STUDY ON CONTAINER SHIP ENERGY CONSUMPTION

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ABSTRACT

The shipping industry is facing three challenges: climate change, increasing bunker fuel price and tightening international rules on pollution and CO_2 emissions. All three challenges can be met by reducing fuel consumption and improving global ship energy efficiency. This paper aims to analyze medium size container vessel energy based on the data collected from the sample ship during two regular voyages. The analysis covers the exergy and energy balance of the main components. Container vessels consume the most fuel of the largest fuel oil consumers as they have the most powerful engines. The propulsion is responsible for 82% of the energy demand on a container vessel, electric power production accounts for 17%, while steam generation is limited to 1%. It has been demonstrated that up to 64% of the ship energy consumption is lost to the environment by the cooling system and exhaust gas from propulsion engine and diesel generators. Exergy losses due to the exhaust gas and heat transfer are other contributors. By focusing studies on these items, we may be able to determine how the ship energy efficiency may be improved.

Keywords: container vessel, energy efficiency, energy, exergy.

1 INTRODUCTION

Maritime transport emits around 1,000 million tons of CO_2 annually and is responsible for about 2.5% of global greenhouse gas emissions [1]. Shipping emissions are predicted to increase between 50% and 250% by 2050, depending on future economic and energy developments. The International Maritime Organization (IMO) is in the development of two indices to create a standard to monitor the emissions and stimulate the improvement with interventions both in the design and in the operational phases. The Energy Efficiency Design Index (EEDI, IMO 2012) measures the CO_2 emissions in relation to a nominal transportation work rate and is related to the ship technical characteristics. The Energy Efficiency Operational Index (EEOI, IMO 2012) strictly depends on the cargo carried in a specific voyage and its length [2]. The IMO resolution MEPC.278 (70) amended MARPOL Annex VI on 1 March 2018 to introduce the new Regulation 22A, which includes a requirement for ships to record and report fuel oil consumption data. Ships over 5000 gross tons trading from 1 January 2018 at EU maritime ports are to monitor and later report their related CO_2 emissions in accordance with their monitoring plans [3].

Measures for the improvement of ship energy efficiency are normally divided into design and operational measures. While the former has been associated to larger saving potential, the latter can still provide a significant reduction in fuel consumption, while requiring a much more limited capital investment. However, the large number of variables influencing ship energy efficiency makes it hard to assess ship performance in relation to a standard baseline. Operational measures include, among others, improvement in voyage execution, reduction of auxiliary power consumption, weather routing, optimized hull and propeller polishing schedule, slow steaming, and trim optimization; many literatures have addressed this issue [4]–[8]. Some other studies focused on the energy performances of the individual machinery component [9], [10]. The main fuel oil consumers onboard container vessels are propulsion engines and auxiliary engines, which are the internal combustion diesel type; the auxiliary boiler fuel consumption may be neglected compared to propulsion engine.

The aim of this paper is to assess the ship energy system performance by analyzing the data provided by ship's records and to evaluate the actual fuel consumption and potential energy saving for better ship energy efficiency. We take as a sample a container vessel of medium size category which represents 20% of the total world container fleet and 30% of the power installed and fuel consumed by the container vessels [11]. The daily report of the ship (noon report) transmits several parameters to the teams ashore; namely, the fuel consumption, the speed of the vessel, the average draught, the loading, the weight of the cargo, the speed and the wind sector, the engine power, electric power, etc. These data are sent every day regardless of the vessel's position (at sea or at the port). Sorting these data was necessary, without, our calculations could be altered because of the zero speed or consumption values corresponding to periods of stop or anchorage. We filter the data and ignore the non-consistent values recorded by mistake or inaccuracy of the crew.

