Journal of Applied Mechanical Engineering

Sinha and Kunjambo, J Appl Mech Eng 2015, 4:3
DOI: 10.4172/2168-9873.1000167

Research Article | Open Access

Ship Energy Efficiency Performance Estimation Using Normal Daily Report Operational Data

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Abstract

A ship is designed to consume ceratin amount of fuel to meet its business objective. But as operating hours build up the state of machinery and surface condition of underwater hull change resulting in increased fuel consumption and rising operating cost. This calls for close monitoring and regular energy efficiency analysis of the ship's energy systems. A true comprehensive energy analysis of the ship requires taking into consideration energy flow across each major power producing and consuming components of the energy systems including those originating from environmental and human factors such as hull fouling, wind, wave, current, ship's draft, and sea temperature. The overall impact of all these factors on ship's energy demand is extremely complex and have been rarely ever correctly assessed. The most effective approach so far to ship energy performance analysis/monitoring has been to quantify the contribution of each energy element by removing the effects of remaining.

The authors in this paper conduct heat balance analysis of the steam power plant and apply filtering technique to the data from ship's daily report to assess the effects of external factors such as hull fouling trim and wind resistance on fuel consumption to estimate the overall energy efficiency performance (EEP) of an LNG ship.

Keywords: Energy efficiency; Specific fuel rate; Shaft power; Hull fouling; Power plant; Liquefied Natural Gas (LNG)

Glossary

EEP: Energy Efficiency Performance

HPT: High Pressure Turbine

LPT: Low Pressure Turbine

T/G: Turbo Generator

LNG: Liquefied Natural Gas

FO: Fuel Oil

LOG: Equipment to measure ship speed with respect to water in nautical miles per hour

HCV: High Calorific Value

Prop SFR: Propulsion Specific Fuel Rate

Ship SFR: Ship Specific Fuel Rate

Introduction

Efficient ship operation means all energy producing and consuming systems in the ship utilize least amount of fuel for a given power output [1]. Therefore, to analyse and estimate fuel consumption of the ship all its major energy exchange processes must be identified and investigated for their energy flow patterns. In steam powered LNG ships the major energy producing/consuming systems are

(i) Main Steam Boilers

(ii) Steam Turbine Propulsion Engines

(iii) Steam condensers and auxiliary machinery

(iv) Turbo Genrators and Motors that produce and consume electrical power

(v) Boiler Feed Pumps

(vi) Ship's hull and propeller which receive power from steam turbines to overcome resistance from water, wind, current, and wave effects.

(vii) Ship's rudder and steering system

To achieve overall best fuel economy by the ship each subsystem needs to be analysed for its energy efficiency [2]. In this paper, the energy efficiency analysis of the thermal system has been carried out by using heat balance diagram of machinery operating data. The EEP of the hull and propeller system has been carried out using data recorded in daily and voyage reports. One major drawback in using operating ship data to estimate EEP of the hull is the presence of large spurious external noise in the data which if not adequately filtered out can affect accuracy and reliablity of the performance baseline. To overcome this problem, authors in this paper use conventional filtering technique to a large volume of actual ship operating data to establish reliable hull condition trends.

Data Acquisition

The ship is fitted with a high capacity data equisition system to record operating parameters automatically and store as excel data sheets. The following operational parameters, as in Table 1, are recorded and forwarded to the head office as the ship's daily/voyage reports for energy analysis by the shore staff [3]. Six months operating

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Received May 18, 2014; **Accepted** June 19, 2015; **Published** June 26, 2015

Citation: Sinha RP, Kunjambo PT (2015) Ship Energy Efficiency Performance Estimation Using Normal Daily Report Operational Data. J Appl Mech Eng 4: 167. doi:10.4172/2168-9873.1000167

