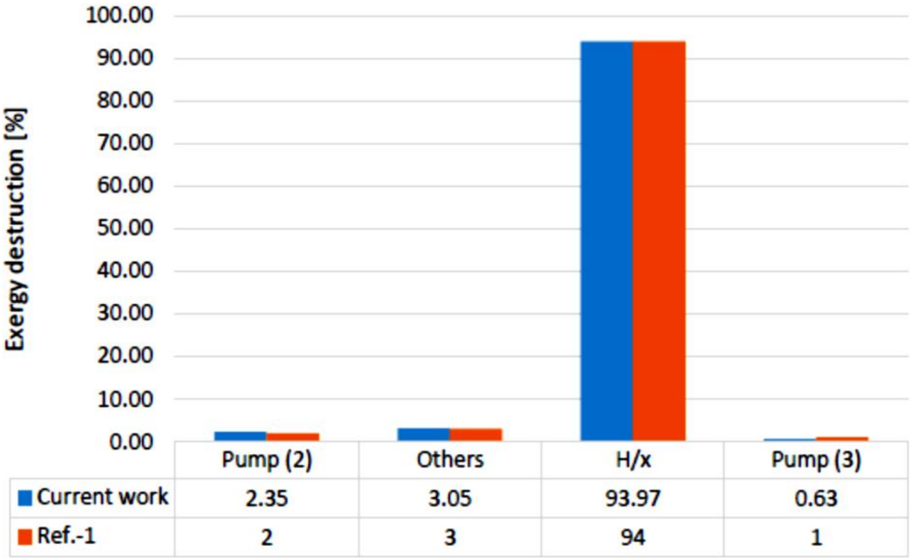
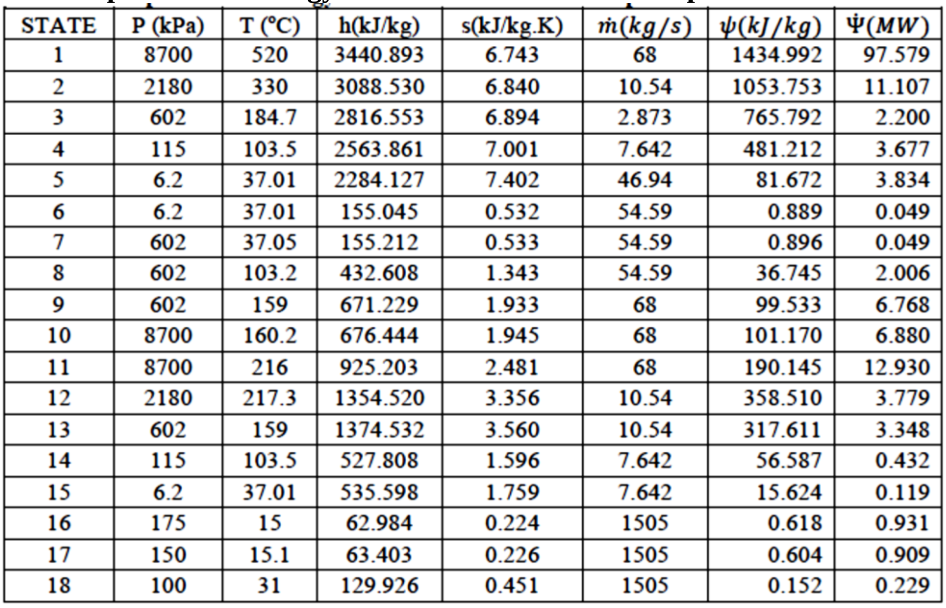


Figure 5: The exergy destruction [%], in comparison with [1]

In the second part of this work, Derna power station is analyzed from the thermodynamic point of view. Table (3) shows the properties and exergy of Derna power station at different states at full load (65 MW). Figure (6) shows the exergy destruction in the main components and its percentage with respect to the total input of exergy.

