JOURNAL OF MARITIME RESEARCH

Vol XIII. No. I (2018) pp 91–96

ISSN: 1697-4040, www.jmr.unican.es

Empirical fuel consumption assessment for two-strokes dual fuel engines on LNG Carriers

C. Gonzalez-Gutierrez[1,*], C. Perez-Labajos[1,2]

ARTICLE INFO

Article history:
Received 9 March 2018;
in revised form 28 March 2018;
accepted 15 April 2018.

Keywords:
LNG, Dual engines, Ship efficiency.

ABSTRACT

This work aims to describe an empirical method for calculating the fuel and gas consumption on two-strokes dual fuel engines with gas (LNG) injection. The empirical analysis is done by collecting data from 12 engine shop tests report of two-strokes dual fuel engines with gas injection for LNG carriers, from the engine makers MAN B&W and WINGD, highlighting the differences between both makers in terms of fuel consumption.
This engine design appears to satisfy the need of having more flexibility in regards of using different fuel types, including LNG as one alternative for mitigate the atmospheric emissions, besides the benefits of using two stroke cycles instead of four strokes, improving the efficiency of power production.

1. Introduction

Although diesel engines are the predominant option within maritime transport, in recent years other more engine concepts have been developed with more flexibility in regards of using various types of fuels, reducing atmospheric emissions. A clear example is the two and four-stroke engines that use LNG as fuel, being able to work under the Diesel and Otto combustion cycles.

The Third IMO Study of Greenhouse Gases of 2014 (International Maritime Organization, 2014) considered that all the engines installed on ships capable of using LNG as fuel, were operating with the Otto cycle and did not relate their specific consumption depending on the load of the engines.

The improvements in designs mean that there are currently diesel cycle engines that might also use LNG as fuel, having different emission ratios than those operating with the Otto cycle. Diesel cycle engines that use LNG are assumed to be approximately 20% more efficient than those that use the Otto cycle, although they have higher NOx emissions due to lower combustion temperatures; On the other hand, Diesel cycle engines that use LNG as fuel have much less methane slip than those who operates with Otto cycle, due to a more complete LNG combustion within the Diesel cycle (Livanos et al., 2014; Olmer et al., 2017b; Stoumpos et al., 2018).

Currently, two manufacturers dominate the market for dual two-stroke engines. These are MAN B&W with its dual engine with high pressure gas injection (i.e., model G70ME-C9.5-GI) and as counterparty, it is found the solution proposed by Winterthur Gas & Diesel (WINGD) with its dual engine with low pressure gas injection (i.e., model W5X72DF).

Due to WinGD and MAN B&W use different technical alternatives, each option has its own advantages and disadvantages in terms of performance, emissions and capital and operational expenditures.

Low-pressure engines have certain advantages in terms of NOx emissions, gas fuel supply systems, and investment costs, while high-pressure engines perform better in terms of thermal efficiency, gas compatibility, and engine methane slip.

In a similar way to the study of the specific consumption of diesel engines carried out by Jalkanen et al., (2012), main engines shop test reports have been analyzed and the consumption data of twelve dual two-stroke engines with high and low gas injection pressure have been retrieved and evaluated, then

[1]University of Cantabria. Germán Gamazo nº 1, 39004 Santander, Cantabria (SPAIN). Coastal and Ocean Planning and Management I+D Group.

[2]Professor of Marine Economics of the Department of Navigation and Naval Construction Science and Techniques. Tel. (+034) 942201362. E-mail Address: clabajos@unican.es

[*]Corresponding author: C. Gonzalez-Gutierrez. Tel. (+034) 620595749. E-mail Address: carlos.gonzalezgu@alumnos.unican.es.

is applied polynomial regressions, getting as result the specific consumption of the engines in diesel and gas mode for any load and engine type.

Normally, the results in the main engine shop test reports are showing the specific fuel oil consumption for diesel mode referred or corrected to a reference condition of lower heating value (LHV), being this reference value of 42.7 MJ/kg, this is the net energy of the standard distillate fuel used (Marine Diesel Oil) by the International Organization for Standardization (ISO), and when the engines operate under gas mode, the gas fuel consumption is corrected to a reference LHV of 50 MJ/kg (ISO, 2002, 2016). Hence, to calculate correctly the actual fuel consumption of the engine, it is necessary to know what is the fuel type in use and what its LHV is, in order to obtain a more accurate fuel consumption for any fuel (Kristenen et al., 2015), due to the energy available in the different fuels have a big impact in the amount of fuel required to produce the demanded power, to proceed with a proper comparison of the engines efficiency, it is necessary to have the results expressed in the same way, in this case, converting the net energy of the fuel used into the reference value established by ISO.

