Introduction to natural gas: A comparative study of its storage, fuel costs and emissions for a harbor tug

Arun Kishore Eswara [*], **S.C. Misra** [†] **and U.S. Ramesh** [†]

[*]School of Maritime Design & Research, and [†]Indian Maritime University, Visakhapatnam, India

Presented at the Annual Meeting of Society of Naval Architects & Marine Engineers (SNAME) on 8th November, 2013 at Bellevue, Washington, USA

This paper discusses the science of natural gas, its composition and ways to determine and coherently express its physical and chemical properties. Pricing of natural gas is shown with regard to weight and energy. A 60 Ton harbor tug employing either a set of constant rpm engines for CPP operation, or a set of variable rpm engines for FPP operation, with a standard load profile is made the basis for discussion. Advantage of evaluating thermal efficiency of gas engines relative to the higher heating value of natural gas, as against its lower heating value is explained. A compendium of storage options and the resulting endurance with the use of natural gas forms such as liquified gas (LNG), compressed gas (CNG) and adsorbed gas (ANG) is presented. Steps to ascertain fuel consumption of the gas engines operated according to the load profile and an approach to evaluate and relate the quantities of LNG, CNG and ANG is shown. Fuel costs and emissions from the tug operation using natural gas as fuel are evaluated per month and compared with diesel and residual fuels. Green House Gas emissions as a summation of emission constituents from the natural gas fuelled tug operation is detailed, and its need emphasized. The concepts of useful work done, emission efficiency parameter and energy efficiency parameter, which may be helpful in the design of harbor tugs and similar service vessels are proposed. The emission efficiency parameter is evaluated and analyzed for the 60 ton harbor tug.

Keywords: Natural Gas | Gas Engine | Emissions | Tug

Abbreviations: CPP, constant pitch propeller; FPP, fixed pitch propeller; Opern., operation; rpm, revolutions per minute; atm, atmospheres; HHV, higher heating value; LHV, lower heating value, STP, standard temperature and pressure; NTP, normal temperature and pressure; CNG, compressed natural gas; LNG, liquified natural gas; ANG, adsorbed natural gas; MCR, maximum continuous rating; NSR, normal service rating; cons., consumption; Qty, quantity; GPA, gas processors association; ISO, international standards organization; IMO, international maritime organisation; STW, sub-committee on standards training and watchkeeping; STCW, standards of training certification and watchkeeping; IGC, international gas code; BLG, IMO sub-committee on bulk liquids and gases; IGF, (international code of safety for gas-fuelled ships) international gas fuel code; IPCC, intergovernmental panel on climate change

List of Symbols

$\mathbf{M}$	*Molecular weight of the gas*
$\mathbf{M}_a$	*Molecular weight of air = 28.97 g/mol*
$\mathbf{M}_i$	*Molecular weight of i^{th} mixture*
$\mathbf{X}_i$	*Mole fraction of i^{th} component*
μ	*Micron 10^{-6} m dimension*
MMCF	*Units of volume in million cubic feet*
$\gamma\mathrm{g}$	*Specific gravity of natural gas*
g	*Units of mass in grams*
kg	*Units of mass in kilo grams*
$\mathbf{P}$	*Pressure*
$\mathbf{V}$	*Volume*
$\mathbf{Z}$	*Compressibility factor of natural gas*
$\mathbf{T}$	*Absolute temperature*
$\mathbf{n}$	*No. of moles*
$\mathbf{R}$	*Universal gas constant*
$\mathbf{P}_{pc}$	*Pseudo-critical pressure*
$\mathbf{T}_{pc}$	*Pseudo-critical temperature*
$\mathbf{nm}^3$	*Normal cubic meter, Cubic meter at NTP condition*
psia	*Units of pressure in pounds per square inch absolute*
barg	*Units of pressure in bar gauge*
$\mathbf{P}_{pr}$	*Pseudo-reduced pressure*
$\mathbf{T}_{tr}$	*Pseudo-reduced temperature*
ρ_g	*Gas density*
MMBtu	*Units of energy in million British Thermal Units*
SCM	*Gas volume in m^3 at STP*
SCF	*Gas volume in $feet^3$ at STP*
MJ	*Units of energy in Mega Joule*
GJ	*Units of energy in Giga Joule*
$\mathbf{X}_i$	*Molar fraction of i^{th} component*
$\mathbf{HHV}_{iv}$	*Higher calorific value of i^{th} component in kJ/m^3*
$\mathbf{HHV}_{im}$	*Molar higher calorific value of i^{th} component in kJ/kg*
$\mathbf{Mv}_i$	*Molar volume of i^{th} component as m^3/mol*
$\mathbf{M}_i$	*Molecular mass of i^{th} component expressed in g/mol*
$\mathbf{LHV}_{NG}$	*Lower Heating Value of natural gas*
$\mathbf{HHV}_{NG}$	*Higher Heating Value of natural gas*
$\mathbf{Qv}_{H_2O}$	*Heat of vaporization of water = 2259.23 kJ/kg*
$\mathbf{n}_{H_2O}$	*Number of moles of water evaporated as vapor*
$\mathbf{n}_{NG}$	*Number of moles of natural gas combusted*
$\frac{H}{C}$	*Hydrogen to Carbon ratio*
MN	*Methane Number*
MON	*Motor Octane Number*
v/v	*Volume by volume ratio*
$\mathbf{GWP}_A$	*Global Warming Potential of A^{th} constituent*
$\mathbf{EED}_{SV}$	*Energy efficiency at design for service vessels*
$\mathbf{GHG}_i$	*Equivalent CO_2 emission in the i^{th} operating condition*

1 Introduction

Natural gas is a gaseous mixture of hydrocarbons occuring in the Earth's crust. It is often found together with petroleum and coal deposits and as a hydrate on sea bed. Natural gas is also generated during decomposition of organic matter such as animal dung and in marshy areas. Composition of natural gas varies from one production facility to another [Kidnay and Parrish [27]]. Natural gas is liquefied (**LNG**) at the production facility by cooling it to -162^0C temperature at atmospheric pressure, for economical storage and transportation. In the process of liquefaction, the gas is refined and the resulting fuel is clean with about 95% of Methane. LNG is either used directly or vaporized to gas and consumed. Further, vaporized gas can be stored as a compressed gas (**CNG**) or as adsorbed gas (**ANG**) for reasons of economic storage. Natural gas is traded in terms of weight or volumes by way of LNG transportation, but it is priced in terms of energy when supplied to consumers. Specific fuel consumption of marine gas engines is calculated as a ratio of the usable energy released by combustion of gas in the engine, to the power developed by the engine in one hour. Quantity of gas consumed should be perspicuously evaluated to compute fuel costs, endurance of the vessel and emissions, which necessitates understanding the science of natural gas.

Table 1. Composition of natural gas ([Speight [47]])

Gas	Composition	Range
Methane	CH_4	$70 \sim 90\%$
Ethane	C_2H_6	
Propane	C_3H_8	$0 \sim 20\%$
Butane	C_4H_{10}	
Pentane and higher hydrocarbons	$C_{5+}H_{12+}$	$0 \sim 10\%$
Carbon dioxide	CO_2	$0 \sim 8\%$
Oxygen	O_2	$0 \sim 0.2\%$
Nitrogen	N_2	$0 \sim 5\%$
Hydrogen sulfide	H_2S	$0 \sim 5\%$
Rare gases like helium	He etc.	traces

1.1 Natural gas fuel properties

Natural gas is a colorless, odorless and tasteless gas, and is lighter than air. At atmospheric pressure, it is in gaseous state above -161^0C temperature. Natural gas composition varies at each point of origin. Its properties can be determined only after assessment of its composition; a popular technique is by gas chromatography. As shown in Table 1, natural gas contains some impurities like hydrogen sulfide, inert gases etc, which have no heat value. These impurities are removed by applying different processes, leaving mostly a hydrocarbon mixture of gases. Natural gas is further refined and the recoverable hydrocarbon gases like propane, butane are extracted based on the properties of weight, boiling point or vapor pressure of constituents. Table 2 shows some properties of processed natural gas. If more quantity of recoverable higher hydrocarbon gases are present in the natural gas, it is termed as "Rich", otherwise "Lean". Sometimes the natural gas is termed "Wet" if liquefiable ethane, propane or butane are present and "Dry" if these are absent. The refined natural gas contains some non recoverable inert gas traces, and other hydrocarbon gases. Consequently, the energy content of a specific volume of natural gas is variable, depending on the composition and is usually priced in terms of energy units. Natural gas can be equated to price per unit volume, if the reference conditions are quoted. Table 3 lists the conditions that refer to Standard Temperature and Pressure (STP).

Table 2. Properties of processed natural gas

Property	Value	Remarks
Boiling Point	-161.5^0C	@ 1 atm
Freezing Point	-182.6^0C	@ 1 atm
LNG Specific Gravity	$0.43 \sim 0.47$	rel to water = 1
Gas density	$0.7 \sim 0.9$	kg/m^3 @ STP
Flammability limits	$4 \sim 15$	by volume in air
Ignition Temperature	538^0C	@ 1 atm
Carbon content	73	by weight
Hydrogen content	24	by weight
Oxygen content	0.4	by weight
Hydrogen/Carbon atomic ratio	$3.0 \sim 4.0$	
Relative Density	$0.72 \sim 0.8$	at 15^0C
Octane Number	$120 \sim 130$	
Methane Number	$69 \sim 99$	

Table 3. STP condition.

Description	English or imperial	SI/Metric Standard	Remarks
Temperature	60^0F (dry)	15^0C (dry)	60^0F = 15.56^0C
Pressure	14.73 psia	101.325 kPa	14.73 psia = 101.56 kPa
Volume	SCF	SCM	1SCM = 35.38SCF

Normal condition (**NTP**) is defined as: Temperature = 0^0C, Pressure = 101.325 kPa (760mm Hg).

$$1nm^3 = 37.33SCF \qquad [1]$$

The physical properties of natural gas are determined by the sum of individual fractional contribution of each constituent gas. Gases exist as tiny particles in a given volume. The ratio of total number of particles of one particular gas, to the total number of particles of the entire mixture is called *mole fraction* ($\mathbf{x}_i$). This concept is the basis for determination of the final property exhibited by natural gas.

1.1.1 Specific gravity (also relative density) of natural gas.

Specific gravity of natural gas is the ratio of molecular weight of the gas to the molecular weight of air at the same temperature. For natural gas of 'N' constituents,

$$\gamma_g = \frac{M}{M_a} \qquad M = \sum_{i=1}^{N} X_i M_i \qquad [2]$$

Molecular weight of natural gas can be determined from its constituent fractions with Eqn.2 [Guo and Ghalambor [22]]. The procedure for calculation of specific gravity of natural gas, when its composition is known is detailed in Table 4.