Table 3: Properties and exergy at different states of Derna power station at full load



STATE	P (kPa)	T (°C)	h(kJ/kg)	s(kJ/kg.K)	$\dot{m}(kg/s)$	$\psi(kJ/kg)$	$\Psi(MW)$
1	8700	520	3440.893	6.743	68	1434.992	97.579
2	2180	330	3088.530	6.840	10.54	1053.753	11.107
3	602	184.7	2816.553	6.894	2.873	765.792	2.200
4	115	103.5	2563.861	7.001	7.642	481.212	3.677
5	6.2	37.01	2284.127	7.402	46.94	81.672	3.834
6	6.2	37.01	155.045	0.532	54.59	0.889	0.049
7	602	37.05	155.212	0.533	54.59	0.896	0.049
8	602	103.2	432.608	1.343	54.59	36.745	2.006
9	602	159	671.229	1.933	68	99.533	6.768
10	8700	160.2	676.444	1.945	68	101.170	6.880
11	8700	216	925.203	2.481	68	190.145	12.930
12	2180	217.3	1354.520	3.356	10.54	358.510	3.779
13	602	159	1374.532	3.560	10.54	317.611	3.348
14	115	103.5	527.808	1.596	7.642	56.587	0.432
15	6.2	37.01	535.598	1.759	7.642	15.624	0.119
16	175	15	62.984	0.224	1505	0.618	0.931
17	150	15.1	63.403	0.226	1505	0.604	0.909
18	100	31	129.926	0.451	1505	0.152	0.229

The total input exergy is obtained as 231.742 MW, this value includes the fuel exergy, the exergy of air of combustion and the exergy for operating the pumps. The total exergy destruction is found equal to 148 MW. The exergatic efficiency is obtained as

31% compared to 30.92% , and the first law efficiency is obtained as 33% compared to 32.9% as given by I. Elfeituri [8].

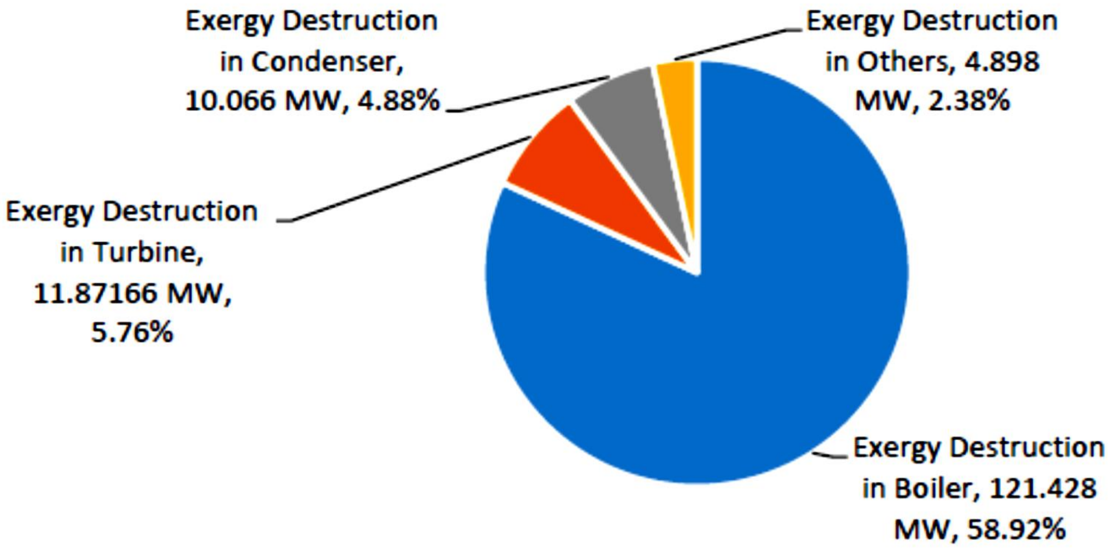


Figure 6: Details of the exergy destruction

The results of the exergy destruction reveals that the steam generator contributes to 58.92% of the total input exergy compared to 58.28% as reported by I. Elfeituri [8], good agreement is obtained as shown in Figure (7).