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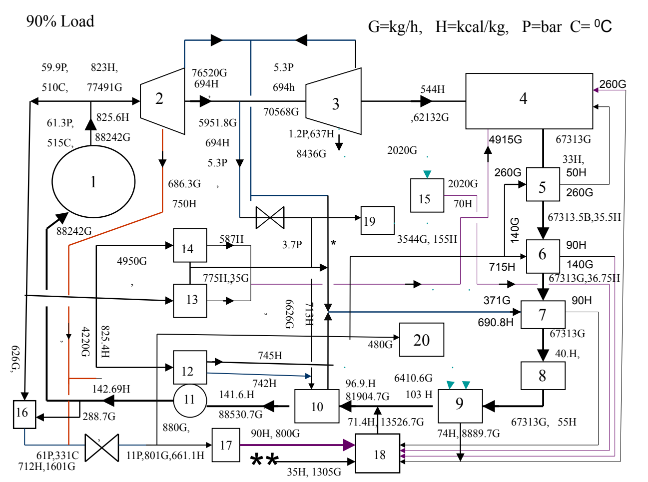

Figure 1: Heat balance diagram at 90% ballast. Source:

High Pressure Linec — HP Bleed Line — Low Pressure Line — LP Bleed Line — Gland Steam — Exhaust Steam — De-superheated Steam

S.No	Parameter	Unit
1	Duration of operationa at sea	Hours
2	Ship Velocity	Knots
3	Shaft Power	kWh
4	T/G 1 Power	kWh
5	T/G 2 Power	kWh
6	D/G Power	kWh
7	Shaft speed	rpm
8	Fuel consumed at sea	tons/day
9	F.O consumed in maneuvr/port	tons/day
10	Distance covered by LOG	nm
11	Draft forward	m
12	Draft aft	m
13	Wind speed	Knots
14	Wind direction	Degree

Table 1: Operating Parameters.

SHP, kW	F.O, t/h	SFR, g/kWh	HCV, kJ/kg	BlrEff (oil)	BlrEff (gas)	T/G1, kW	Evap, t/d	S.W ⁰C
22693	6514.45	299.81	43052	88.5	84	1210	30	24

Table 2: Sea Trials with 90% Ballast Load.

data from January-June 2014 has been used in this investigation to estimate energy efficiency of the ship. As the main machinery operating parameters are not entered in the daily report, the power plant EEP has been estimated using the archieved sea trials data.

Machinery Performance and Heat Balance

Knowledge of how well energy exchange between various components of the ship propulsion system taking place is best illustrated by preparing a heat balance diagram [4]. The heat balance analysis is a method based on the energy conservation principle of the first law of thermodynamics and commonly used in process and power plant industry to measure energy efficiency. It essentially provides the energy flow topology of the power plant giving visual realizations of energy exchanges taking place within the system and its environment. It is of great assistance in identifying areas of plant improvements for better fuel economy. The heat balance diagram prepared from the data recorded during the full power sea trials at 90% ballast load condition is shown in Figure 1. Table 2 shows the baseline data for the sea trial.

Using energy flow information in Figure 1, the enthalpy drop and power produced in different components of the steam power plant