Table 4. Determination of gas specific gravity

Constituent	$\mathbf{X}_i$	$\mathbf{M}_i$	$\mathbf{X}_i\mathbf{M}_i$
CH_4	0.901	16	14.416
C_2H_6	0.041	30	1.23
C_3H_8	0.021	44	0.924
He	0.0002	2	0.0004
N_2	0.036	28	1.008
	$\sum \mathbf{X}_i\mathbf{M}_i$		17.5784

Dry air has a molecular weight of 28.97 g/mol, which gives the specific gravity of this mixture.

$$\gamma_g = \frac{\sum_{i=1}^{N} X_i M_i}{M_a} = \frac{17.5784}{28.97} = 0.60678 \qquad [3]$$

1.1.2 Gas law . Natural gas is a real gas, i.e. it does not obey ideal gas laws. Its volume is lesser than the volume of an ideal gas due to Van der Waals forces between the atoms and / or molecules. The ratio of real volume to the ideal volume is a measure of deviation of the gas from ideal behaviour and is called compressibility factor, Z. Natural gas obeys Eqn.4 [Ahmed [3]].

$$PV = ZnRT \qquad [4]$$

The compressibility factor Z is close to 1 at high temperatures and at low pressures, approaching ideal gas behaviour owing to large separation between individual atoms or molecules. This separation lessens the effect of intermolecular forces. At atmospheric conditions it is approximately 1. At all other temperatures and pressures, determination of the compressibility Z involves finding the reduced pressures (ratio of real pressure to critical pressure) and the reduced temperatures (ratio of real temperature to critical temperature).

1.1.3 Steps to determine compressibility 'Z' of natural gas.

(Pressure should be represented in 'psia' and temperature in 'Rankine scale'. (Fahrenheit + 459.67 = Rankine))

Natural gas equations are developed in USC system where, Universal gas constant R = 10.73164 $\frac{psia.ft^3}{lb\ mol\ ^0R}$ [Menon and Menon [31]]. Compressibility factor of natural gases of various composition can be determined with sufficient accuracy using dimensionless quantities of pseudo-reduced temperature and pressure for the mixture [Ahmed [3]]. To determine these quantities, critical pressure and temperatures for a gaseous mixture should be understood. Critical pressure and temperature for a mixture of gases are called pseudo-critical pressure (P_{pc}) and pseudo-critical temperature (T_{pc}) respectively. If there are 'N' constituents of individual gases and mole fraction of 'i^{th}' constituent be '$\mathbf{y}_i$' then the pseudo-critical pressure and temperature can be determined by Eqn.5 [Mokhatab et al. [33]].

$$T_{pc} = \sum_{i=1}^{N} y_i T_{pc} \qquad P_{pc} = \sum_{i=1}^{N} y_i P_{pc} \qquad [\mathbf{5}]$$

Sutton[Sutton [49]] analyzed 264 different natural gas samples and formulated Eqs.6 and 7 to determine pseudo-critical pressure and temperature of natural gas as a function of its specific gravity. Sutton used regression analysis on raw data to obtain the second-order curve fitting for the pseudocritical properties and proposed Eqs.6 and 7.

$$P_{pc} = 756.8 - 131.07\gamma_g - 3.6\gamma_g^2 \qquad [\mathbf{6}]$$

$$T_{pc} = 169.2 + 349.5\gamma_g - 74.0\gamma_g^2 \qquad [\mathbf{7}]$$

These equations are valid over the range of specific gravities $0.57 < \gamma_g < 1.68$. Pseudo-reduced pressure ($\mathbf{P}_{pr}$) of the natural gas is defined as a ratio of pressure of the natural gas to its pseudo-critical pressure. Pseudo-reduced temperature ($\mathbf{T}_{tr}$) of the natural gas is defined as a ratio of the temperature of the natural gas to its pseudo-critical temperature. Mathematically, they are shown in Eqn.8 [Mokhatab et al. [33]] for a natural gas, which is at a pressure of ($\mathbf{P}$) and temperature ($\mathbf{T}$).

$$P_{pr} = \frac{P}{P_{pc}} \qquad T_{tr} = \frac{T}{T_{pc}} \qquad [\mathbf{8}]$$

Hall and Yarborough [Hall and Yarborough [23]] have developed a method to determine compressibility $\mathbf{Z}$ in the following steps:

$$t = \frac{1}{T_{tr}} \qquad [\mathbf{9}]$$

$$A1 = 0.06125te^{-1.2(1-t)^2} \qquad [\mathbf{10}]$$

$$A2 = t(14.76 - 9.76t + 4.58t^2) \qquad [\mathbf{11}]$$

$$A3 = t(90.7 - 242.2t + 42.4t^2) \qquad [\mathbf{12}]$$

$$A4 = 2.18 + 2.82t \qquad [\mathbf{13}]$$

$$Z = \frac{A1 \times P_{pr}}{Y} \qquad [\mathbf{14}]$$

Where, Y should be calculated as root of Eqn.15.

$$\begin{aligned} f(Y) = \frac{Y + Y^2 + Y^3 - Y^4}{(1-Y)^3} - (A1) \times P_{pr} \\ - (A2) \times Y^2 + (A3) \times Y^{(A4)} = 0 \end{aligned} \qquad [\mathbf{15}]$$

Determination of the compressibility factor Z requires solving Eqn.15 [Guo and Ghalambor [22]] using Newton-Raphson method and taking care of 'NaN's (*Not a Number*) conditions. In this paper, calculations are based on this method of solving Eqn.15 for computing compressibility Z of natural gas.

1.1.4 Gas density. Gas density 'ρ_g' is defined as mass per unit volume. For 'ρ_g' in kg/m^3, Pressure (absolute) in kilo-Pascal (kPa) & Temperature in ^{0}K,

$$\rho_g = \frac{m}{V} = \frac{PM}{ZRT} = 3.488\left(\frac{P\gamma_g}{ZT}\right) \qquad [\mathbf{16}]$$

1.2 Energy content of natural gas

The heating value or calorific value of natural gas varies depending on its constituent gases. Gross or Higher Heating Value (GHV or HHV) is the total amount of heat recoverable by complete combustion of a unit volume of natural gas at stoichiometrically correct amount of air. It is referenced commonly at 15^0C temperature (SI units) or 60^0F (US and in Petroleum industry) and at atmospheric pressure. HHV is also defined as the amount of heat in Btu released by complete combustion of 1SCF of natural gas [GPSA [21]].

Table 5. Energy content of hydrocarbon gases

Gas	HHV (MJ)/(m^3)	X$_i$	X$_i$HHV$_i$
Methane	37.694	0.89	33.54766
Ethane	66.032	0.068	4.490176
Propane	93.972	0.012	1.127664
iso-Butane	121.426	0.001	0.121426
n-Butane	121.779	0	0
n-Pentane	149.660	0	0
	$\sum$		39.286926

(at 15^0C, 1 atmosphere pressure)

Measuring specific heat released by combustion of known mass of fuel is done by calorimetry [Sherway and Jewett.Jr. [44]]. It is based on the conservation of energy principle. The energy that leaves a fuel sample (which is combusted in an apparatus) of unknown specific heat is equal to the amount of heat gained by water, which is in contact with the apparatus. At the referenced temperature (15^0C or 60^0F), hydrogen present in fuels is oxidized to water (Liquid) in the laboratory test employing calorimetry. On the other hand, if the same fuel is combusted in engines, boilers, or turbines, hydrogen is oxidized to water, which is present as vapor or steam. This is the fundamental difference, which gives rise to two calorific values; Higher Heat Value (HHV) and Lower Heat Value (LHV) for fuels. The quoted heat value at the time of purchase of natural gas is the heat value determined by a laboratory test and is the Higher Heat Value. This entire heat amount is not available in Internal combustion engines and Boilers, whose exhaust gas temperatures are higher than 100^0C (water is lost as steam). Depending on whether the final state of water is a vapor (steam) or a liquid, determination of the heat liberated gives,

1. Gross Heating Value **(GHV)** or Higher Heating Value **(HHV)**, if the water is in liquid form.
2. Net Heating Value **(NHV)** or Lower Heating Value **(LHV)**, if the water is lost as vapor or steam.

In a natural gas engine or a boiler used in ships, water formed from the combustion of fuel is lost as steam or vapor. The recoverable energy from the fuel is Lower Heating Value **(LHV)** in these machinery. A list of Higher Heating Values (**HHV**) of hydrocarbon gases and an example to evaluate HHV for a natural gas are shown in Table 5. Composition of gas is shown in column $\mathbf{X}_i$ of the table. Higher Heating Value (**HHV**) of natural gas is the sum of individual heating values of the constituents multiplied by their mole fraction. Eqs.17 to 19 show calculations for HHV and LHV [GIIGNL [19]].

$$HHV_{vol} = \frac{\sum(X_i \times HHV_{iv})}{Z} \qquad \textbf{[17]}$$

$$HHV_{mass} = \frac{\sum(X_i \times M_i \times HHV_{im})}{\sum(X_i \times M_i)} \qquad \textbf{[18]}$$

HHV of natural gas has a normal range of $37.5 \sim 39.5 MJ/nm^3$. For heat values expressed in kJ/kg, Lower Heat Value (**LHV**) can be calculated as,

$$LHV_{NG} = HHV_{NG} - Qv_{H_2O} \times \frac{n_{H_2O}}{n_{NG}} \qquad \textbf{[19]}$$

LHV range for natural gas is $33.7 \sim 35.6 MJ/nm^3$. HHV of the natural gas evaluated in Table 5 is $\frac{39.286926}{0.9977512} = 39.3755$ MJ/m^3.

1.3 Wobbe index or number

Wobbe index is an indicator for interchangeability of fuel gases [GPSA [21]], it is expressed as a ratio of HHV to square root of the gas specific gravity as shown in Eqn.20. If different gases have same Wobbe index, they will release same heat value at the burner tip for the same flow rate. It is used to obtain constant heat flows from gases of varying compositions. It represents the heating value of natural gas from the gas line at the orifice where a burner is located. The index is named after Goffredo Wobbe who formulated the ratio. It can be visualized from 'Graham's Law of rate of effusion', which states that rate of effusion is inversely proportional to the square root of the molar mass. Natural gas composition and its HHV changes significantly at each bunker station. Wobbe index suggests the changes to air to fuel ratio to ensure proper combustion of the natural gas. Gas engine makers specify a range of Wobbe indices over which the engine can be operated.

$$Wobbe\ Index = \frac{HHV}{\sqrt{\gamma_g}} \qquad \textbf{[20]}$$

γ_g is the specific gravity or relative density of natural gas. Large variations in Wobbe index will alter combustion characteristics and emissions of NO$_x$ and Carbon monoxide (**CO**) primarily [AEMO [2]]. So it is important to run gas engines in the range of Wobbe indices specified by the engine maker.

Effects of high Wobbe index [AEMO [2]] and [Edgar Cuipers [15]]:

1. Larger the Wobbe index, larger is its heating value. This leads to increased power input, as a given volume of gas contains more energy with increasing Wobbe index.
2. Higher Wobbe index decreases air to fuel ratio, leading to incomplete combustion and formation of more Carbon monoxide and soot.
3. Higher Wobbe index causes engine to mis-fire or knock due to fuel-air mixture detonation inside the combustion chamber.
4. Higher Wobbe index results in over heating or burning out of the equipment.

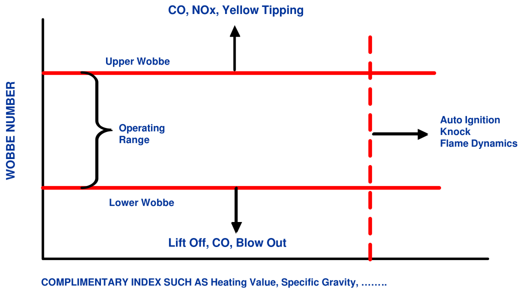


Fig. 1. Effects of changes in Wobbe index - Source:[Edgar Cuipers [15]]

The effects of variation in Wobbe index on combustion are illustrated in Fig.1.