Even though exergy analysis is similar to energy analysis in characteristics, there are some fundamental differences between them [12]. While the energy analysis is based on the first law of thermodynamics (energy conservation), exergy analysis is based on the second law (degradation of energy). Degradation of energy means the loss of exergy systems from the irreversibility. Using only energy analysis is not adequate to analyze energy utilization processes and, additionally, it leads to poor decisions about them. Exergy analysis, more complicated than energy analysis, determines the portion of energy which cannot be used, and it states where the losses occur in a system. By applying it to a thermal system in addition to the energy analysis, irreversibility could be detected and so the best ways to minimize energy destruction and losses and increase efficiency can be understood. Energy analysis will provide the amount of energy variation as a function of energy transfer across the boundaries as heat or work which is related to mass flow passing these boundaries.

2 ENERGY AND EXERGY THEORY

2.1 Diesel engine

Internal combustion engines [13] are mainly used in shipbuilding for propulsion and power generation purposes. As depicted in Fig. 1, the diesel engine converts the chemical energy to mechanical energy in the form of shaft rotation by burning fuel oil; part of the energy is transferred to the atmosphere by exhaust gas and a cooling system.
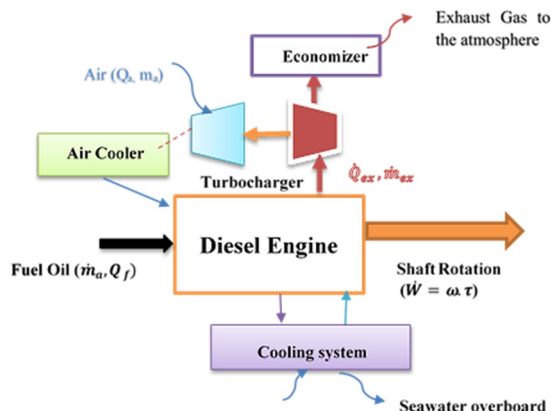

Figure 1: Diesel engine flows.

2.1.1 Energy flow

Energy analysis provides a calculation of the internal energy variation as a function of energy transfers across the boundaries as heat or work and the enthalpy which is related to the mass flow passing these boundaries [14]. Before applying it to the test engine, the following assumptions must be made to simplify the calculations:

- The engine is in a steady-state condition.
- It is assumed that the system is an open system and the reference state is defined as T_0 = 293 K and P_0 = 1 atm.
- The combustion air and exhaust gases are ideal gas mixtures.
- The potential and kinetic energy effects of the incoming fluid streams and outgoing fluid streams are ignored [15].

In general, work and heat can be expressed as eqn (1):

$$W = \dot{m}(\text{Ke} + \text{Pe}) + W_d . \quad Q = \dot{m}\text{h} . Q_d, \tag{1}$$

where $\dot{m}$ is the mass flow rate carrying the kinetic K_e and potential P_e energy work or enthalpy h.

W_d, Q_d is the direct input/output energy to/from the system.

Mass balance for the control volume in steady-state condition can be written as eqn (2):

$$\sum \dot{m}_i \quad = \sum \dot{m}_o, \tag{2}$$

where $\dot{m}_i$ represents the inlet flow rate of the mass that consists of air and fuel and $\dot{m}_o$ represents outlet mass consisting of exhaust gases. Considering that fuel enters the engine, with mass flow $\dot{m}_f$ rate and is mixed with air $\dot{m}_a$ to form $\dot{m}_i$.

Energy balance for the control volume in steady-state conditions, kinetic and potential energy being neglected, is given by eqn (3) in the general sense:

$$\dot{Q} + \dot{W} = \sum \dot{m}_o h_o - \sum \dot{m}_\iota h_\iota, \tag{3}$$

where $\dot{m}$ is the mass flow rate; h is the specific enthalpy. Besides, Q indicates the net heat transfer rate and W indicates the brake power. Considering that the diesel engine generates brake power and some heat produced by combustion is transferred to the environment, eqn (3) can be written as eqn (4), where Q_f is the fuel energy rate, $\dot{Q}_{ex}$ is the exhaust energy rate, $\dot{Q}_d$ is the lost energy rate which is transferred to the environment by cooling, lubricating, heat transfer except for the exhaust:

$$\dot{Q}_f = \dot{W} + \dot{Q}_{ex} + \dot{Q}_d. \tag{4}$$

The brake power is denoted by eqn (5):

$$\dot{W} = \omega.\tau, \tag{5}$$

where (w) is the angular velocity; and (τ) is the engine torque.