S.No	Equipment	Mass flow (kg/s)	h(kJ/kg)	m.x h (kW)	Remarks
1	Boiler	24.51	2860.4	70108.5	---
	Main Turbines				
2(a)	HP Turbine	21.52	542.25	**11669.3**	Net shaft power
(b)	Power from HPT Bleed	0.19	306	**58**	
3(a)	LP Turbine	17.255	628.2	**10838.9**	
(b)	Power from LPT Bleed	2.336	238.77	**557.8**	
	Power produced by HP and LP turbines			**23124**	
4	Condenser				
(a)	Heat from LPT exhaust	17.255	2140.06	36926.9	Heat lost to sea
(b)	Heat from TG exhaust	1.365	2320.15	-3167	
(c)	Heat from Air ejec drain	0.0722	71.196	-5.14	
	Heat lost to cooling sea water			40099	
	Auxiliary machinery and systems				Heat loss, kW
5(a)	Air ejector(steam)	0.0722	2774.55	-200.3	Negligible
(b)	Air ejector(FW)	18.7	10.51	196.53	
6(a)	After condenser(steam)	0.0388	2604.93	-101.07	Negligible
(b)	After condenser (FW)	18.7	5.235	98	
7(a)	Gland cond.(FW)	18.74	13.61	254.5	Negligible
(b)	Gland cond(Steam)	0.103	2516.15	-259.16	
8	Fresh W Gen (FW)	18.7	62.82	1174.73	
9(a)	LP heater (FW)	18.7	200.02	3759.15	Negligible
(b)	LP heater(bleed)	1.448	2357.84	-3414.15	
(c)	LP htr (exst steam)	0.984	339.2	-333.8	
10(a)	De-aerator (FW)	22..75	187.2	+4259..25	145.53
(b)	De-aerator(steam)	1.84	2393.8	-4404.6	
11	Feed pump(FW)	24.51	0.444	133.44	---
12	Feed PP (steam)	1.171	349.28	**409**	**---**
13(a)	Turbo Gen2	0	0	0	---
(b)	Turbo Gen1(drain)	0.0097	211.91	-2.05	---
14	Turbo Gen1	1.375	998.42	**1373.4**	**---**
15	Evaporator(inlet steam)	0.561	2374.59	-1332.41	---
16(a)	De-super heater(steam)	0.2277	474.08	-107.94	17.94
(b)	De-super heater(FW)	0.0377	2387.16	90	
17(a)	Aux de-super heater(FW)	--	--	--	
(b)	Aux de-super heater (steam)	--	--	--	
18	Auxiliary De-sup services	0.222	2391.5	-530.91	---
19(a)	Atmospheric drain tank	0.362	152.44	55.2	Negligible
(b)	Atmospheric drain tank	2.47	36.01	-26.89	
(c)	Atmospheric drain tank	0.222	77.9	-17.32	
(d)	Atmospheric drain tank	0.103	77.9	-8.02	
(e)	Atmospheric drain tank	0.0388	77.9	-3.03	
20	Heat to combustion air	0.984	2394.3	2355.97	
21	Atomizing and soot blow	0.133	2558	341	
	Remarks: +ve temperature rise , -ve Temperature drop.				

Table 3: Heat balance analysis data [2].

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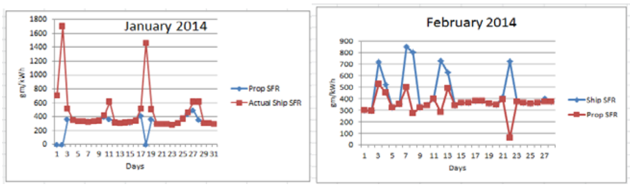
1	Mean Draft	10, m
2	Trim	<± 0.5, m
3	Speed from LOG	>14 knot
4	Speed difference (LOG-GPS)	<± 0.3 knot
5	Beaufort Sea State	≤3
6	Wind Speed	<15 knot

Table 4: Baseline Operating Conditions [3].



(a) (b)

Figure 2: Ship SFR- Prop. SFR.

have been calculated and placed in Table 3. The High Pressure Turbine (HPT), Low Pressure Turbine (LPT), Turbo Generators (T/G) and feed pumps are the units of the power plant which actually convert heat into useful mechanical shaft power. The remaining components referred to as auxiliary units of the plant essentially exchange heat to raise temperature of water condensate, combustion air, liquid/gas fuel and sea cooling water of the evaporator to improve overall plant efficiency.

A comparison of shaft power together with T/G power recorded during the sea trial (Table 2) is in close agreement within error margin of 2% with the ship power calculated from Heat Balance analysis in Table 3. The overall thermal efficiency of 35.52% calculated from heat balance for steam power plant is consistent with Industry standards for marine steam turbines.