Effects of low Wobbe index [AEMO [2]] and [Edgar Cuipers [15]]:

1. Lower Wobbe index results in an unstable flame and ignition difficulties.
2. In gas engines, it may lead to lean mis-fire. Flame could be blown off from burner or injector causing improper combustion in engines and boilers.
3. Lower Wobbe index can also result in the formation of carbon monoxide and there is a possibility of flashback in boilers.

1.4 Methane Number (MN)

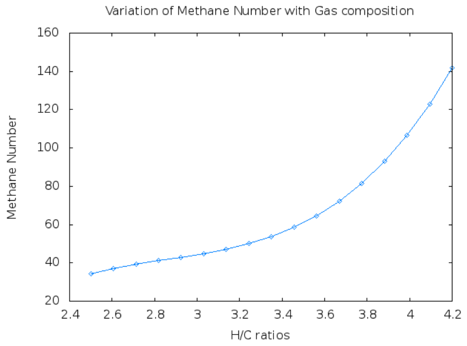


Fig. 2. Variation of Methane Number with composition of natural gas - Source:[CARB [8]]

Methane number is a relative scale of measure of the gas tendency to resist knock, when used as a fuel in a reciprocating engine. For natural gas both Motor Octane Number (**MON**) and Methane Number (**MN**) are often quoted. MON for natural gas is in the range of 120 ~ 130. Methane number for natural gas, is defined on a scale of 0 to 100. Fuel gas of pure Methane is defined as 100 *(resists knock)* and pure Hydrogen *(readily knocks)* is defined as 0. Methane number is the volumetric mixture ratio of methane and hydrogen. This scale of 0 to 100 of methane number provides information about the natural gas fuel detonation limits. MN for natural gas is normally in the range of 69 ~ 99. LNG boil off is used as a source for natural gas on ships; this would be purely methane and nitrogen (can be concluded from their boiling points). LNG boil off gas methane number would be close to that of methane, which is 100. If forced boil off from LNG is used, it would contain higher hydrocarbon fractions and hence a lower methane number. Natural boil off fuel from LNG tanks is a better source of fuel in comparison to forced boil off gas in terms of fuel knock resistance [CIMAC [11]]. Methane number is empirically found to depend on the hydrogen to carbon ratio of the gas as shown in Fig.2. The regression equation established for $2.5 < \frac{H}{C}$ and inert concentration $< 5\%$ is shown in Eqn.21 [CARB [8]].

$$\begin{aligned} MN = -778.67136 + 825.057(\frac{H}{C}) - 281.8452(\frac{H}{C})^2 \\ + 32.75608(\frac{H}{C})^3 \end{aligned} \qquad [21]$$

1.5 Flame speed

The velocity with which flame propagates in a gas or a gaseous mixture in laminar flow conditions is called 'Laminar Flame Velocity'. It is maximum when the air/fuel ratio is 1 and decreases with increasing air (lean mixture), or with increasing fuel concentration (rich mixture). This parameter together with methane number is very important for usability of the fuel in gas engines. If the gas flow speed is lesser than the flame speed in a burner, the flame will travel back and is called 'blow-back' [Downie [14]]. These define the possibility of detonation of the fuel air mixture within the combustion space, which is damaging to the engine. Natural gas is a mixture of flammable gases. So a constituent which ignites first will suffer dilution due to the presence of other constituents. In a compression ignition engine when the compressed lean mixture is ignited, the expanding flame compresses the gas inside the combustion chamber. The propagating and expanding flame will ignite lean fuel mixtures at other parts. The possibility that the mixture will knock depends on the equivalence ratio and the methane number. Marine natural gas engines evaluated in the later sections of this paper have a lower methane number limitation of about 70 for normal operation [Rolls-Royce [41]].

1.6 Accuracy of measurements

Quantification of natural gas is very important for both technical and financial assessment of the plant. The accuracy of measurement and calculations can lead to substantial variation and affect profitability. Natural gas fractional analysis is done mainly by gas chromatography, to ascertain the constituent gases and their concentrations. Commercially HHV of the gaseous mixture is determined by applying GPA standard 2145-03. The standard provides for conversion from the concentration of constituent gases to HHV/SCF, by multiplying constants for each constituent. GPA specifies an accuracy of these constants as no more than 1 Btu in 1000 Btu measurement [MATHESON [30]]. The manufacturers of measuring instruments certify that their instruments have a precision of about 0.5 in 1000 or ±0.5 Btu in 1000 Btu measurement.

1.7 Natural gas quality

Natural gas quality primarily is based on calorific value, methane number, Wobbe index and flame speed. Further these values are dependent on the composition of the gas. GPA 2145-03 approach to determine HHV/SCF is a quality parameter, which gives energy available per standard cubic feet of the gas. To facilitate leak identification, certain odorizers are added which may or may not be sulfur based mercaptans. The odorizers have a safety requirement of facilitating leak detection at a concentration of $1/5^{th}$ of their lower explosive limits [GPSA [21]]. The gas sulfur content should not exceed certain limits to prevent SO_x emissions from its combustion. Presence of water will damage components by corrosion and blockage, through ice formation. All the factors discussed essentially describe the quality of natural gas. Some of the known international quality parameters are shown in Tables 6 to 8.

1.7.1 Classification of natural gas in Europe EN437. Europe has adopted a Gas families and groups approach for classifying fuel gases, which is based on Gross Wobbe index at 15^0C and 1013.25 milibar. Natural gas grades used in marine applications can be summarized as in Table 6.

1.7.2 Classification of natural gas in United States. US GPA specifies the pipe line quality of the natural gas as shown in Table 7. The quality parameters are constituent gas concentrations, HHV/SCF, sulfur content in gas, odorizer in the gas and purity in terms of presence of water and solids.

Table 6. Second family class gases EN437:2003 ([Marcogaz [29]])

Gas families	Gross Wobbe Index (MJ/m^3) @ 15^0C & 1013.25 mbar	
	Minimum	**Maximum**
Second Family	39.1	54.7
Group H	45.7	54.7
Group L	39.1	44.8
Group E	40.9	54.7

Table 7. Pipeline quality of natural gas ([GPSA [21]])

Description	Minimum	Maximum
Methane	75	-
Ethane	-	10
Propane	-	5
Butane	-	2
Pentane and heavier	-	0.5
Nitrogen and other inerts	-	3
Carbon dioxide	-	$2 \sim 3$
Total diluent gases	-	$4 \sim 5$
Hydrogen sulfide	-	$0.25 \sim 0.3$ g/100SCF
Mercaptan sulfur	-	-
Total sulfur	-	$5 \sim 20$ g/100SCF
Water vapor	-	$4.0 \sim 7.0$ lb/MMCF
Oxygen	-	1.0%
Heating value (Btu/SCF)	950	1150
Solids	-	$3 \sim 15\mu$

Table 8. Gas quality and safety values ([AEMO [2]])

Parameter	Injection Limit	Units
Wobbe Max	52	MJ/m^3
Wobbe Min	46	MJ/m^3
Oxygen Max	0.2%	Mol %
H_2S Max	5.7	mg/m^3
Sulfur Max	50	mg/m^3
Water dew point	0^oC	@15000 kPa
Water content Max	73	mg/m^3
Total Inerts Max	7 %	mol %
Gas Odorisation Min	7	mg/m^3
Gas Odorisation Max	14	mg/m^3
Hydrocarbon dew point	2^0C	3500 kPag
Temperature Max	50^0C	
Temperature Min	2^0C	

1.7.3 Classification of natural gas in Australia. Australian Energy Market Operator Ltd. [AEMO [2]] specifies gas quality in terms of practical parameters for usage of the gas. The parameters shown in Table 8 are Wobbe index, purity, sulfur and water.

1.8 Natural gas as fuel on ships

Gas-fuelled ships are much sought in maritime industry today, primarily due to cheaper price of the natural gas compared to diesel and residual bunkers and to comply with recent pollution legislations. IMO's initiative for reducing emission of GHG's, NO_x and SO_x and discovery of shale gas which has lowered natural gas prices in a market of rising oil prices has shifted attention to the use of natural gas. Use of natural gas as marine fuel demands frameworks or standards to safely store, bunker, design, man and operate gas ships. Some frame works developed and / or in the development stage include:

1. ISO TC 67/WG 10 (Guidelines for systems and installations for supply of LNG as fuel to ships) is a frame work developed for utilizing natural gas as fuel for ships and marine crafts.
2. STW 44/17/2 (USA), STW 44/17/3 (Norway) and STW 44/17/4 (Denmark) relating to training requirements for officers and crew on board ships using low-flashpoint fuels, and proposals to amend the STCW Convention and Code - submitted to sub-committee on STW.
3. IMO Interim guidelines on safety for natural gas fuelled engine installations in ships adopted in June 2009 MSC.285(86)
4. The revised draft of International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (the IGC Code) was agreed upon by the Sub-Committee on Bulk Liquids and Gases (BLG). It will be considered by IMO's MSC for adoption in 2014.
5. New international code of safety for ships using gases or other low-flash point fuels (IGF Code).
6. Classification societies have formulated rules to facilitate use of natural gas as fuel in ships safely.

Table 9. Technology status for use of natural gas.

(**Source:**Internet)

State	Description	Technology status
Liquid	Liquefied Natural Gas or LNG	Developed / Commercial
Pressurized Gas	Compressed Natural Gas or CNG	Developed / Commercial
Pressurized Gas	Adsorbed Natural Gas or ANG	Developed / Research
Solid	Methane Hydrates	Developing

1.9 Natural gas storage - Status of present technology

Gases are made up of a number of atoms or molecules, which tend to occupy whole of the volume they are confined to. The gas density is quite low compared to solids or liquids. This is a major drawback for use of natural gas in gaseous state on ships. For fuels, the energy density follows the order - solids > liquids > compressed gases > gases. Table 9 shows storage options for natural gas and availability of the storage technology for commercial application. Ability to store more energy in a given volume increases endurance of the vessel and reduces bunkering intervals, associated costs and interruption to the ship's activity. Comparison of energy density of common marine fuels is shown in Table 10. To increase the energy density, natural gas can be compressed, cooled or adsorbed or dissolved in media. CNG is a compressed natural gas stored or transported as a pressurized gas at about 250 barg . ANG has been developed as an alternative to CNG to reduce stored pressure. It is the storage of natural gas at about 35 barg with equivalent energy density as that of CNG. This is a safer option as we have gas at reduced pressures. Also this would mean less work is required to compress natural gas, which ultimately results in reduced filling times. Research to make natural gas dissolve in liquids for increased energy density is being undertaken at Oklahoma University in US [Starling et al. [48]]. Table 10 shows a comparison of liquid marine fuels and natural gas. The energy density is energy content per cubic meter of gas. Tank volume shown in the table considers the 'fill ratio' and minimum volume of LNG retained in the cryogenic tank to maintain its temperature.