Since the combustion air is in the same state as the standard reference state defined as T_0 = 293 K and P_0 = 1 atm, the energy of the combustion air can be neglected so the heat input rate to the control volume by mass is represented only by chemical energy of fuel $\dot{E}_f$ which can be calculated using the mass flow rate of the fuel $\dot{m}_f$ and Net calorific value of fuel as expressed by eqn (6):

$$\dot{E}_f = \dot{m}_f.NCV. \tag{6}$$

Exhaust energy rate ($\dot{Q}_{ex}$) can be calculated as a function of the mass flow rate of each exhaust gas components ($\dot{m}_{ex}$) which is obtained using combustion equations and the enthalpy change (Δh) represented by the difference between the enthalpy of the exhaust temperature and the reference temperature of each exhaust gas species as given in eqn (7):

$$\dot{Q}_{ex} = \dot{m}_{ex}.\Delta h. \tag{7}$$

The engine characteristics are essentially expressed by thermal efficiency (γ) and brake specific fuel consumption (Sfoc). While thermal efficiency is determined as the ratio of brake power to the fuel energy rate of the control volume, "Sfoc" is defined as a measure of how much fuel is consumed in one hour to obtain one-kilowatt brake power and they are denoted as in eqns (8) and (9):

$$\gamma = \frac{\dot{W}}{\dot{E}_f}, \tag{8}$$

$$\text{Sfoc} = \frac{\dot{m}_f}{\dot{W}}. \tag{9}$$

2.1.2 Exergy flow

The assumptions made for energy analysis is also applicable to exergy analysis. Based on these assumptions, the exergy balance for the control volume can be given in the general sense by eqn (10):

$$\dot{B}_Q + \dot{B}_W - \dot{B}_d = \sum \dot{m}_o \psi_o - \sum \dot{m}_\iota \psi_\iota, \tag{10}$$

where $\dot{B}_Q$ is the exergy transfer rate related to heat transfer between the control volume and the environment; $\dot{B}_w$ is the exergy transfer rate associated with work transfer; $\dot{B}_d$ is the exergy destruction rate of the control volume, and ($\dot{m}_o\psi_o/\dot{m}_\iota\psi_i$) are the exergy transfer through the intake and exhaust process, where (ψ_i / ψ_o) are the specific exergies of the fuel and exhaust gas.

Similarly ($\dot{m}_i$ $\dot{m}_o$) are the mass flow rates of the fuel and exhaust gas. Exergy input rate with mass transfer to the engine is formed mainly by fuel exergy, the combustion air exergy can be neglected by assuming that intake air enters the engine at ambient conditions. The specific chemical exergy of fuel is obtained by multiplying the net calorific value of fuel and chemical exergy factor as per eqn (11):

$$\psi_f = \varphi \, NCV. \tag{11}$$

The chemical exergy factor φ is based on the composition of fuel oil (C, H, O, S) [16]. The exergy transfer rate associated with work is equal to the network for the engine, eqn (12):

$$\dot{B}_w = \dot{W}. \tag{12}$$

Exergy output rate with mass transfer from the engine consists of exhaust exergy which can be expressed as in eqn (13):

$$\dot{B}_{ex} = \dot{m}_{ex}\psi = \dot{m}_{ex} \, C_{pex} \, T_0 \left(\frac{T}{T_0} - 1 - In\frac{T}{T_0}\right). \tag{13}$$

Exhaust exergy per unit mass (ψ) can be expressed as the sum of the specific thermomechanical and chemical exergies of the exhaust gases with the assumption that the exhaust gas is an ideal gas mixture [17].