This work is structured in three more sections: 2. Methodology, 3. Results 4. Conclusions.

2. Methodology.

In this work, the methodology used to assess the fuel consumption of the marine two-stroked dual fuel engines with gas injection, starts from the collection and analysis of the data retrieved from twelve engine shot test reports from the engine manufactures MAN B&W and Winterthur Gas & Diesel, for 12 series of LNG carriers at newbuilding stage.

The method proposed in this work to evaluate the fuel consumption of this type of engines is based on the calculation of the specific fuel consumption for any engine power, and therefore, knowing the power produced, it is possible to calculate the estimated fuel consumption of the engine.

In the following subsections, it is analyzed separately the two types of two-strokes dual fuel engines with gas injection to highlight the differences of these two designs.

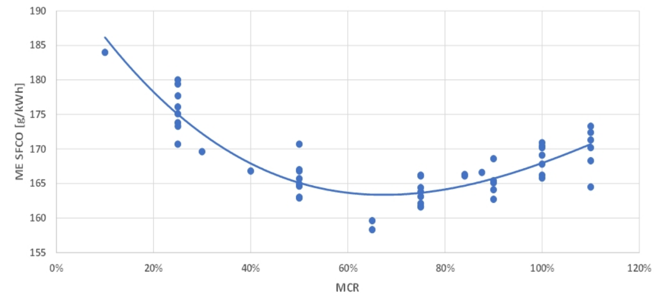
2.1. Specific fuel consumption for two-Strokes dual fuel engines with gas injection at high pressure.

In this section, it is analyzed the engine shop test results of 8 engines, model G70ME-C9.5-GI, from the engine manufacture MAN B&W.

The data is retrieved at various engines loads (MCR, Maximum Continuous Rating) and under diesel and gas modes.

The first step to calculate the fuel consumption is to define the specific fuel oil consumption (SFOC) of the engines under diesel and gas mode.

Figure 1: SFOC of dual engines with high pressure gas injection in diesel mode.



Source: Authors.

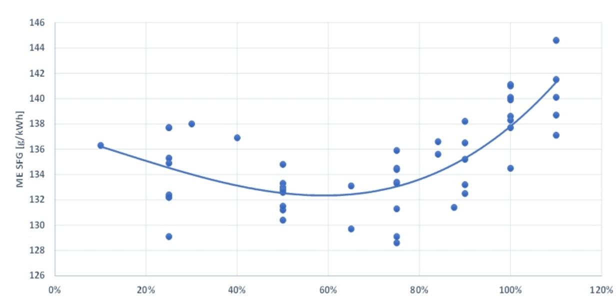
Then, a polynomial regression is applied obtaining the SFOC under diesel mode for the two-stroke dual fuel engines with high pressure gas injection (equation 1).

$$SFOC_{HPDE} = \frac{(-28.79 \cdot MCR^3 + 110.94 \cdot MCR^2 - 110.29 \cdot MCR + 196.12) \cdot 42{,}7}{LHV_i} \quad (1)$$

Where SFOC$_{HPDE}$ is the SFOC under diesel mode for the two-stroke dual fuel engines with high pressure gas injection in g/kWh, MCR is the engine load referred to the Maximum Continuous Rating expressed as a decimal, LHV is the lower heating value of the fuel in use as MJ/kg and i is the type of fuel in use.

When the engines are operating in gas mode, the amount of gas required to produce a kW of power is different from the amount of fuel needed to make the same kW of power under diesel mode. This is due to the differences between the net energy available in the residual or distillate fuels (for diesel mode operation) and the net energy available in the LNG as fuel.

Figure 2: Specific Gas consumption (SFG) for dual engines with high pressure gas injection in gas mode.



Source: Authors.