1.9.1 Adsorbed Natural Gas (ANG).

Storage of natural gas at pressures in excess of 200 barg increases the stored energy and is a potential risk. Increasing potential energy of a flammable gas by way of increasing pressure (compression) for storage, is a potential explosion hazard. ANG was developed to reduce this risk of stored energy and at the same time achieve CNG equivalent energy density. Storage of natural gas at lesser pressure saves energy required for compression. ANG has an advantage over LNG, as it does not require energy for cooling. Increasing the energy density (storage) means packing more gas particles in lesser volumes. This involves increasing pressure as pressure is inversely related to volume for a gas. Physical properties of a gas such as pressure, heat(temperature) are a measure of kinetic energy of all the constituent gas particles. LNG with a higher energy density is achieved with removal of heat (cooling), meaning reducing the kinetic energy of the constituent gas particles. CNG has interstage and afterstage cooling processes (not comparable to liquefaction) to keep the gas temperatures low during compression. The processes involved are aimed at effectively reducing movement of the gas particles. ANG is based on similar principles of reducing kinetic energy of constituent gas particles by keeping a highly porous medium inside the tank. The porous medium adsorbs (penetration of methane gas into solid porous structure) methane and reduces gas to gas and gas to cylinder walls collisions. Also the attractive forces *(Van der Waals)* between the porous medium and methane molecules augment this effect. This in effect minimizes the gas particles movement or kinetic energy of the gas constituents [Solar et al. [46]]. The important properties of the porous medium are its density (reflects weight), surface area (more surface means highly porous), chemical properties (reactivity with natural gas and gas retention), mechanical strength and price. Fig.3 shows possibilities of pores [Rouquerol et al. [43]].

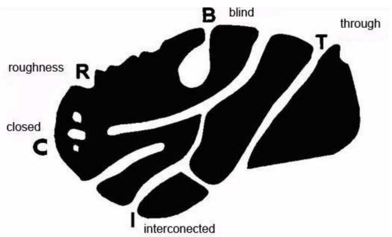


Fig. 3. Analysis of pore showing increased surface area, [Rouquerol et al. [43]] - Source: [Solar et al. [46]]

Increased roughness and smaller pores give more surface area. Larger surface areas allow large quantity of methane adsorption and storage of more concentration of gas at lower pressures. ANG storage efficiency is shown by a volumetric ratio, which is the maximum capacity of gas stored per net storage space of the container. For example a 100 liter container of volumetric efficiency 190 v/v would store 19000 liters of gas. Theoretically 270 v/v ratios are possible [Judd et al. [26]], but 180 v/v has been attained in laboratory [Menon and Komarneni [32]]. CNG tanks have a volumetric ratio of 200 v/v while LNG tanks have 615 v/v [Ginzburg [20]]. It should be noted that the volumetric efficiency is quoted at the rated pressure and ambient temperature. Rated pressure for ANG is 35 bar, while CNG is about 200 $\sim$ 250 bar.

2 Natural gas fuelled harbor tug

2.1 Efficiency of engines

Manufacturers publish engine thermal efficiency figures based on LHV of the fuel consumed. For gas engines it is prudent to know

Table 10. Energy density of marine fuels and natural gas.

Fuel	LHV	Density	Energy Density	Tank weight-volume
	(MJ/kg)	(kg/m^3)	(GJ/m^3)	(approx. relation for) (vol in liters, weight in Kg)
LNG	48.632	428.22	20.825	$0.23 \times vol$
CNG	47.141	182.14 @ 200barg	8.586	$0.67 \times vol$ (Fiber) $0.43 \times vol$ (carbon)
ANG(190 v/v)	47.141	148 @ 35 barg	7	$0.43 \times vol$
Natural Gas	47.141	0.7769	0.0366	NA
MDO/MGO	42.612	846.94	36.089	$0.072 \times vol$
HFO	40∼42.5	989.1	39.564∼42.036	$0.073 \times vol$
ICE Gas Oil	42.79	836.63	35.80	$0.072 \times vol$

(Extrapolated data from: [ANL [5]], [Bengtsson et al. [6]], [Sinor [45]])

Table 11. Engine data and efficiency relative to HHV of fuel used

Engine Specification	MCR	Thermal Efficiency	SFOC or SFGC	Fuel		Thermal Efficiency
	(kW)	(quoted)	(per kW-hr)	LHV	HHV	(wrt HHV)
Wartsila 9L20 (Diesel)	1800	45.6	185g	42.7 MJ/kg	45.6 MJ/kg	42.67
Wartsila 6L26 (Diesel)	2040	45.8	184g	42.7 MJ/kg	45.6 MJ/kg	42.91
Rolls Royce (Gas) C26:33L8PG	2160	48	7500 kJ	36 MJ/nm^3	39.96 MJ/nm^3	43.24

the engine thermal efficiency relative to HHV of the fuel consumed, as the gas bunkers are priced for their HHV. This approach conflates the technical and commercial approach, as the thermal efficiency so calculated also reflects the percentage of fuel price converted to useful work. Table 11 shows efficiency of engines for tug, worked out relative to HHV of the fuel used. Conditions for which the SFOC (Liquid fuelled engines) or SFGC (Gas engines) is quoted is shown in Table 12. The engine's thermal efficiency (quoted by maker) is calculated using Eqs.22 to 25.

Table 12. Engine reference conditions

Quantity	Description
Power Rating	max 45^{0}C ambient air temperature, 38^{0}C sea water temperature (ISO 3046-1)
SFOC	for Marine Diesel Oil, LHV 42.7 MJ/kg and with no engine driven pumps (for each, 0.5% SFOC additional)(as per ISO 15550:2002 E)
Power Rating	max 45^{0}C ambient air temperature, 32^{0}C sea water temperature (ISO 3046-1)
SFGC	for natural gas feed pressure at 4.5 barg, temperature 20-40^{0}C, LHV 36 MJ/nm^3 and Methane Number of 70 and above. Figures are quoted with no engine driven pumps (for each, 0.5% SFOC additional)

(Source: Wartsila & Rolls Royce Bergen respectively)

$$\text{Engine output} = MCR \times Time \quad [\mathbf{22}]$$

$$\text{Heat Input} = SFOC \times MCR \times LHV \times 1000 \quad [\mathbf{23}]$$

For SFOC in g/kWh, MCR in kW and LHV in MJ/kg.

$$\eta_{thermal} = \frac{\text{Engine output}}{\text{Heat Input}} \quad [\mathbf{24}]$$

$$\eta_{thermal} = \frac{3600}{SFOC(g/kWh) \times LHV(MJ/kg)} \quad [\mathbf{25}]$$

The equations applied for gas engines are similar except for Eqs.23 and 25, which should be replaced by Eqn.26.

$$\eta_{thermal} = \frac{3600}{SFGC(kJ/kWh)} \quad [\mathbf{26}]$$

2.2 Natural gas price - Comparison with marine liquid fuels

Table 13. Energy pricing perspective

Item	Units	Market Price	Price Weight	Price Energy
			USD/MT	USD/GJ
Natural gas	USD/MMBtu	4.06	185.7	3.85
ICE Gas Oil	USD/MT	876	876	19.5
IFO 380	USD/MT	585.5	585.5	14.4
IFO 180	USD/MT	654	654	15.6
MGO	USD/MT	955.5	955.5	21.4

(As on 18th May 2013)

Energy pricing from market[1] data [2] is shown in Table 13 with regard to weight and energy content. It should be noted that the typical distillate (MGO/MDO) and residual (HFO) fuels are priced in \$/metric-tonne and are representative of fuel available in ports worldwide. Usually, these liquid fuels' bunkering delivery costs increase 1 to 2 % over the fuel cost quoted as market price. Here in the following calculations, an increment by 1.5% over market price is used to depict the fuel costs in harbor tug operation. On the other hand, natural gas fuels' price at delivery to ships or tugs can significantly vary from its market price. The inflated price of natural gas delivered to a ship is due to transportation, storage, reliquifaction, compression or other tariff. These supply chain costs should be accounted for fuel costing for harbor tug operation. In this paper, fuel costing with respect to 10 \$/MMBtu and 15 \$/MMBtu

---

[1] Natural gas & ICE Gas oil - are from Bloomberg on 18th May 2013

[2] Marine Bunker Prices - are from www.bunkerworld.com on 18th May 2013

are shown for natural gas [Robert Allan et al. [40]]. These values are projected to bring out a realistic picture. Natural gas of HHV MJ/m^3 metric standard, with a Wobbe index of 'Wobbe' (data shows a perspective of a 50 Wobbe index fuel gas) is priced in the market in USD/Energy units. The pricing can be extrapolated for USD/(Unit weight) by using Eqs.27 to 32.

$$PV = ZnRT = \frac{m}{M} ZRT \tag{27}$$

$$Wobbe = \frac{HHV}{\sqrt{\gamma_g}} \tag{28}$$

$$\implies M = M_a \times \left(\frac{HHV}{Wobbe}\right)^2 \tag{29}$$

$$\implies m = \frac{PVM}{ZRT} \tag{30}$$

Where, m is the mass of gas.

$$\therefore \text{mass of } 1m^3 \text{gas} = \frac{(1.01325 \times 10^5 \times 0.018504)}{(0.996902 \times 273.15 \times 8.3145)} \tag{31}$$

$$= 0.82812 \text{ kg @ NTP} \tag{32}$$

2.3 Assessment of natural gas requirement[3]

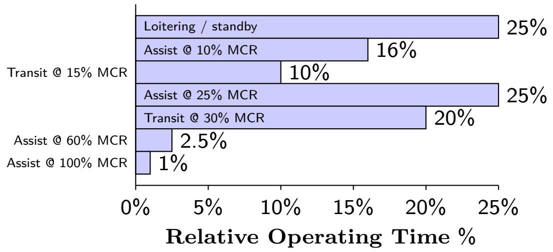


Fig. 4. Load profile [Van der Linden et al. [53]]

Gas bunker requirement is estimated using the gas consumption plots available for a bergen K-gas engine[4], which are shown in Figs.5 and 6. The plots are modelled to an approximate mathematical function and are superimposed on the load profile [Van der Linden et al. [53]], shown in Fig.4 for a 60 Ton harbor tug; to evaluate consumption at each point of operation. The following analysis is about propulsion engines alone. The 60 Ton harbor tug is discussed with two installed engines operated according to the load profile, with each rated at 1800 kW at NSR for gas and 1800kW at MCR for diesel options. The gas energy costing calculations for each mode of operation - constant rpm (CPP) and variable rpm (FPP) are shown in Eqs.33 to 37. A harbor tug does not operate according to a pure CPP operation [Robert Allan et al. [40]], but in the absence of valid data of a representative combinator curve that harbor tugs adopt, a theoretical CPP scenario is illustrated.

$$HHV = 1.11 \times LHV \tag{33}$$

$$\text{Engine output} = Power \times Time \tag{34}$$

$$\text{Engine input} = \text{Engine output} \times SFGC \tag{35}$$

$$\text{Gas energy input} = \text{Engine input} \times 1.11 \tag{36}$$

$$\text{Price of Engine output} = \text{Gas Price} \times \text{Gas energy input} \tag{37}$$

Eqn.33 is valid for GPA pipeline quality gas. Eqn.35 yields LHV of the gas consumed and Eqn.36 yields HHV of the gas consumed by the engine in one hour. For natural gas bunkers priced at 10 \$/MMBtu and for a tug operated with FPP, one engine at NSR consumes - *(1MMBtu = 1055 MJ)*

$$10 \times \frac{1800 \times 1(hour) \times 8.624 \times 1.11}{1055} = 163.33 \ \$/hour.$$

In general terms, gas cost per hour of engine operation can be calculated as:

$$\text{Gas Price (\$/MMBtu)} \times \frac{P \times SFGC_P \times 1.11}{1055} \tag{38}$$

Where, P is power developed by the engine and SFGC$_P$ is its corresponding SFGC value. The following calculations show an annual assessment carried out for a harbor tug, having about 3500 running hours in one year.