Exergy transfer rate associated with the heat transfer is obtained by eqn (14):

$$\dot{B}_Q = \sum(1 - \frac{T_0}{T})\dot{B}_d. \tag{14}$$

T is the cooling water temperature equal to the system boundary temperature.

$\dot{B}_d$ is the lost (wasted) energy rate which is transferred to the environment by cooling, lubricating, heat transfer except for the exhaust gas.

The exergy efficiency is expressed as the ratio of the brake power exergy to the fuel exergy of the control volume, eqn (15):

$$\gamma = \frac{\dot{W}}{\dot{B}_f}. \tag{15}$$

2.2 Boiler

One oil-fired boiler is generally installed onboard container vessels for heating systems of fuel oil, lubricating oil, cooling water, sanitary and air conditioning. The boiler energy flows are represented in Fig. 2.
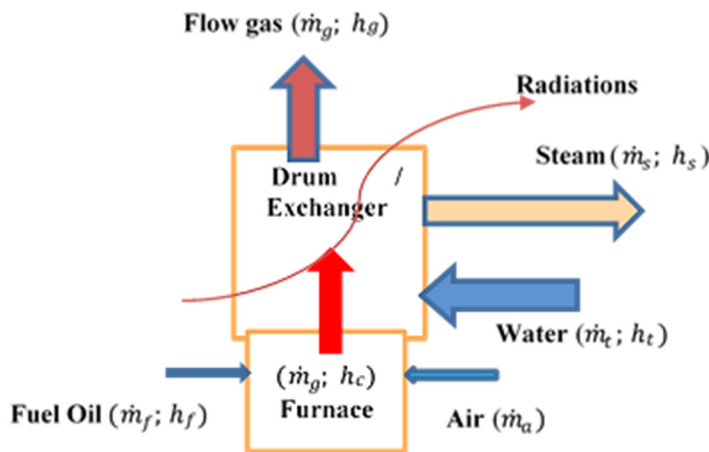

Figure 2:   Diagram boiler energy flow. Specific enthalpy (h); specific exergy (ψ); mass flow ($\dot{m}$). Subscripts: air (a); combustion (c); fuel oil (f); flow gas (g); incoming (i); outgoing (o); steam (s); water (t).

The boiler is usually well insulated so no heat dissipation to the surroundings, nor any kind of work is generated. Also, the kinetic and potential energies of the fluid's streams are usually negligible. Then only total energies of the incoming streams and the outgoing mixture will be considered for this study.

2.2.1 Energy analysis

In the boiler furnace, we assume that the combustion is complete and take place at constant pressure, and therefore the total chemical energy of fuel oil is transferred to the flue gases.

Assumptions: Steady operating conditions exist. Kinetic and potential energy changes are negligible. Air properties are used for exhaust gases; pressure drops in the heat exchanger are negligible.

The mass flow of flue gases is the sum of the fuel oil (f) mass follow and combustion air (a) mass flow (eqn (16)):

$$\dot{m}_g = \dot{m}_f + \dot{m}_a. \tag{16}$$

We assume that the mass flow of the steam produced is equal to the mass flow of the feeding water $\dot{m}_s = \dot{m}_t$.

The heat from combustion gas is transmitted to the water to produce steam. The energy flow $\dot{Q}$ is given by eqn (17):

$$\dot{Q} = \dot{m}_g \left(h_c - h_g \right) + \dot{m}_s (h_s - h_t). \tag{17}$$

2.2.2 Exergy analysis

The maximum paid work of the boiler is defined from exergy balance considering an environment of: $T_0 = 293$ K and $P_0 = 1$ atm.

As an open system, the exergy balance can be expressed as per eqn (18):

$$\dot{B}_i - \dot{B}_o = \dot{B}_w. \tag{18}$$

$\dot{B}_i$ and $\dot{B}_o$ represent the exergy flow entering and leaving the boiler.

$\dot{B}_w$ denotes the total exergy destruction in the boiler, eqn (21).