Hull and Propeller Performance Analysis

Major hurdle in hull performance analysis arises from the interference of environmental and operational factors such as wind, wave, current, draft/trim, sea water temperature and rudder transients [3,5]. Because of that the actual power needed to move the ship through water has very complex functional dependence on these variables and requires conducting special experiments with application of advanced mathematical tools to investigate their individual impact on the overall fuel consumption. To estimate true impact of hull and propeller fouling on fuel consumption will require complete elimination of interference from those factors. In this paper, the authors use conventional data filtering technique as in [3,5] to eliminate effects of undesirable external disturbances by establishing a baseline operating condition as filter (Table 4).

Remarks

(a) As draft/trim has influence on skin friction through the wetted surface area of the hull it must be maintained constant for comparative analysis. The standard mean draft is selected based on the historical archived data from previous voyages.

(b) Although skin friction due to hull fouling is highly sensitive to speed through water its effect below 10 knots is not so significant. Therefore, ship speeds by LOG below 10 knots have not been considered to ensure that the impact of hull/propeller fouling on fuel consumption is effectively captured.

(c) The effect of ocean currents and rudder oscillations is reflected in the difference between speed through water and speed over ground. Heavy weather condition results in increased difference between LOG speed and GPS speed signalling greater impact on increased hull resistance and vice versa. For this reason, any data with speed difference exceeding 3% has not been considered for analysis.

(d) Effects from wind and waves have been filtered out by considering data only where wind speed is below 15 knots. Similarly to eliminate effects of bad weather conditions the data has been considered only when sea state was below Beaufort scale of 3.

Data Analysis

Three months operating data from archived daily reports have been taken and filtered to baseline conditions for estimating energy efficiency performance indicators. The propulsion specific fuel rate (Prop SFR) and ship specific fuel rate (ship SFR) are defined as fuel consumed in grams to produce one kWh of power and has been taken as the ship's energy efficiency performance indicator [3,6].

$$Prop\,SFR = \frac{Fuel\,Consumed\,at\,sea\,per\,Day}{Total(SHP + T/G\ power)\ kWh}$$

$$Ship\,SFR = \frac{Fuel\,Consumed\,at\,(sea + port)\,per\,Day}{Total(SHP + T/G\ power)\ kWh}$$

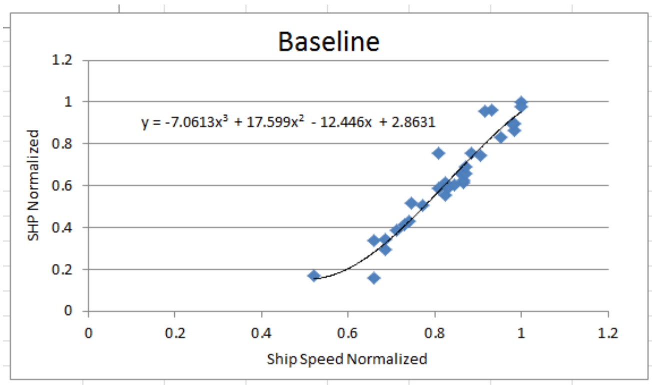


Figure 3: Ship speed–Shaft power.

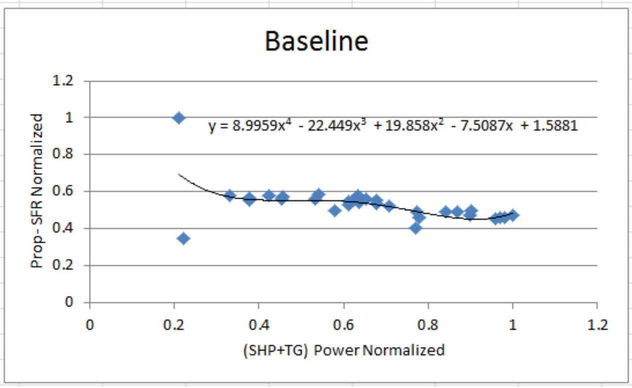


Figure 4: Shaft power – Prop SFR.