CPP operation is indicative of performance of an engine as constant speed engine only. It may not be applicable to a harbor tug. [Robert Allan et al. [40]]. ***However, it is an important inclusion for developing an understanding of the behavior of gas engines.***

2.4 CPP operation

The following approach is employed for calculating volume consumption of natural gas engine:

1. Given: HHV = 39.96MJ/nm^3; Metric standard, Wobbe = 50, SFGC (MJ/kWh)
2. To calculate: Volume consumption of gas in m^3/hr at 4.5 barg, 40^{0}C

$$PV = ZnRT \tag{39}$$

$$\implies \frac{P_1V_1}{Z_1T_1} = Constant \tag{40}$$

$$\frac{1.01325 \times 1}{0.996902 \times 273.15} = \frac{5.51325 \times V}{0.9893126 \times 313.15} \tag{41}$$

$$\implies V \approx 0.21m^3 \tag{42}$$

1m^3 of gas at 1.01325 bar and 0^{0}C (NTP) would contain the same amount of Higher Heating Value as 0.21m^3 of gas at 40^{0}C and 4.5 bar gauge pressure. Volume consumption (m^3/h), of the engine at a power P kW and SFGC$_P$ at the power P in MJ/kWh would be:

$$\frac{0.21 \times 1.11}{HHV \times 1nm^3} \times SFGC_P \times P \tag{43}$$

In general terms, gas consumption per hour can be calculated as:

$$\frac{SFGC_P \times P \times 1.11}{\text{Corrected HHV for inlet condition}} \tag{44}$$

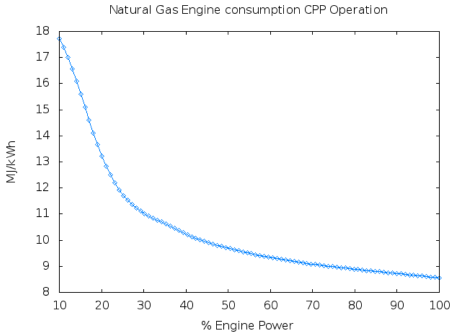


Fig. 5. Gas consumption of the engine as constant rpm operation (source: Mathematical model of Rolls Royce Bergen data)

---

[3] Any Gas Engine tuning for installation is not considered.

[4] K-Gas Engines individual power and consumption may be different from these modelled curves. Maker has indicated that the figures will change due to constant engine development.

Table 14. Gas consumption for CPP operation - Yearly figures

(Fuel costing as on 18^{th} May 2013)

Operation	Load Factor	Utility Factor	SFGC (MJ/kWh)	Consumption		Thermal Efficiency		Gas Price US$	
				Volume (m^3)	Energy (GJ)	LHV	HHV	($10/MMBtu)	($15/MMBtu)
Loitering	0.05	0.25	17.8	16283.17	3111.885	20.22	18.22	29496.54	44244.81
Assist	0.1	0.16	17.724	20753.47	3966.21	20.3	18.3	37594.37	56391.55
Transit	0.15	0.10	15.6	17124.77	3272.72	23.1	20.8	31021.08	46531.62
Assist	0.25	0.25	11.7	53514.92	10227.26	30.77	27.7	96940.88	145411.32
Transit	0.30	0.20	11.0	48300.64	9230.76	32.73	29.5	87495.36	131243.03
Assist	0.60	0.03	9.3	12250.8	2341.26	38.71	34.9	22192.0	33288.0
Assist	1	0.01	8.54	6249.81	1194.4	42.16	37.98	11321.37	16982.05
	$\sum$			174477.6	33344.5	29.29	26.39	316061.59	474092.39

Table 15. Gas consumption for FPP operation - Yearly figures

(Fuel costing as on 18^{th} May 2013)

Operation	Load Factor	Utility Factor	SFGC (MJ/kWh)	Consumption		Thermal Efficiency		Gas Price US$	
				Volume (m^3)	Energy (GJ)	LHV	HHV	($10/MMBtu)	($15/MMBtu)
Loitering	0.05	0.25	10.76	9843.09	1881.12	33.46	30.14	17830.49	26745.74
Assist	0.1	0.16	10.754	12592.12	2406.49	33.48	30.16	22810.3	34215.46
Transit	0.15	0.10	10.19	11186.0	2137.76	35.33	31.83	20263.13	30394.7
Assist	0.25	0.25	9.38	42903.41	8199.3	38.38	34.58	77718.412	116577.62
Transit	0.30	0.20	9.15	40177.35	7678.314	39.34	35.44	72780.23	109170.34
Assist	0.60	0.03	8.65	11394.56	2177.62	41.62	37.5	20640.95	30961.43
Assist	1	0.01	8.624	6311.28	1206.15	41.74	37.6	11432.73	17149.1
	$\sum$			134407.8	25686.74	38.03	34.26	243476.2	365214.36

For the two engines, the likely gas volume required at engine inlet for 3500 running hours (annual), when operated in the referenced load profile is **174477.6m^3** (at 40^{0}C and 4.5 bar gauge pressure). Total energy bill for the two propulsion units would be approximately **\$316061.59** $\sim$ **\$474092.39**. Net thermal efficiency will be **29.29%**. In other words, **26.39%** of energy bill appears as meaningful work done by the propulsion units. The figures will differ with quality of natural gas. The calculations are based on HHV value of 39.96 MJ/nm^3, which is a standard value used by Rolls Royce and other gas engine makers. The calculated values for each load point of the engine is shown in Table 14.

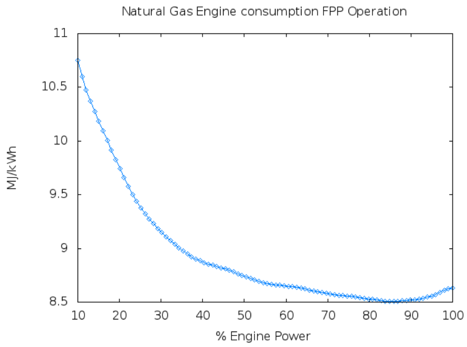


Fig. 6. Gas consumption of the engine for FPP operation (source: Mathematical model of Rolls Royce Bergen data)

2.5 FPP operation

Table 15 shows the gas consumption for the tug fitted with two gas engines and fixed pitch propeller. The improved propulsion efficiency reflects in the cost savings of the gas price. For the two propulsion units in FPP operation, the likely gas volume required at engine inlet per 3500 running hours (annual) in load profile operation is **134407.8m^3** (at 40^{0}C and 4.5 bar gauge pressure). Total energy bill for the main propulsion units would be approximately **\$243476.2** $\sim$ **\$365214.36**. Net thermal efficiency will be **38.03%**. In other words, **34.26%** of energy bill appears as meaningful work done by the propulsion units. The calculations are based on the standard HHV value.

Table 16. Natural gas densities

Gas	Liquid density kg/m^3 @ boiling point 1.01325 bar	Gas density Kg/m^3 @ STP
Methane	422.62	0.68
Ethane	546.49	1.282
Propane	582	1.91
n-Butane	601.4	2.52
i-Butane	593.4	2.51
Nitrogen	808.607	1.185
Helium	124.96	0.169

(Source: [CCNR/OCIMF [10]] and [Airliquide [4]])

2.6 Liquid volume of the gas consumed

Application of gas laws is valid only for gaseous state. When there is a change of state, either from liquid to gas or from gas to liquid the volumes differ significantly. There are gas law models that when applied to real gases, can produce results with a fair degree of accuracy during changes of state. These models are often complex. [Airliquide [4]] has valuable information on gas properties and gas-liquid conversions. A method based on conservation of mass, that approximates LNG (liquid) volume from a volume of gas at known conditions is explained below:

1. Convert quantity of gas requirement to STP condition, 15^{0}C, 1.01325 bar. (Eqs.45 $\sim$ 47)
2. From the composition of natural gas estimate individual constituent fractional volumes at STP.

3. Using Table 16, calculate mass of each constituent = (constituent vol @ STP)×(constituent gas density @ STP).
4. Using Table 16, calculate equivalent liquid volume = (Mass)/(Liquid density).
5. Summation of each of the constituent volume gives approximate LNG requirement.

For example, calculation for FPP opern. for gas engine consumption (from Table 14) is shown in Table 17 for a natural gas made up of Methane - 90.1%, Ethane - 4.1%, Propane - 2.1%, Helium - 0.02%, Nitrogen - 3.6% (by volume). In the following steps a HHV correction at STP condition is applied, to account for the change in natural gas composition.

$$\text{Volume consumption @ STP} = 134407.8 \times 5.04422 \quad \textbf{[45]}$$

$$= 677982.51m^3 \quad \textbf{[46]}$$

$$\text{Applying HHV correction @ STP, Volume} = 662650.2m^3 \quad \textbf{[47]}$$

LNG volume required = 1105.2m^3 for annual FPP operation of the harbor tug. Normally a 5% filling ratio *(for thermal expansion)* is suggested for the LNG cryogenic storage tanks (LNG tank should not be filled above 95% of its total volume). Some amount of LNG should always be stored (not emptied completely) to keep the cryogenic storage tank cool. Otherwise during bunkering, it should be cooled first either by using nitrogen or LNG from the bunker station. If 5% of the tank is to be kept full always to keep the tank at optimum temperatures, net cryogenic tank volume required = 1228 m^3 (FPP annual operation). CNG net volume is usually quoted as liquid volume of each cylinder. Bottles are available with 200 barg pressure to 250 barg pressure. For example, a CNG bottle of 1000 Liters at 200 barg can hold a gas volume of 245.2 m^3 at ambient temperature and pressure. Approximate CNG and ANG storage net volumes required for the equivalent storage is shown in Table 18.

Table 17. LNG volume estimation for FPP operation - Monthly figures

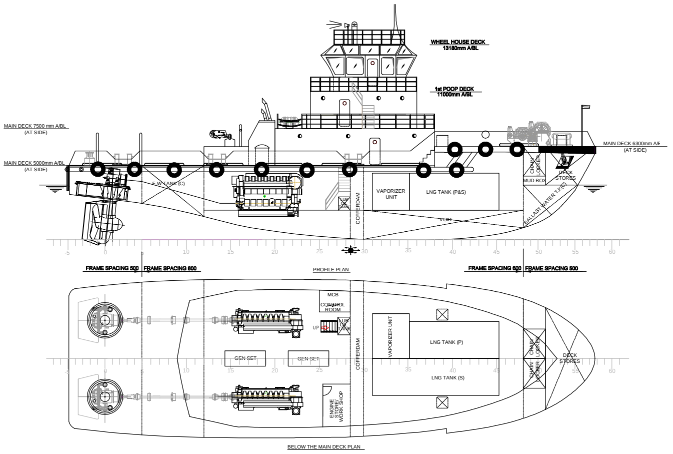
Gas	Gas Vol. m^3 @ STP	Mass @ STP kg	Liquid Vol. m^3
Methane	597047.9	405992.6	960.7
Ethane	27168.7	34830.2	63.7
Propane	13915.7	26578.9	45.7
Helium	132.5	22.4	0.2
Nitrogen	23855.4	28268.7	35
	$\sum$		1105.2

Table 18. Natural gas options and volume requirement for the 60 ton harbor tug - Monthly bunkering

Opern.	Gas Vol(m^3), 40^{0}C (@ 4.5barg)	CNG Net Vol(Nm^3)	LNG Net Vol(m^3) (Cryogenic)	ANG Net Vol(m^3), 40^{0}C (190v/v @ 35barg)
CPP opern.	14539.8	69491.1	132.8	419.7
FPP opern.	11200.7	53532.3	102.3	323.4

2.7 Tug design

Here, a natural gas fuelled 60-Ton bollard pull harbor tug is designed with a provision to store gas, either as LNG or CNG. ANG storage is likely to be similar to that of CNG arrangement. The General Arrangement shown in Fig.7, is standardized for the harbor tug with natural gas as fuel. The endurance of the vessel with LNG option is shown in Table 19 and that with CNG option is shown in Table 20. LNG option is found to give about 8% more endurance compared to CNG option with the present configuration. CNG storage within an enclosed space such as the tank room of the tug illustrated in Fig.8, is permitted only if there are certain safeguards to limit dangerous accumulation of pressures in case of failure of the CNG containment bottles and subsequent fire. IMO Interim guidelines - resolution MSC.285(86) (adopted on 1 June 2009) has mentioned the requisite safeguards. LNG storage by tanks of IMO type 'C' with a maximum allowable working pressure (**MAWP**) exceeding 10 bar is not permitted within an enclosed tank room [USCG [50]]. When tank room is used for housing CNG containers, a high capacity pressure relief vent should be fitted to the tank room. Access to the tank room is provided from the open deck area by means of hatch openings and ladders. Evaporators required for vaporizing LNG for use in engines are accommodated within the tank room.