Combustion process: $(\dot{B}_{wc})$ is the exergy destroyed (wasted) during fuel oil combustion, expressed in accordance with eqn (19):

$$\dot{B}_{wc} = \dot{m}_f . \psi_f + \dot{m}_a . \psi_a - \dot{m}_g . \psi_g. \tag{19}$$

Heat exchange: $(\dot{B}_{wh})$ is the exergy destroyed (wasted) during heat exchange gas/water, expressed in accordance with eqn (20):

$$\dot{B}_{wh} = \dot{m}_g \left(\psi_c - \psi_g \right) + \dot{m}_s (\psi_t - \psi_s), \tag{20}$$

$$\dot{B}_w = \dot{B}_{wc} + \dot{B}_{wh}, \tag{21}$$

$$\psi_i = h_t - \dot{T}_0 \, s_t, \tag{22}$$

where h: enthalpy. s: entropy. T_0: 298°K.

In Table 1, we summarize the different efficiency formulas for the boiler energy and exergy flows.

Table 1: Summary of boiler energy flow efficiencies.

	Energy	Exergy
Combustion	$\eta_c = \dfrac{\dot{m}_g h_c}{\dot{m}_f h_f}$	$\mu_c = \dfrac{\dot{m}_g . \psi_c}{\dot{m}_f . \psi_f}$
Heat exchange	$\eta_h = \dfrac{\dot{m}_s (h_s - h_t)}{\dot{m}_f h_f}$	$\mu_h = \dfrac{\dot{m}_s (\psi_s - \psi_t)}{\dot{m}_g (\psi_c - \psi_g)}$
Boiler	$\eta = \dfrac{\dot{m}_s (h_c - h_t)}{\dot{m}_f h_f}$	$\mu = \dfrac{\dot{m}_s (\psi_s - \psi_t)}{\dot{m}_f \psi_f}$

3 CASE STUDY

3.1 Vessel under study:

Our study will be based on the machinery arrangements of a typical container vessel; its main particulars are shown in Table 2.

Table 2: Ship understudy main particulars.

Length (m)	200	Propulsion engine	21,770 KW
Breadth (m)	29.8	Diesel generator set (KW)	3 sets: 1890 KW @ 720 rpm
Draught (m)	11.4	Boiler	2.5t/h @ 9 bars
Gross tonnage	26,190	Cargo capacity	2600 TEU

The ship machinery consists of the propulsion system and auxiliary machines.

- Propulsion engine: this ship is fitted with one main diesel engine (ME) for propulsion turning single propeller at a maximum speed of 25 Knots. The diesel engine is converting chemical energy to mechanical energy by burning fuel oil.
- Auxiliary diesel engine (AE): The ship is also fitted with three diesel generators of 1890 KW each producing electric power needed for auxiliary machinery operations and cargo reefer containers feed.
- Auxiliary machines necessary for the safe operations of propulsion system, navigation system and crew living condition on board: boilers, cooling pumps, lubricating pumps, fuel oil treatment, firefighting system, air compressors, air conditioning, deck machinery, etc.
- Auxiliary steam boiler (AB): One oil-fired boiler is installed onboard for heating systems of fuel oil, lubricating oil, cooling water, sanitary and air conditioning. During sea passage, the exhaust gases flow from the main engine is enough to produce steam without the need for firing the oil-fired boiler. In the port and during ship slow down, the main engine exhaust gas flow is missing or reduced therefore, the oil-fired boiler is used to supply the heating steam.

3.2 Measurements

The ship is trading between north Europe, Morocco and West Africa in the regular line. We collected the noon reports and ship's records for two round voyages lasting approximatively three months. Sorting of these data was necessary, as without this, our calculations could be altered because of the zero speed or consumption values corresponding to periods of stop or anchorage. We filter the data and ignore the non-consistent values recorded by mistake or inaccuracy by the crew.

In addition to the noon report, the engine and auxiliary engine performance records at different loads were provided by the crew in addition to equipment instruction books. Some parameter values were collected from engine logbook mainly engine parameters and electric power consumption.