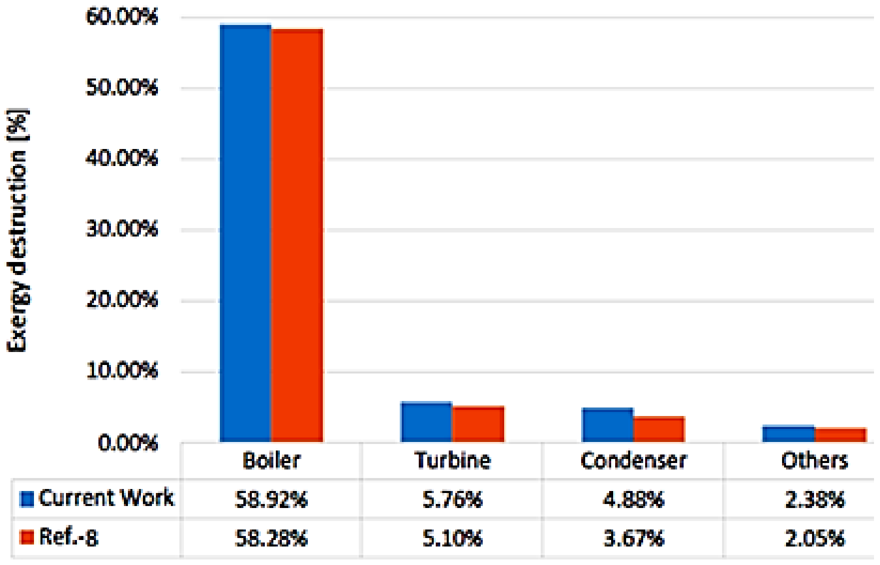


Figure 7: Exergy destruction [%], in comparison to that reported by [8]

It is desired to elevate the thermodynamic performance of Derna power station by taking advantage of the gasifying processes of the liquefied natural gas. The model is further extended and simulated by connecting the power station with the gasifying cycle via the condenser as shown in Figure (3). The mass flow rate of the LNG and the inlet temperature of the NG turbine, both significantly affect the performance of the combined power-regasification cycle. As the rejected heat by the condenser is kept constant (103.8 MW), the temperature of the NG entering the NG turbine and hence the enthalpy decrease with the increase in the mass flow rate of the LNG, see Figure (8). Therefore, the mass flow rate of LNG and the NG turbine inlet temperature have adverse effects on the power output of the NG turbine, and hence on the net power output of the LNG cycle.