Tug Particulars

Length O.A	35.00 meters
Length B.P	32.00 meters
Length W.L	34.00 meters
Beam, moulded	10.75 meters
Depth, moulded	5 meters
Design draft	3.7 meters
Free running speed	12 Knots
Bollard Pull	60 Ton

Fig. 7. General Arrangement of Tug

2.7.1 LNG Option. LNG is accommodated in the tank room shown in the General Arrangement using EN 13458 pressurized cryogenic tank. The tank consists of outer and inner stainless steel tanks, with the annular space under vacuum and with perlite insulation. Specification of LNG tanks proposed for endurance evaluation are shown in Fig.8. Filling of the LNG tanks is limited to 95% of its volume, to facilitate thermal expansion of the cryogenic liquid. The tanks are located longitudinally in the compartment to minimize sloshing, which may otherwise enhance boil-off rate of the cryogenic liquid. It is expected that in future, this configuration will be accepted by the statutory bodies with certain safeguards. In case the harbor tug is not in operation for longer periods, occasional starting of the engines or consumption of the gas for power generation will prevent pressure build up inside the cryogenic LNG tanks. The endurance with LNG option can be increased with custom made tanks which can be tailored to have a high volumetric efficiency in the tank room. The tanks will incorporate connections for filling (bunkering) or cooling the tanks. Each tank is fitted with safety relief valves, venting out to safe outside atmosphere. The venting may be provided based on tanker ships' guidelines.

Container	Length	OD	Tare	Water Vol.	CNG Vol.	Pressure
	(m)	(mm)	(kg)	(Liters)	(Nm^3)	barg
FIBA-3299	7.6	559	1903	1538	428	227

CNG Container - source: FIBA Technologies inc, USA - www.fibatech.com

Tank	Gross Vol	Net Vol 95%	OD	Height	Length	Tare kg
	(Liters)	(Liters)	(mm)	(mm)	(mm)	18 barg tank
HT 20	20130	19124	2500	2760	7384	11710
HT 26	26110	24805	2500	2760	9215	14150

LNG ISO tank - source: CHART Industries Group D&S, - www.chart-ferox.com

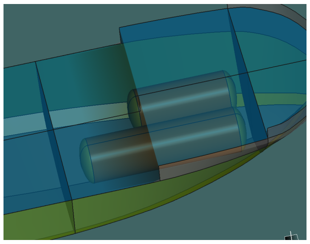


Fig. 8. Tank room 3D model showing EN 13458 LNG Cryogenic tanks (20.13 + 26.11) m^3

Table 19. Load profile operation - LNG option

Opern.	Net Volume required	Net Volume available	Endurance
	(per month m^3)	(m^3)	(Days)
CPP opern.	132.8	43.929	∼ 9.9 days
FPP opern.	102.3	43.929	∼ 12.9 days

2.7.2 CNG and ANG option. CNG storage is achieved by means of high pressure seamless steel pressure vessels (ASME) arranged in saddle racks inside the tank room. Each pressure vessel will be fitted with safety relief valves, venting out to safe outside atmosphere. Bunkering options either by filling the CNG vessels or by replacing the entire CNG battery are possible. The dimensions of ANG storage are expected to be similar to that of the CNG arrangement system. CNG pressure vessels details are specified in Fig.8 and the endurance estimated is presented in Table 20. Large storage options for ANG can be custom made and similar endurance can be expected.

Table 20. Load profile operation - CNG option - 10x5 Containers

Opern.	Net Volume required	Net Volume available	Endurance
	(per month nm^3)	(nm^3)	(Days)
CPP opern.	69491.1	21400	∼ 9.2 days
FPP opern.	53532.3	21400	∼ 11.9 days

3 Harbor Tug with Diesel / HFO as Fuel

SFOC to engine power approximate relation is worked out analyzing data from major engine makers - Cummins, MANBW, Caterpillar and Wartsila . The obtained relations are plotted as shown in Figs.9 and 10. These are the basis for the evaluation of diesel fuel consumption at each load point of the harbor tug operation. A 1.5% price hike over the market price of MGO and HFO is used to reflect fuel cost delivered to the tug.

3.1 CPP operation

For the two propulsion units in CPP operation, the likely consumption of fuel oil for yearly running hours of 3500 and according to the referenced load cycle operation is **613.32 MT**. Money spent on MGO and HFO-380 bunkers for the main propulsion units would be approximately **$594817.67** and **$364485.34** respectively. Net thermal efficiency will be likely **30.17%**. In other words, **28.25%** of bunker's bill appears as meaningful work done by the propulsion units. The values may change with quality of bunkers. Table 21 details the calculations.

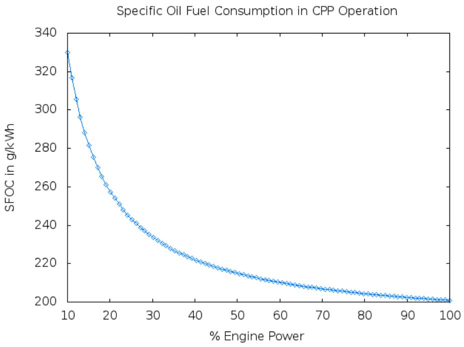


Fig. 9. Oil fuel consumption of main engine for CPP operation

3.2 FPP operation

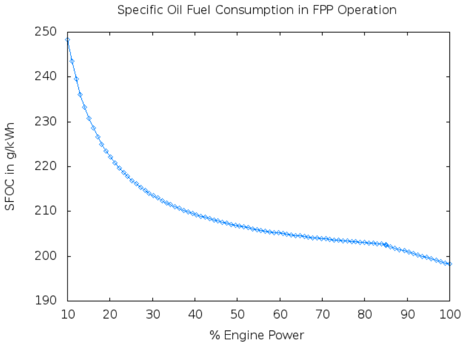


Fig. 10. Oil fuel consumption of main engine for FPP operation

For the two propulsion units in FPP operation, the likely consumption of fuel oil per 3500 running hours (annual) and while in operation according to the referenced load profile is **536.8 MT**. Money

Table 21. Oil consumption for CPP operation - Yearly figures

Operation	Load	Time	SFOC	Cons.	Thermal Efficieny		Oil Prices	
	Factor	Factor	(g/kWh)	Quantity	LHV	HHV	USD ($)(18th May 2013)	
				(MT)			**MGO**	**HFO**
Loitering	0.05	0.25	330.036	51.98	25.55	23.92	50411.89	30890.8
Assist	0.1	0.16	330.036	66.54	25.55	23.92	64532.655	39543.558
Transit	0.15	0.10	281.774	53.26	29.92	28.01	51653.279	31651.486
Assist	0.25	0.25	243.44	191.71	34.63	32.43	185926.589	113929.898
Transit	0.30	0.20	233.9151	176.84	36.04	33.75	171505.179	105092.917
Assist	0.60	0.03	210.2494	47.68	40.1	37.55	46241.614	28335.39
Assist	1.0	0.01	200.8766	25.31	41.97	39.3	24546.461	15041.29
	$\sum$			613.32	30.17	28.25	594817.67	364485.343

Table 22. Oil consumption for FPP operation - Yearly figures

Operation	Load	Time	SFOC	Cons.	Thermal Efficieny		Oil Prices	
	Factor	Factor	(g/kWh)	Quantity	LHV	HHV	USD ($)(18th May 2013)	
				(MT)			**MGO**	**HFO**
Loitering	0.05	0.25	248.4	39.12	33.94	31.78	37939.847	23248.331
Assist	0.1	0.16	248.342	50.07	33.95	31.79	48559.513	29755.725
Transit	0.15	0.10	230.93	43.65	36.51	34.19	42333.189	25940.431
Assist	0.25	0.25	217.1	170.97	38.83	36.36	165812.263	101604.479
Transit	0.30	0.20	213.663	161.53	39.46	36.95	156657.044	95994.452
Assist	0.60	0.03	205.133	46.52	41.1	38.49	45116.608	27646.022
Assist	1.0	0.01	197.92	24.94	42.6	39.89	24187.623	14821.406
	$\sum$			536.8	36.65	34.31	520606.087	319010.846

Table 23. NO$_x$ Emissions from natural gas engines for tug load profile operation. - Yearly figures

Activity	Load	Time	CPP opern.		FPP opern.	
	Factor	Factor	(g/kWh)	(kg)	(g/kWh)	(kg)
Loitering	0.05	0.25	0.0351	5.53	0.553	87.1
Assist	0.10	0.16	0.0351	7.08	0.553	111.48
Transit	0.15	0.10	0.866	163.67	0.861	162.73
Assist	0.25	0.25	1.99	1567.13	1.5	1181.25
Transit	0.30	0.20	1.854	1401.62	1.74	1315.44
Assist	0.60	0.03	1.37	310.72	2.1	476.28
Assist	1	0.01	1.41	177.66	1.45	182.7
	$\sum$			3633.4		3516.98

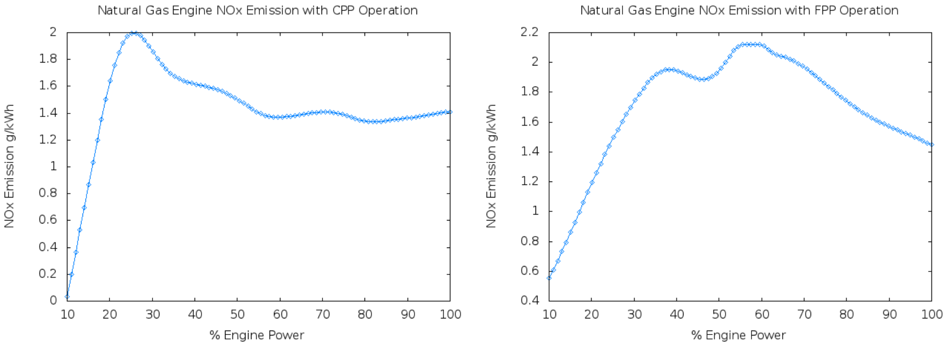


Fig. 11. NO$_x$ Emission from natural gas engine for CPP (left) and FPP (right) operation

spent on MGO and HFO-380 bunkers for the main propulsion units would be approximately **$520606.087** and **$319010.846** respectively. Net thermal efficiency will be around **36.65%**. In other words, **34.31%** of the bunkers bill appears as meaningful work done by the propulsion units. The calculated values may change with quality of bunkers. Table 22 details the complete assessment of the consumption and pricing.