Fig. 3 represents the ME load during the three-voyage period under study. Most of the time the engine is used below 60% of its nominal power for example ME was running during

3% of total running time at 5% of load only. In Table 3 we summarized the average percentage of load versus running hours. The fuel oil consumption at each % of load and the exhaust temperature are obtained from ship's records. The fuel oil chemical energy is obtained from eqn (6) while the exhaust gas flue is calculated based on the engine specifications and tests as stated in the engine approved technical files.
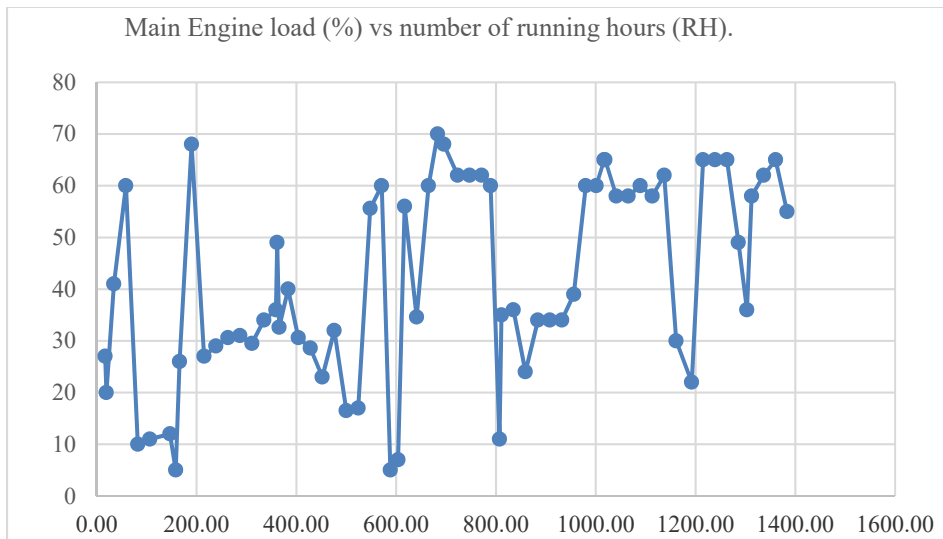

Figure 3: Engine running load over time.

Table 3: Main engine average load, power and fuel oil consumption vs % running hours.

Load %	5	15	25	35	55	65
% of total time	3	11	15	24	15	32
Power (KW)	1,090	3,100	5,100	7,150	11,700	14,050
FO cons. (Kg/h)	410	750	1,120	1,416	2,192	2,625
E f (MJ) (6)	4,795	8,771	13,109	16,560	25,634	30,698
Exhaust gas temp after T/C	300	295	290	290	280	260
Exhaust gas flow (t/h)	20	39	58	75	115	140

The same approach was adopted for the AE parameters as shown in Table 4. The average power is 1050KW, which is represents 55% of the engine nominal power. According to the performance record provided by the crew, at 55% load the diesel engine exhaust temperature after the turbine is 395°C (the energy and exergy values for AE shown in Table 6 are calculated based on the engine parameters at 55% of load). The boiler is used mainly when the main engine is stopped, to provide the steam needs in the port or at anchorage. The boiler is adjusted to 70% of maximum load. The parameters stated in Table 5 are taken from the ship's records and boiler specifications.

Table 4: Auxiliary engine load vs running hours.

AE (KW)	880	850	900	950	1,000	1,050	1,100
Period (h)	18	15	17.25	428	44.5	358	50.5
AE (KW)	1,150	1,200	1,250	1,300	1,350	1,400	1,500
Period (h)	72	24	772	45	45	12.5	40.5

Table 5: Auxiliary boiler parameters (values based on the steam diagram at 7 bars).