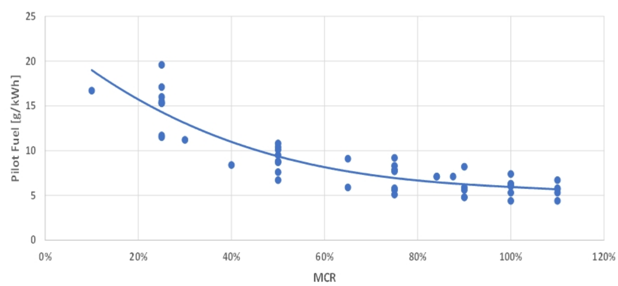
A polynomial regression is applied obtaining the SFG under gas mode for the two-stroke dual fuel engines with high pressure gas injection (equation 2).

$$SFG_{HPDE} = \frac{(18.36 \cdot MCR^3 - 7.43 \cdot MCR^2 - 10.43 \cdot MCR + 137.32) \cdot 50}{LHV_{gas}} \quad (2)$$

Where SFG_{HPDE} is the SFG under gas mode for the two-stroke dual fuel engines with high pressure gas injection in g/kWh, MCR is the engine load referred to the Maximum Continuous Rating expressed as a decimal and LHV_{gas} is the lower heating value of the gas in use as MJ/kg.

Dual engines when operating in gas mode, they need a small amount of liquid fuel, either residual or distillate, known as pilot fuel, for proper combustion inside the cylinders. The pilot fuel is used in gas mode only in this type of engine. The pilot fuel needed in gas mode is shown in the Figure 3 and equation 3.

Figure 3: Pilot fuel consumption for dual engines with high pressure gas injection in gas mode.



Source: Authors.

$$PF_{HPDE} = \frac{(-11.99 \cdot MCR^3 + 38.30 \cdot MCR^2 - 43.33 \cdot MCR + 22.95) \cdot 42{,}7}{LHV_i} \quad (3)$$

Where PF_{HPDE} is the specific pilot fuel consumption under gas mode for the two-stroke dual fuel engines with high pressure gas injection in g/kWh, MCR is the engine load referred to the Maximum Continuous Rating expressed as a decimal, LHV is the lower heating value of the pilot fuel in use as MJ/kg and I is the pilot fuel in use.

Once is established the way of obtaining the SFOC, SFG and the pilot fuel consumption for this type of engines, then it is possible to calculate the fuel consumption as a function of the engine power (in kW) due to the values obtained in the equations 1, 2 and 3 are expressed as grams of fuel per kilowatt and hour.

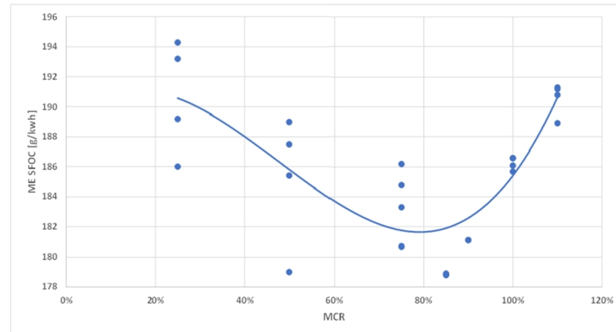
2.2. *Specific fuel consumption for two-Strokes dual fuel engines with gas injection at low pressure.*

In the same way as it has been done for the two-strokes dual fuel engines with gas injection at high pressure, in this section, it is analysed the main engine shop test results of 4 engines, model W5x72DF, from the engine manufacture Winterthur Gas & Diesel.

The data is retrieved at various engines loads (MCR, Maximum Continuous Rating) and under diesel and gas modes.

As it is done for the high-pressure gas injection dual engines, polynomial regression is applied on the data collected from the engine shop test reports at diesel and gas mode, and for the specific pilot fuel consumption under gas mode.

Figure 4: SFOC of dual engines with low pressure gas injection in diesel mode.