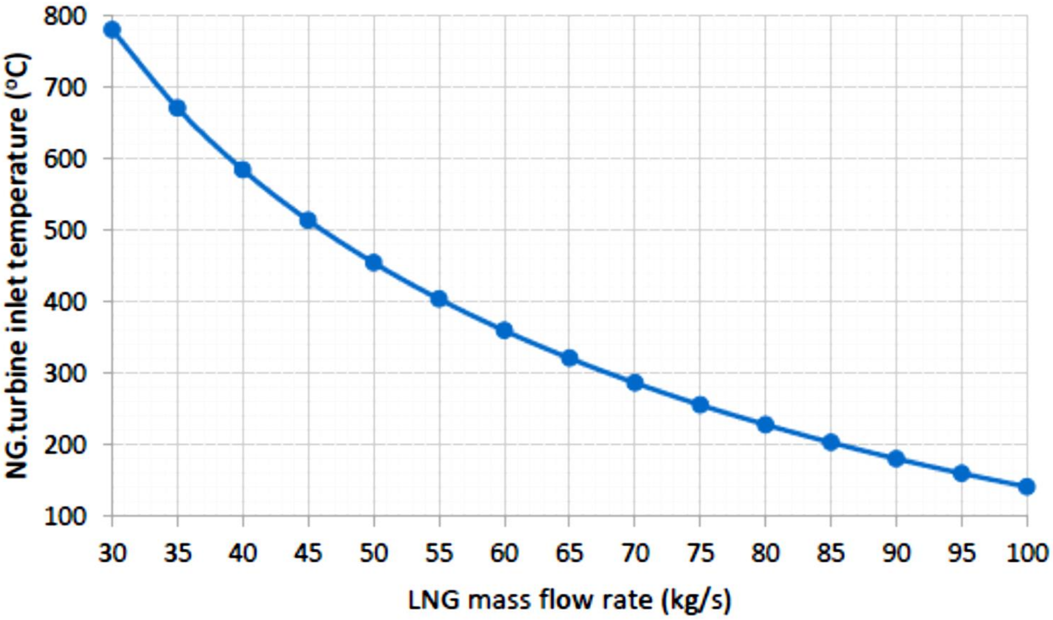


Figure 8: Effect of LNG mass flow rate on NG turbine inlet temperature

Figure (9) illustrates the effect of LNG mass flow rate on the power output of NG gas turbine and on the net power output of LNG gasification cycle. Since the LNG mass flow rate and the NG inlet turbine temperature have an adverse effect on the power output, the NG gas turbine power has a maximum value of 10 MW at LNG flow rate of 80 kg/s, beyond which the power decreases as the reduction in the input enthalpy becomes the dominating factor. As the input power for operating the LNG pump and the compressor increases with the increase in LNG mass flow rate, the net power output of the LNG cycle has a maximum power output of 6.853 MW at LNG flow rate of 40 kg/s.

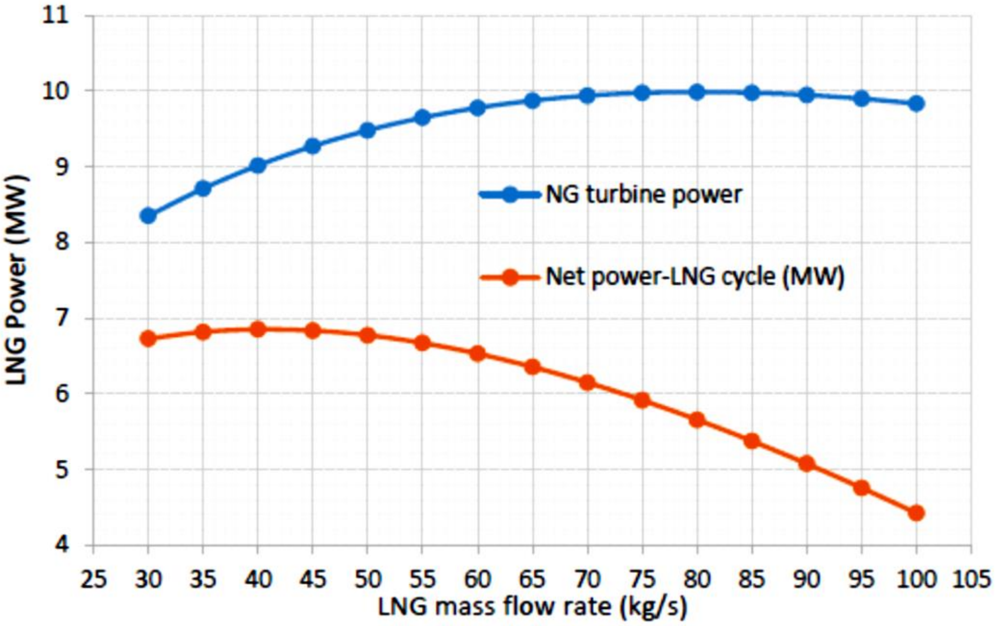


Figure 9: Effects of the LNG mass flow rate on the power of LNG cycle

The benefit of adopting the proposed cycle is depicted in Figure (10), where the net power output is plotted against the LNG mass flow rate. As can be seen the combined cycle net power output is always greater than the original power cycle. The net power output reaches its maximum value of 71.75 MW with percentage increase over the standalone power cycle of 12.1% is obtained at LNG flow rate of 40 kg/s. At this maxima, the first law efficiency is 37.1% and the second law efficiency is 34.82%.