	Water	Steam	Fuel oil	Air	Combustion gas	Flue gas
Temperature (°C)	85	183.5	145	30	–	357
Flow rate (Kg/h)	1,050	1,050	71	1,189	1,260	1,260
Enthalpy (KJ/Kg)	285	2782	42,700	303.64	3,504	361
Entropy (KJ/Kg °K)	1.135	5.56	1.99	6.88	7.0	1.9

4 RESULTS AND DISCUSSION

4.1 Energy and exergy inputs

The fuel used onboard is the heavy fuel oil IFO 380 Density @ 15°C, kg/m^3. We take the net calorific values of fuel oil: NCV = 42.7 MJ/Kg and the exhaust gas specific heat Cp = 1.1KJ/Kg °K [17], where the values shown in Table 6 are calculated.

4.2 Efficiencies

By substitution of values shown in Table 6 in the eqns (4), (7)–(9) and (13)–(15), we calculate the different efficiencies shown in Table 7.

Table 6: Component calculated parameters.

	At sea			At port			Total		
	ME	AE	AB	ME	AE	AB	ME	AE	AB
FO cons. (ton)	2,313	380	–	–	105	29.28	2,313	485	29.28
Running hours	1,384	1,384	–	–	521	412	1,384	1,905	412
$\dot{E}_f$ (TJ)	98,765	16,226	–	–	4,483.5	1,272.5	98,765	20,709.5	1,272.5
$\dot{B}_f$ (TJ)	105,086	17,264	–	–	4,770.4	1,353.9	105,086	22,035	1,353.9
Cons. /hour	1.67	0.274	–	–	0.201	0.084	1.67	0.25	0.071
$\dot{E}_f$ (TJ/h)	71.36	11.72	–	–			71.36	10.87	3.09
$\dot{B}_f$ (TJ/h)	75.93	12.47	–	–			75.93	11.57	3.29
$\dot{E}_f$ (%)	85.9	14.1	–	–	70.49	29.51	81.8	17.15	1.05
$\dot{B}_f$ (%)	85.9	14.1	–	–	70.49	29.51	81.8	17.15	1.05

Table 7: Diesel engine efficiencies.

	Av. (KW)	$\dot{Q}_{ex}$(KW) (7)	$\dot{Q}_d$ (KW) (4)	$\dot{B}_{ex}$ (KW) (13)	$\dot{B}_Q$(KW) (14)	γ (8) (%)	γ (15) (%)	Sfoc (9) g/KwH
ME	7,530	5,750	6,542	2,079	233	37	35.7	221
% of $\dot{E}_f$	38	29	33	-				
% of $\dot{B}_f$	35.7	-	-	11.5	1.1			
AE	1,050	960	1,009	243		34.5	32.7	238
% of $\dot{E}_f$	34.5	32	33.5	-	36			
% of $\dot{B}_f$	32.7	30	-	10	1.12			

For the total voyage, the propulsion (main engine) is responsible for 82% of the ship's total energy (fuel oil) consumption. Electric power production accounts for 17 to 18% of fuel energy demand, while the heating by auxiliary boiler is approximatively at 1%. This is because the heating is mainly maintained by ME exhaust gas boiler where exhaust gas wasted heat is recovered.

At sea, 82% of energy consumption is due to propulsion while in the port 70.5% of the energy consumed is for producing electric power needs.

In the main engine, 37% of the input energy flow (fuel oil) is converted to work (propulsion), 29% of energy is transferred to exhaust gas, part of this energy is recovered by exhaust gas economizer producing steam for heating needs. The remaining 34% is wasted to the environment through the cooling system, shaft frictions, and radiations. Part of the cooling heat is recovered by domestic heating system.

The specific fuel oil consumption measured is 221 g/KWh, much higher than the maker's value which is 180. This is due to low load, the ship operating at a low load of less than 55%, while the engine is designed for running at 85% of nominal power.

Less than 35% of fuel oil exergy is transformed to break power; 12% is evacuated by exhaust gas; the rest is lost by exergy destruction.