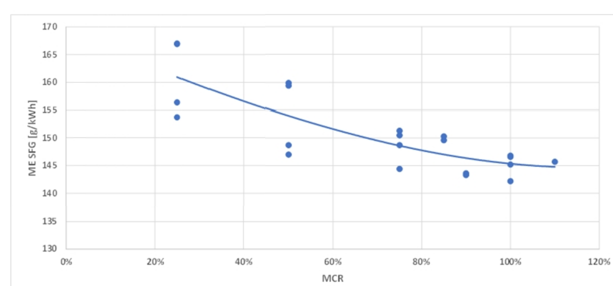


Source: Authors.

$$SFOC_{LPDE} = \frac{(75.1 \cdot MCR^3 - 107.1 \cdot MCR^2 + 28.42 \cdot MCR + 188.98) \cdot 42{,}7}{LHV_i} \quad (4)$$

Where $SFOC_{LPDE}$ is the SFOC under diesel mode for the two-stroke dual fuel engines with low pressure gas injection in g/kWh, MCR is the engine load referred to the Maximum Continuous Rating expressed as a decimal, LHV is the lower heating value of the fuel in use as MJ/kg and i is the type of fuel in use.

Figure 5: SFG of dual engines with low pressure gas injection in gas mode.

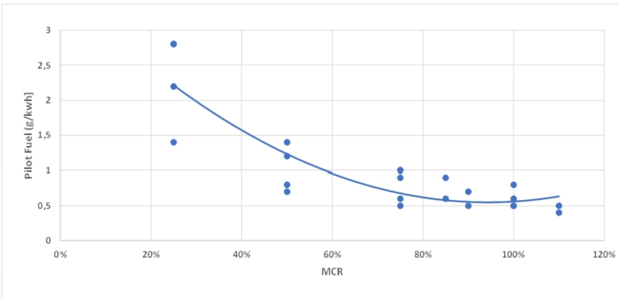


Source: Authors.

$$SFG_{LPDE} = \frac{(6.22 \cdot MCR^3 + 3.07 \cdot MCR^2 - 32.76 \cdot MCR + 168.84) \cdot 50}{LHV_{gas}} \quad (5)$$

Where SFG_{LPDE} is the SFG under gas mode for the two-stroke dual fuel engines with low pressure gas injection in g/kWh, MCR is the engine load referred to the Maximum Continuous Rating expressed as a decimal and LHV_{gas} is the lower heating value of the gas in use as MJ/kg.

Figure 6: Pilot fuel consumption for dual engines with low pressure gas injection in gas mode.



Source: Authors.

$$PF_{LPDE} = \frac{(3.47 \cdot MCR^2 - 6.55 \cdot MCR + 3.64) \cdot 42{,}7}{LHV_i} \tag{6}$$

Where PF_{LPDE} is the specific pilot fuel consumption under gas mode for the two-stroke dual fuel engines with low pressure gas injection in g/kWh, MCR is the engine load referred to the Maximum Continuous Rating expressed as a decimal, LHV is the lower heating value of the pilot fuel in use as MJ/kg and i is the pilot fuel in use.

In this type of engines, when they are under diesel mode, there is also pilot fuel used to protect the pilot fuel injectors. This amount of pilot fuel under diesel mode is already accounted in the equation 4, therefore the equation 6 is only applicable when the engines is under gas mode.

2.3. *Fuel consumption approach for two-Strokes dual fuel engines with gas injection.*

The information of the specific fuel consumption of the engines is an essential data and a starting point on various studies of the industries that focus on the ship efficiency, atmospheric emissions, bottom-up emissions inventories among others; and also it is essential to use the corrected specific fuel oil consumption depending on the engine MCR due to the value of the specific fuel consumption is very dependent on the engine load because they are optimized to have the higher efficiencies between 70 and 85% MCR (Corbett et al., 2003, 2004; Schreier et al., 2007; De Meyer et al., 2008; Dalsøren et al., 2009).

The aim of this section is to formulize the mathematical expressions required to calculate the hourly fuel consumption for the two-strokes dual fuel engines with gas injection from the specific fuel consumption.

When the engines are operating under diesel mode, only liquid fuel will be used (residual and/or distillate oil). However, under gas mode, it will be consumed gas fuel and liquid fuel as pilot (residual and/or distillate oil). Therefore, the hourly fuel consumptions of the engines under diesel mode are shown in the Eq. 7 and the hourly fuel consumptions under gas mode are expressed in the equations 8 and 9.

$$M_{D,i} = \frac{SFOC_{,i} \cdot P_e}{10^6} \tag{7}$$

Where M_D is the hourly fuel consumption under diesel mode in kg/h, SFOC is the specific fuel oil consumption, P_e is the engine power in kW and i is the liquid fuel type in use.

$$M_G = \frac{SFG \cdot P_e}{10^6} \tag{8}$$

Where M_G is the hourly gas consumption under gas mode in kg/h, SFG is the specific gas consumption and P_e is the engine power in kW.