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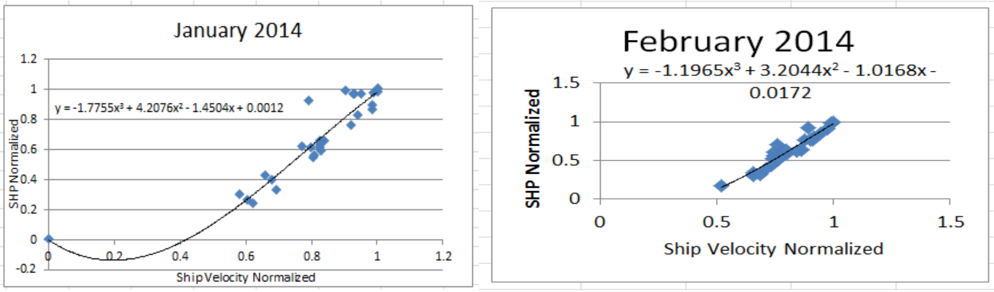


(a) (b)

Figure 5: Ship speed – Shaft power.

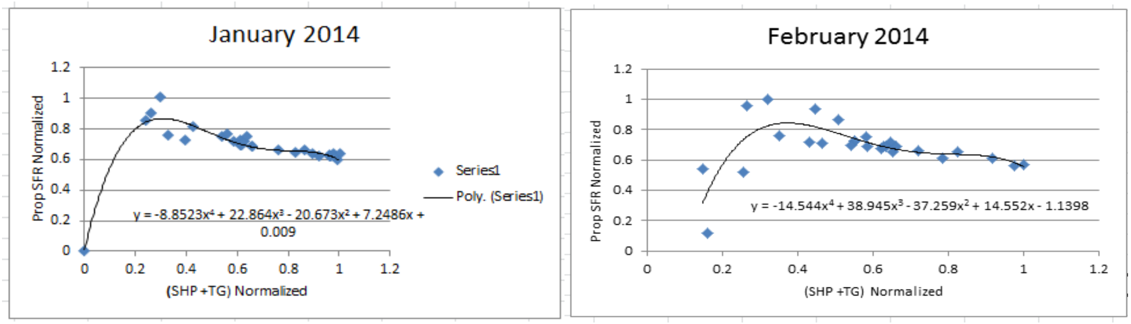
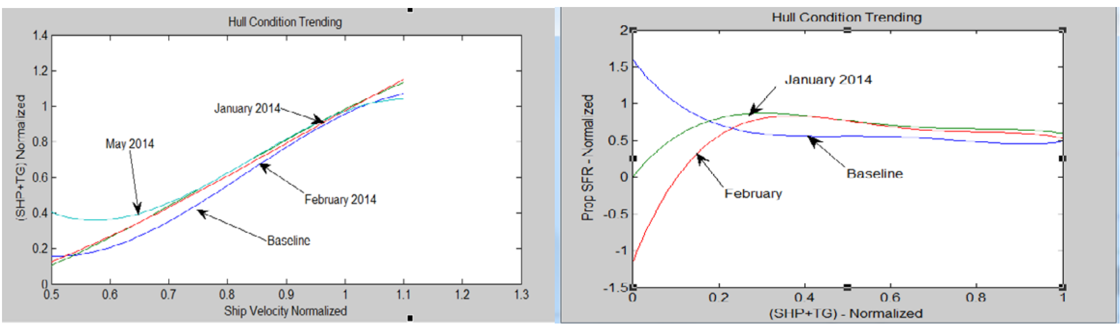


Figure 6: Shaft power- Prop. SFR.



(a) (b)

Figure 7: Hull fouling – Ship speed, Prop. SFR.

From definitions, the ship and propulsion SFRs are expected to be the same during sea voyage and will differ only when ship is in port, as in Figure 2a and 2b. The separation of two energy efficiency terms has been made to keep track on fuel consumption during cargo operations in the port.