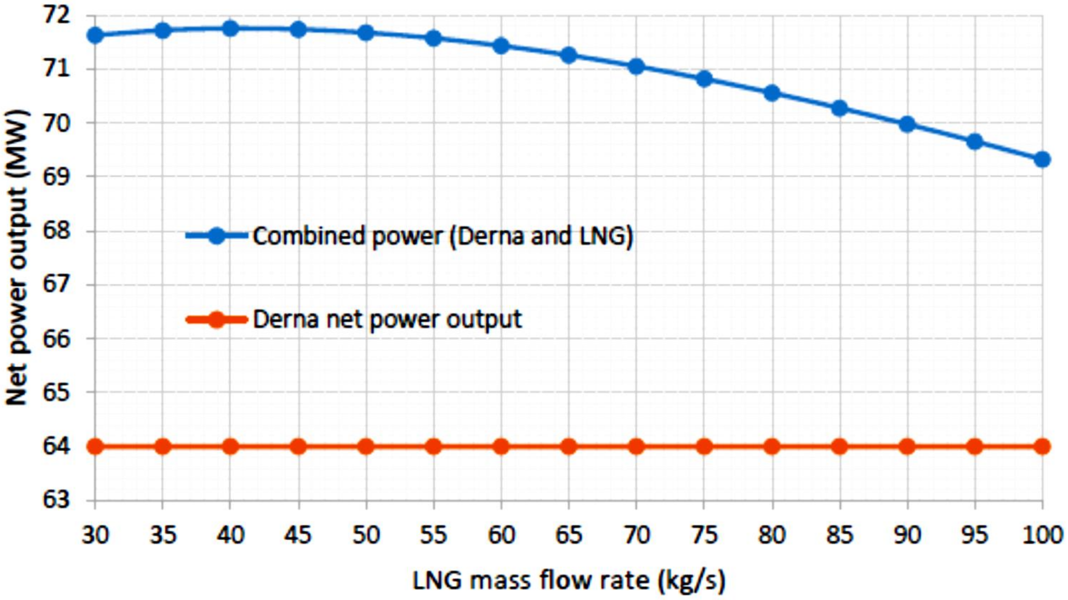


Figure 10: Effects of the LNG mass flow rate on the combined power cycle

CONCLUSIONS

The current paper contributes to the issue of what so called cold exergy. Materials at temperatures less than the atmospheric temperature may possess a large amount of physical cold exergy.

It is found 42.53% of the physical exergy could be destroyed during the traditional regasification process of the liquefied natural gas.

In this work, the cold exergy which is possessed by the liquefied natural gas is recognized and recovered. It is proposed to gasify the LNG (sink) by exchanging heat with sea water (source) by utilizing a reversible heat engine. The results are compared and validated with good agreement against other reported results.

Since, the heat rejected from the power plant through the condenser is fixed and determined by the plant itself, the temperature and hence the enthalpy of the NG which is flowing into the NG gas turbine, is influenced by the mass flow rate of the LNG.

Both LNG mass flow rate and NG temperature have an adverse influence on the power output of the NG turbine, hence the net output power of the new cycle, has maximum value at 40 kg/s LNG mass flow rate of 71.75 MW, this is 12.1 % increase over the original cycle.

At LNG mass flow rate of 40 kg/s, the first law efficiency is found equal to 37.1% and the second law efficiency is equal to 34.82%.

NOMENCLATURE

Symbol		**Greek letters**	
h (kJ/kg)	enthalpy	η	efficiency

s (kJ/kg. K)	entropy	ε	effectiveness
$\dot{Q}$ (kW)	heat rate	$\dot{\Psi}$	exergy rate
$\dot{m}$ (kg/s)	mass flow rate	**Subscript**	
$\dot{W}$ (kW)	power	e	exit
$\dot{I}$ (kW)	irreversibility rate	i	inlet
T (^{o}C)	temperature	o	reference state

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