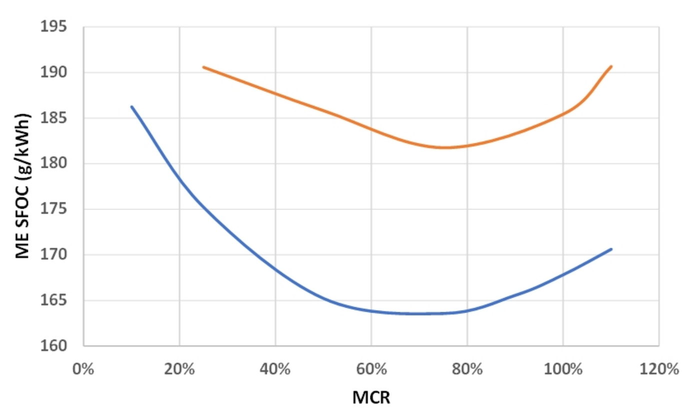
$$M_{PF,i} = \frac{PF_i \cdot P_e}{10^6} \tag{9}$$

Where M_{PF} is the hourly pilot fuel consumption under gas mode in kg/h, PF is the specific pilot fuel oil consumption, P_e is the engine power in kW and i is the liquid fuel type in use.

3. Results.

In this section a comparison of the specific fuel consumption obtained for the two types of two-strokes dual fuel engines with gas injection is presented in the figures 7, 8, 9.

Figure 7: SFOC of dual engines with low- and high-pressure gas injection in diesel mode. Orange line: low pressure gas injection engine. Blue line: high pressure gas injection engine.

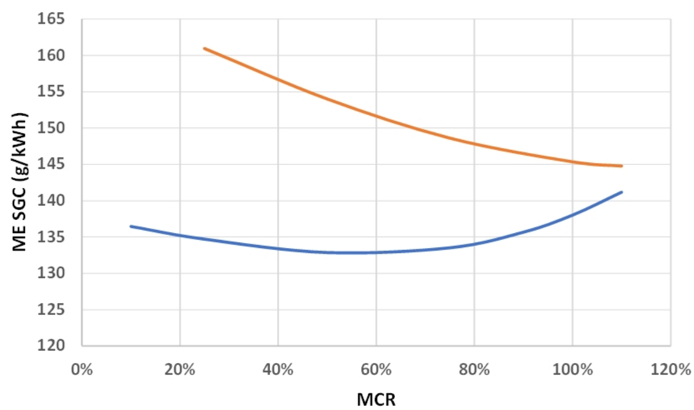


Source: Authors.

The two-stroke dual engine with high pressure gas injection has lower specific fuel consumption in diesel and gas mode than the engine with low pressure gas injection. However, the amount of pilot fuel needed under gas mode is much bigger in the high-pressure gas injection engines than in the low-pressure gas injection engines.

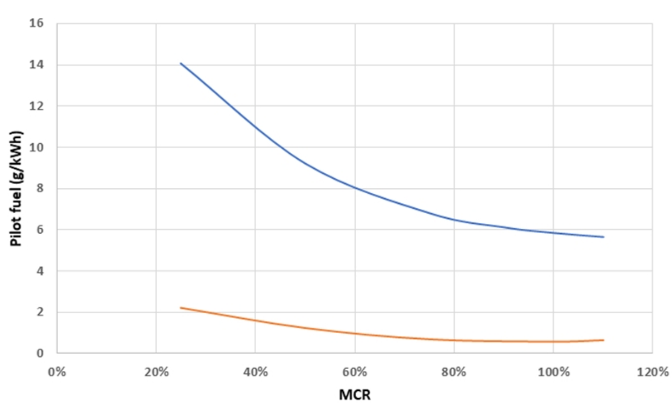
This analysis shows that in terms of fuel efficiency, the high-pressure gas injection engines have higher efficiencies if we strictly assess the efficiency of the engine from the specific fuel consumption.

Figure 8: SFG of dual engines with low- and high-pressure gas injection in gas mode. Orange line: low pressure gas injection engine. Blue line: high pressure gas injection engine.



Source: Authors.

Figure 9: Pilot fuel consumption for dual engines with low- and high-pressure gas injection in gas mode. Orange line: low pressure gas injection engine. Blue line: high pressure gas injection engine.