The auxiliary engine is a four-stroke type engine, 34% of the fuel consumed is converted to electric power, 32% is wasted to engine exhaust gas and 34% expelled to the cooling system, radiations, mechanical frictions.

The exergy balance is similar to the main engine: 33% of fuel energy is transformed to work while 10% is evacuated by exhaust gas and the remaining is destructed by heat transfer.

The specific fuel oil consumption measured is 238 g/KWh much higher than the maker's value which is 210. The reason is the same of the main engine, running at 55% load away from a design point. It was demonstrated by other literatures [18] that for such auxiliary engine size the global energy efficiency can be enhanced by installing economizer on the exhaust system similar to the one fitted on main engine. Hence the steam produced will partly compensate the lack of steam produced by main engine economizer in the port

This result can be extended to similar vessel's category however it should be noted that the container vessels are operated at low speed due to market shrinkage and bunker rate, in normal operations the share of propulsive power would be much higher.

The auxiliary engine is designed for normal safe operation of the ship and supplying the reefer containers. Due to low market the number of reefer containers loaded are less than the ship's capacity. Otherwise the auxiliary engine could be operated at higher loads and at efficient range (generally 75–85% of the maximum output).

By equations stated in Table 1 and parameters from Table 4, we calculate the boiler's efficiencies as shown in Table 8.

Table 8: Boiler efficiencies.

	Energy	Exergy
Combustion	$\eta_c = \dfrac{\dot{m}_g h_c}{\dot{m}_f h_f} = 1$	$\mu_c = \dfrac{\dot{m}_g . \psi_c}{\dot{m}_f . \psi_f} = 0.60$
Heat exchange	$\eta_h = \dfrac{\dot{m}_s (h_s - h_t)}{\dot{m}_f h_f} = 0.86$	$\mu_h = \dfrac{\dot{m}_s (\psi_s - \psi_t)}{\dot{m}_g (\psi_c - \psi_g)} = 0.65$
Boiler	$\eta = \dfrac{\dot{m}_s (h_c - h_t)}{\dot{m}_f h_f} = 0.86$	$\mu = \dfrac{\dot{m}_s (\psi_s - \psi_t)}{\dot{m}_f \psi_f} = 30$

The energy efficiency of the boiler is 86% which is within the range of marine boiler, the lost energy is partly expelled by exhaust gas and partly due to blowing down operation, surface heat transfer conditions. Most of the heat loss take place in the heat exchanger.

The overall exergy efficiency is approximately 30%, mostly due to irreversibility. The exhaust gas heat can be recovered from the flue gas through a heat exchanger which may be used for preheating boiler fuel oil or feed water.

5 CONCLUSION

In this study, we represented the energy and exergy balance of a typical container vessel. The study is based on actual measurements and records provided by the ship crew. It has been demonstrated that the propulsion plant is responsible for 82% of the total energy demand, electric power generation is accounted for 17% while the production of steam is responsible for 1% which is negligible compared to others. Steam needs are mainly supplied by an exhaust gas economizer fitted on the main engine.

The overall energy and exergy efficiencies of the ship are approximatively 34–36% and mainly influenced by diesel engine performances. The boiler efficiency is not affecting much the ship energy and exergy efficiencies.

The low efficiencies can be explained by low performance of diesel engine at low loads. The container vessels are designed for a cruise speed of 24 knots but due to the high cost of fuel oil, companies are adopting economic speed to reduce fuel consumption. The same has been observed for the ship understudy, in that the auxiliary engine is mostly operating at 60% of the nominal power, probably due to low fret. The generator is designed for the safe operation of the ship and reefer container energy supply.

There's a huge amount of energy lost by the cooling system and exhaust gas: up to 65% of total energy consumed.

There is considerable potential for waste heat recovery on container vessels. Various solutions are already existing and a plethora of technologies available for retrofitting on existing vessels however to improve the overall energy efficiency techno-economic study is to be done on waste heat recovery solutions for each category of the vessels and trading mode.

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