3.3 Endurance with oil fuels

It is found that the entire fuel requirement for a month with the oil fuels can be accommodated in the design. The endurance of the harbor tug with oil fuels can be taken as 30 days with the referenced load profile.

4 Emissions

4.1 Harbor tug emissions - Natural gas operation

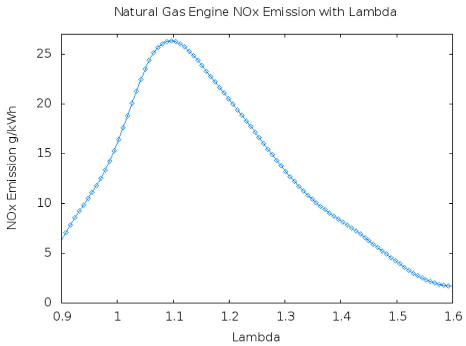


Fig. 12. NOx variation with Lambda *(1/Equivalence Ratio)* **(Source: Mathematical model [Caterpillar [9]])**

4.1.1 NO$_x$ emissions.

In a natural gas engine, NO$_x$ emissions are greatly influenced by air/fuel ratio, and can be approximated as shown in the Fig.12. The figure shows the advantage of lean burn engines ($\boldsymbol{\lambda} > 1$) over rich burn engines ($\boldsymbol{\lambda} < 1$). Marine lean burn engines operate with $1.6 < \boldsymbol{\lambda} < 1.8$. Lean burning is combustion of fuel with equivalence ratios < 1. In engine references often inverse of equivalence ratio termed 'λ' is used instead of equivalence ratio; in which case $\lambda > 1$ for lean burning. Fig.11 shows likely NO$_x$ emissions from natural gas engines in CPP and FPP operations. The plots are a mathematical approximation of data based on MARINTEK presentation on 'Gas Fuelled Ships' [Dag Stenersen [13]]. A rough estimation of the total NO$_x$ generated during an assumed 3500 running hours in a year for a harbor tug operation, according to the load profile chosen is shown in Table 23. For the tug operation in the period, it is likely that the NO$_x$ emissions from the load cycle operation of the gas engines will be about **3633.403 kg** for CPP operation or **3516.98 kg** for FPP operation.

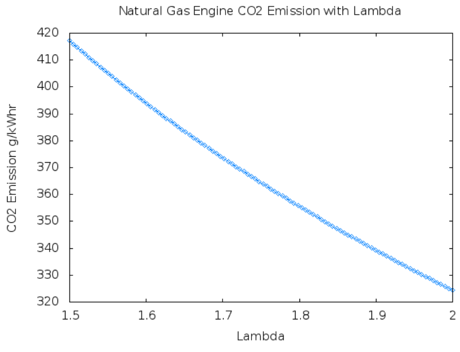


Fig. 13. CO$_2$ emissions from lean burn natural gas engines

4.1.2 Carbon dioxide emissions.

CO$_2$ emission graphs and tables for natural gas engines are developed from the works of [Podolski et al. [38]]; [Pilusa et al. [37]]; and [Caterpillar [9]]. As can be seen in Fig.13, CO$_2$ emissions are maximum at $\lambda = 1$, they decrease with increasing λ due to difficulty in combustion as the flame spreads unevenly. Problems arise as flame hits cylinder walls, which quench the flame. Presence of trapped methane in crevice volumes causes incomplete combustion of the fuel and lesser CO$_2$ emissions. Table 24 shows the computed CO$_2$ emissions from the harbor tug operation.

Table 24. CO$_2$ Emissions from natural gas engines - Yearly figures

Opern.	Load	Time	CPP opern.		FPP opern.	
	Factor	Factor	CO$_2$ (g/kWh)	Qty (MT)	CO$_2$ (g/kWh)	Qty (MT)
Loitering	0.05	0.25	324.4	51.09	377.5	59.46
Assist	0.10	0.16	324.4	65.4	377.5	76.1
Transit	0.15	0.10	387.6	73.26	387.6	73.26
Assist	0.25	0.25	408.4	321.62	400.6	315.47
Transit	0.30	0.20	406.5	307.31	405.1	306.26
Assist	0.60	0.03	398.8	90.45	409.9	92.97
Assist	1	0.01	399.7	50.36	400.6	50.48
$\sum$				959.49		973.99

4.1.3 Carbon monoxide emissions.

Carbon monoxide formation occurs as a result of incomplete combustion. If the combustion is controlled and equivalence ratio is made to approach 1 (Stoichiometric combustion) from fuel rich conditions, carbon monoxide emissions reduce. This is due to combustion of entire carbon into carbon dioxide. But if we take the combustion to fuel lean conditions (equivalence ratio < 1), carbon monoxide starts to increase; this can be explained by flame being blown off by excess air, resulting in some partial combustion and due to methane trapped in the crevice volumes. The discussed effects can be seen in CO emissions vs lambda plot in Fig.14. Carbon monoxide emission[5] for the tug operating in the load profile is as shown in Table 25.

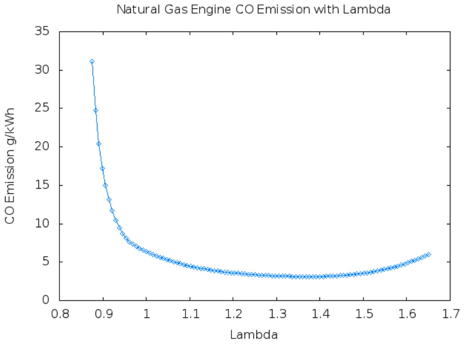


Fig. 14. CO emissions from lean burn natural gas engines

---

[5] The model discussed is based on 2007 data. Present day standards for CO emission from lean burn engines is about 2.682 g/kwh for stationary sources [RICE [39]]

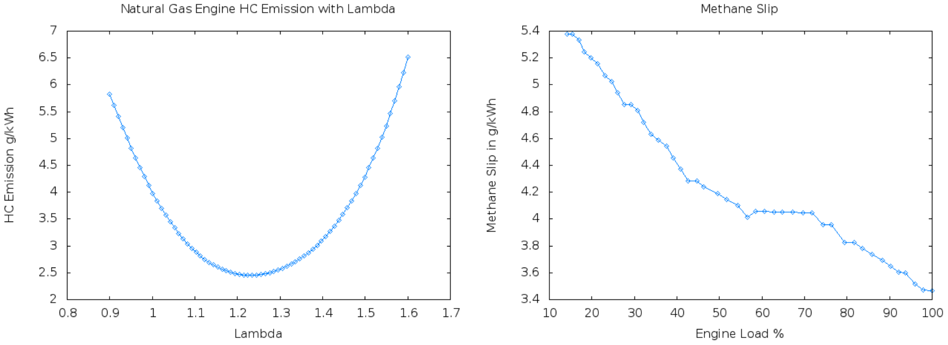


Fig. 15. THC emissions (left) and Methane slip (right) from lean burn natural gas engines

Table 25. CO Emissions from natural gas engines - Yearly figures

Opern.	Load Factor	Time Factor	CPP opern. CO $(\frac{g}{kWh})$	CPP opern. Qty (kg)	FPP opern. CO $(\frac{g}{kWh})$	FPP opern. Qty (kg)
Loitering	0.05	0.25	35.3	5559.75	7.0	1102.5
Assist	0.10	0.16	35.3	7116.48	7.0	1411.2
Transit	0.15	0.10	5.5	1039.5	5.5	1039.5
Assist	0.25	0.25	3.9	3071.25	4.3	3386.25
Transit	0.30	0.20	4.0	3024	4.1	3099.6
Assist	0.60	0.03	4.5	1020.6	3.8	861.84
Assist	1	0.01	4.4	554.4	4.3	541.8
	$\sum$			21385.98		11442.69

4.1.4 Total hydrocarbon (THC) emissions. Total hydrocarbon emissions likely from the gas engines is shown in Fig.15 using a mathematical function [Caterpillar [9]]. THC emissions will include Methane emissions in the exhaust and other Non-Methane Hydro-Carbon (NMHC) emissions. The emissions estimated from the tug operation are shown in Table 26.

Table 26. THC emissions from natural gas engine exhaust - Yearly figures

Opern.	Load Factor	Time Factor	CPP opern. THC $(\frac{g}{kWh})$	CPP opern. Qty (kg)	FPP opern. THC $(\frac{g}{kWh})$	FPP opern. Qty (kg)
Loitering	0.05	0.25	28.9	4551.75	9.3	1464.75
Assist	0.10	0.16	28.9	5826.24	9.3	1874.88
Transit	0.15	0.10	7.4	1398.6	7.4	1398.6
Assist	0.25	0.25	5.0	3945.38	5.7	4488.75
Transit	0.30	0.20	5.1	3855.6	5.2	3931.2
Assist	0.60	0.03	5.9	1338.12	4.8	1088.64
Assist	1	0.01	5.8	730.8	5.7	718.2
	$\sum$			21646.49		14965.02

4.1.5 Methane slip. Engines have an unburnt fuel component in the exhaust, which in reference to natural gas engines, is called 'Methane Slip'. Unburnt fuel arises majorly due to methane trapped in crevice spaces. The crevice spaces are the gaps between piston rings and piston, between piston crown, top piston ring and cylinder liner. Methane has a high auto-ignition point and may not burn in these trapped spaces, leading to unburnt methane in the exhaust. Table 27 shows the methane slip from the lean burn gas engines during the tug operation. Fig.15 [Rolls-Royce [42]] shows methane emissions from each engine for its complete loading conditions. Methane is an important greenhouse gas and should be accounted for while calculating GHG emissions from natural gas fuelled vessels. Makers of engines state methane slip in g/kwh for gas engines.

Table 27. CH_4 Emissions from natural gas engines - Yearly figures

Opern.	Load Factor	Time Factor	Methane Slip (g/kWh)	Methane Emission (kg)
Loitering	0.05	0.25	5.38	847.35
Assist	0.10	0.16	5.38	1084.608
Transit	0.15	0.10	5.37	1014.93
Assist	0.25	0.25	5.01	3945.38
Transit	0.30	0.20	4.83	3651.48
Assist	0.60	0.03	4.05	918.54
Assist	1	0.01	3.46	435.96
	$\sum$			11898.24

Table 28. NMHC emissions from natural gas engine exhaust - Yearly figures

Opern.	Load Factor	Time Factor	CPP opern. Qty. (kg)	FPP opern. Qty. (kg)
Loitering	0.10	0.25	3704.4	617.4
Assist	0.10	0.16	4741.63	790.27
Transit	0.15	0.10	383.67	383.67
Assist	0.25	0.25	0	543.38
Transit	0.30	0.20	204.12	279.72
Assist	0.60	0.03	419.58	170.1
Assist	1	0.01	294.84	282.24
	$\sum$		9748.24	3066.78

Table 29. EMEP/CORINAIR emission estimation for Diesel engines - Yearly figures

	NO_x	CO_2	CO	NMHC	CH_4	N_2O
	(kg)	(kg)	(kg)	(kg)	(kg)	(kg)
Emission Factor (kg/Ton)	57	3170	7.4	2.4	0.3	0.08
CPP Opern.	34959.24	1944224.4	4538.568	1471.968	183.996	49.0656
FPP Opern.	30597.6	1701656	3972.32	1288.32	161.04	42.944

(Emission Factors Source: EMEP/CORINAIR, from chapter 3.2 page 16 of Cooper [12])

4.1.6 NMHC emissions. Non-Methane Hydro-Carbon (NMHC) emissions likely from the tug operation are approximated and presented in Table 28. These are hydrocarbon emissions other than methane. Non-Methane Hydro-Carbon emissions are computed as total hydrocarbon emissions less the methane emissions [Cooper [12]].