Source: Authors.

Conclusions.

The two-strokes dual fuel engines with gas injection are in the next level in regards of operation flexibility compared with traditions marine diesel engines.

The ability of using liquid fuels (residual and distillate oils) and gas fuel (LNG) in addition to the fact of being two stroke engines, which are more efficient than the four-stroke engines from power production point of view, makes the two-stroke dual engine a very interesting alternative as propulsion system for the ships to reduce the atmospheric emissions in near future.

The focus of the analysis done in this work is purely fuel efficiency of the engines. At this regard, the two-stroke dual engine with high pressure gas injection is consuming less fuel than the two-stroke dual engine with low pressure gas injection.

However, this result is only considering the engines isolated, factors like maintenance costs and auxiliary systems are not considered in this evaluation. Therefore, it is not a complete assessment for the propulsion overall efficiency nor ship overall efficiency when the engines are installed on board, because among other reasons, it is not considered the auxiliary systems that the engines require for its operation. Just for naming one example of an auxiliary system that would have impact in the whole ship efficiency, the two-stroke dual engine with high pressure gas injection needs a very advance compressors to rise the gas supply pressure up to the require injection pressure which would require additional investment in the building phase, higher maintenance costs and more auxiliary energy to operate the compressors, while in the low-pressure engines, the gas injection is at ambient pressure without requirements of additional auxiliary systems, apart of the fuel supply units requires for all engines.

References.

Corbett, J. J. and Koehler, H. W. (2003) 'Updated emissions from ocean shipping', Journal of Geophysical Research - Atmospheres, 108(D20), p. 4650.

Corbett, J. J. and Koehler, H. W. (2004) 'Considering alternative input parameters in an activity-based ship fuel consumption and emissions model: Reply to comment by Øyvind Endresen et al. on "Updated emissions from ocean shipping"', Journal of Geophysical Research D: Atmospheres, 109(23), pp. 1–8. doi: 10.1029/2004JD005030.

Dalsøren, S. B. et al. (2009) 'Update on emissions and environmental impacts from the international fleet of ships: The contribution from major ship types and ports', Atmospheric Chemistry and Physics, 9(6), pp. 2171–2194. doi: 10.5194/acp-9-2171-2009.

International Maritime Organization (2014) Third IMO Greenhouse Gas Study 2014. London.

ISO (2002) ISO 3046-1:2002 Reciprocating internal combustion engines — Performance — Part 1: Declarations of power, fuel and lubricating oil consumptions, and test methods — Additional requirements for engines for general use. 3046–1:2002.

ISO (2016) 'ISO 15550:2016 Internal combustion engines — Determination and method for the measurement of engine power — General requirements'. Internation Standard Organization.

Jalkanen, J. P. et al. (2012) 'Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide', Atmospheric Chemistry and Physics, 12(5), pp. 2641–2659. doi: 10.5194/acp-12-2641-2012.

Kristenen, H. O. and Kristensen, H. O. (2015) 'Energy demand and exhaust gas emissions of marine engines by', (2014).

Livanos, G. A., Theotokatos, G. and Pagonis, D. N. (2014) 'Techno-economic investigation of alternative propulsion plants for Ferries and RoRo ships', Energy Conversion and Management. Elsevier Ltd, 79, pp. 640–651. doi: 10.1016/j.enconman.-2013.12.050.

De Meyer, P., Maes, F. and Volckaert, A. (2008) 'Emissions from international shipping in the Belgian part of the North Sea and the Belgian seaports', Atmospheric Environment, 42(1), pp. 196–206. doi: 10.1016/j.atmosenv.2007.06.059.

Olmer, N. et al. (2017) 'ICCT: Greenhouse gas emissions from global shipping, 2013–2015: Detailed methodology', (October), p. 59.Schreier, M. et al. (2007) 'Global ship track distribution and radiative forcing from 1 year of AATSR data', Geophysical Research Letters, 34(17). doi: 10.1029/2007GL030664.

Stoumpos, S. et al. (2018) 'Marine dual fuel engine modelling and parametric investigation of engine settings effect on performance-emissions trade-offs', Ocean Engineering. Elsevier Ltd, 157(December 2016), pp. 376–386. doi: 10.1016/j.oceaneng.2018.03.059.