Figures 3 and 4 show ship's baseline EEP plots obtained from the filtered data, As expected, Figure 3 shows a 3rd order functional relationship between ship speed and shaft power. A decrease in propulsion SFR (Figure 4) with rising shaft power indicates improvement in fuel consumption at higher powers. But in this study because of the narrow data base of this investigation the minimum fuel estimate of 300 gms/kWh (0.45N) as shown in the graph may not be the true conclusive baseline EEP. A larger data base is expected to provide more accurate and convincing result. Besides that the actual data in daily report is referenced to Beaufort sea state 7 as against 3 originally intended to be used for data filtering which is also expected to introduce some error in the baseline performance estimate. But since no other better data is currently available until the ship begins her next post docking operating cycle these estimates are treated as benchmark for ship energy EEP comparison [7].

The minimum ship SFR estimate of 0.45 N (300 gms/kWh) (Figure 4) is about 10% higher compared to 272.53 gms/kWh obtained in power plant heat balance analysis. This 10% variance in ship SFR estimate is considered little high which may be due to error in data filtering and also the fact that the ship is already in operation for over half its next dry docking cycle. After setting the baseline for EEP, daily report data from January-May 2014 has been analysed to estimate impact of hull fouling on ship's energy efficiency. The results of analysis is discussed and presented in the following section [8].

Result of Investigation

Figures 5a,5b and 6a,6b show plots of ship velocity versus SHP and SHP versus prop SFR respectively. These plots have been obtained after normalizing the original daily report data to remove error in curve fitting a rising f rom p oorly c onditioned d ata p oints. A lthough as expected, the ship Velocity–SHP plots in Figures 5a and 5b retain 3rd order functional dependence but model coefficients show some variations from baseline (Figure 3), due to effect of hull fouling. Similar, result can be observed in Figure 6a and 6b with respect to the specific fuel rate consumption of the ship during sea passage [9].

As the impact of hull fouling on ship speed is less detectable at lower velocities, ship speeds of 15 knots and above only have been considered for estimating its impact on fuel consumption. Also the hull fouling being a slow process progressing with time its impact on energy efficiency performance is visible only by way of gradual loss in ship's speed and increased fuel consumption. Figure 7a shows deviation in ship's speed from the baseline for the January and February 2014 data. Although one month time interval to measure effect of hull fouling on ship speed is too short to detect any significant variation but still at speed above 15 knots the trend indicates slight drop in ship speed from January-May 2014. But as expected, the drop in speed due to hull fouling with reference to baseline for the same period is clearly noticeable. Similar conclusion is also drawn from the plots in Figure 7b which shows small increase in propulsion SFR from baseline in February 2014.

Conclusions

A practical and operator friendly approach, free from complex mathematical computations to estimate ship energy efficiency performance, using operational data from daily/voyage report has been presented. The energy efficiency performance of maj or power plant components such as boiler, turbines, condenser and Turbo Generators has been estimated using heat flow diagram. The effect of hull fouling on vessel speed and increased SFR has been estimated by eliminating the external disturbing factors through use of data filters. Result of the investigation may be summarized as follows.

(i) The method proposed in this paper is simple and economical to implement.

(ii) Reliability of result will depend on the accuracy of data filter used.

(iii) The R2 values and corresponding residues of data fits in Figures 3-7 show satisfactory result.

(iv) In present investigation the data base was very small hence result is more qualitative than quantitative. Further investigation with wider data base is continuing.

(v)The estimated baseline Prop SFR of 300 gms/kWh is only approximate and needs further refinement by using post dry dock operational data.

Acknowledgement

The authors express sincere appreciation to Malaysian International Shipping Corporation Berhad for continuous encouragement and providing noon report data from their LNG fleet to carry out this research. The work presented here is part of ongoing Ship Energy Efficiency Research project at the Malaysian Maritime Academy.

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