4.2 Harbor tug emissions - Diesel fuel operation

Diesel engines emissions are quantified on the basis of fuel consumed and EMEP/CORINAIR emission factors [Cooper [12]] for the fuel used. Tables 29 and 31 show the emission estimates for the harbor tug operation with diesel as fuel and its corresponding GHG equivalent emissions.

Table 30. Total effective GHG emission from gas engines - Yearly figures

(N_2O emission is approximated, Refer section:4.2)

	GWP		CPP opern.		FPP opern.	
			GHG CO_2 equivalent		GHG CO_2 equivalent	
Time (years)	20	100	20	100	20	100
			Qty.(MT)	Qty.(MT)	Qty.(MT)	Qty.(MT)
CO_2	1	1	959.49	959.49	973.99	973.99
CH_4	72	25	856.67	297.46	856.67	297.46
N_2O	289	298	24.1	24.85	18.56	19.14
$\sum GHG$			1840.26	1281.79	1849.22	1290.58

GWP Source: [IPCC [25]]

4.3 GHG emissions from harbor tug

Green house gas emissions from ships using natural gas as fuel should be quantified as shown in Eqn.48.

$$CO_2 + [CH_4] \times GWP_{[CH_4]} + [N_2O] \times GWP_{[N_2O]} \qquad [48]$$

Global Warming Potential (GWP) is a ratio of the amount of radiation that a unit emission of the gas absorbs over a given time frame to the radiation of a unit emission that CO_2 absorbs in the atmosphere over the same time period. In simpler terms, GWP is a ratio to estimate the warming effects of green house gases relative to each other. GWP value of CO_2 is always 1. GWP for other pollutants shows the number of times they are powerful than CO_2 in their contribution to global warming [E+EOCW [16]]. Methane is a more powerful Green House Gas (GHG) than CO_2. In a longer time interval of 100 years, 1 kg of CH_4 has equivalent effect of 25 kg of CO_2. In a shorter time frame of 20 years and considering the other indirect effects of methane (its effects on other pollutants and free radicals in atmosphere), 1 kg of CH_4 has equivalent effect of 72 Kg of CO_2 [IPCC [25]]. Similar global warming risks exist with other combustion engine pollutants such as NO_2, NMHC and CO. These emissions were subsequently deleted from the later Intergovernmental Panel on Climate Change (IPCC) reports due to lack of agreement on appropriate quantification [OECD [35]]. Emission Factors for Greenhouse Gas inventories published by US EPA [USEPA [52]] does not contain natural gas marine engines N_2O emission factor. In its absence, a close approximate value of 0.22 g/gallon for LPG non-highway vehicles from the inventory is chosen here for evaluating comparative N_2O emissions from the harbor tug operation. LNG volume, equivalent of the gas consumed is used in computing the values. There could be a correction of up to 83.38kg of N_2O for CPP operation and 64.23kg for FPP operation for a harbor tug in one year, 3500 running hours basis. Their GHG equivalents are shown in Tables 30 & 31. GHG quantities are expressed in the time frame of years, to show the effect of pollutant released for that period. All pollutants have a life time in the atmosphere; the effects of global warming of the pollutants are calculated as summation (integral) over the time frame. Methane 100 year GWP will be lesser than its 20 year value, because of its life time, which is about 12 years [USEPA [51]]. In the United States, environment regulators like Environmental Protection Agency (EPA), California Air Resources Board (CARB) use the 100 year GWP time frame [Howarth et al. [24]].

Table 31. GHG emission from diesel engines - Yearly figures

	GWP		CPP opern.		FPP opern.	
			GHG CO_2 equivalent		GHG CO_2 equivalent	
Time (years)	20	100	20	100	20	100
			Qty.(MT)	Qty.(MT)	Qty.(MT)	Qty.(MT)
CO_2	1	1	1944.22	1944.22	1701.66	1701.66
CH_4	72	25	13.25	4.6	11.6	4.03
N_2O	289	298	14.18	14.62	12.41	12.8
$\sum GHG$			1971.65	1963.45	1725.66	1718.48

GWP Source: [IPCC [25]]

4.4 Comparison of emissions from harbor tug in natural gas and diesel operation

Emissions analyzed from gas fuel and diesel fuel options for harbor tug are summarized in Table 32. Tables 33 and 34 are a representation of this data in percentage change of emissions from diesel option for harbor tug. Table 33 summarizes estimated emission gains in tug operation by switching over to natural gas fuel. In addition, gas engines have a distinct advantage over diesel engines with regard to SO_x and particulate emissions that depend on the sulfur content of the fuel (these are not evaluated here) [Blumberg et al. [7]]. Table 34 predicts increased emissions of CO, NMHC, CH_4 and N_2O from gas engines. In Table 33, the data is expressed as % emission reduction estimated from gas engines over diesel engines. In Table 34, the data is expressed as % increased emissions from gas engines over diesel engines. The comparison excludes likely fugitive emissions from use of natural gas as fuel such as methane leaks from pipelines, equipment, storage and operations. Makers of gas engines are bringing in certain modifications by way of efficient lambda (λ) control systems [Pelkmans et al. [36]] and implementation of 'Miller cycle' [Fukuzawa et al. [18]], [Wik and Hallbaeck [54]] for further improvement of emission performance and efficiency. Gas engines are a good option to meet IMO Tier III and SO_x norms. There is economic advantage in the fuel costs of natural gas over diesel fuel in the harbor tug operation. This is likely in the range of 53% ∼ 29.85% of fuel cost savings with natural gas (priced 10 ∼ 15 \$/MMBtu) compared to Gas oil (968.8 \$/MT) as shown in Table 33. However, it is observed that in a similar comparison of natural gas with heavy fuel oil, natural gas is expensive at 15\$/MMBtu pricing by about 14.5% above that of fuel oil pricing.

Table 32. Summary of emission comparison (Qty.) of natural gas engines and diesel engines in a harbor tug - Yearly figures

Pollutant	CPP opern. (kg)		FPP opern. (kg)	
	Natural gas	Diesel	Natural gas	Diesel
GHG (100 year)	1281790.96	1963445.85	1290582.8	1718479.31
CO_2	959487.48	1944224.1	973985.67	1701656
CO	21385.98	4538.57	11442.69	3972.32
NMHC	9748.24	1471.97	3066.78	1288.32
CH_4	11898.24	184	11898.24	161.04
NO_x	3633.40	34959.24	3516.98	30597.6
N_2O	83.38	49.1	64.23	42.94

Table 33. Estimated (%) reduction by use of natural gas engines over diesel engines in a harbor tug

Opern.	GHG (100)	CO_2	NO_x	Fuel cost savings
CPP opern.	34.71	50.65	89.61	46.86 ∼ 20.3
FPP opern.	24.9	42.76	88.51	53.23 ∼ 29.85

Fuel cost savings are shown relative to MGO, for a gas price of 10 ∼ 15 \$/MMBtu

Table 34. Estimated (%) increased pollutants by use of natural gas engines over diesel engines in a harbor tug

Opern.	CO	NMHC	CH_4	N_2O
CPP opern.	371.2	562.26	6366.6	69.94
FPP opern.	188.1	138.04	7288.4	49.57

4.5 Emission efficiency at design

After long deliberations at IMO regarding GHG emission from ships, an Energy Efficiency Design Index (EEDI) has been suggested by IMO for cargo carrying ocean going ships, which sets a limit on CO_2 produced per unit of transport work performed. But for non-transport service vessels, this index is not applicable; particularly for service vessels such as tugs, trawlers and dredgers, since there is no transportation work performed. Therefore, its activity should be changed to "useful work", which could be measured in terms of thrust generated for a particular load condition or the power produced by engines at that load condition. Further, when using natural gas as fuel, it is not adequate to use CO_2 alone as the measure of pollution or as the lone contributor to global warming. Perhaps the total GHG emission should be estimated including CO_2, Methane, CO, NMHC, NO_2 and N_2O as significant pollutants contributing to global warming. However, in this paper, the effects of CO, NMHC and NO_x are not included so as to work on the same lines as IPCC [OECD [35]]. Eqn.48 is proposed to be the equivalent GHG emission. Thus an emission measure could be GHG emission per useful work done. Also, since these service vessels have different load profiles, associated time frame is as shown in Fig.4 for a tug. The overall emission measure could be as shown in Eqn.49.

$$EED_{sv} = \sum \left[\frac{(GHG)_i \times f_i}{(\text{Useful work done})_i} \right] \qquad \textbf{[49]}$$

Where i indicates, the i^{th} load condition and f_i indicates the fraction of time spent on the i^{th} load condition. The emission efficiency at design proposed in Eqn.49, emphasizes the importance of load profile of a service vessel. As demonstrated by calculations in Tables 15 and 16 for gas engines or in Tables 21 and 22 for diesel engines, the thermal efficiency of engines quoted at maximum load point is an indicator of their design and does not convey a complete picture of the actual operation. Similarly, the emission performance of engines is dictated by their operational load profiles. In a real world operation of harbor tugs or other service vessels, total emission and emission efficiency is dependant on their load profile.

Table 35. Emission efficiency at design - results from Eqn.49 in one month of operation

Load Factor	f_i Time	CPP opern. (EED_{sv})		FPP opern. (EED_{sv})	
		kg(GHG)/kW			
		Natural gas	Diesel	Natural gas	Diesel
0.05	0.25	103.61	231.12	113.95	173.94
0.10	0.16	42.43	94.67	46.67	71.24
0.15	0.10	18.72	31.57	18.56	25.88
0.25	0.25	118.85	170.48	116.73	152.04
0.30	0.20	75.1	104.84	74.68	95.76
0.60	0.03	1.6	2.12	1.63	2.07
1	0.01	0.17	0.23	0.17	0.22
Total opern.		360.47	635.03	372.39	521.15

Small EED_{sv} value infers that the operation is less polluting in terms of GHG.

Conclusion

Table 33 shows that natural gas has clear merits as a fuel for harbor tug operation, considering the fuel pricing and NO_x emissions. Also since natural gas is supplied almost free from sulfur content, its use does not emit considerable SO_x and particulate emissions [Blumberg et al. [7]]. However GHG gains in Table 33 may be negated, when the life cycle (production, transportation, storage and use) methane and nitrous oxide emissions [Kirchgessner et al. [28]] from the use of natural gas are computed. Their contributing effects to global warming are 25 times and 298 times respectively of the pollutant emitted, so there is a need to accurately determine these emissions. Table 34 highlights a need to account for these powerful greenhouse gases. Also, a level field needs to be identified for diesel fuels and gaseous fuels to claim absolute GHG gains. US Dept.of Energy 'Well to Wheels' [EERE [17]] approach for understanding life cycle of fuels for comparing different fuel options is a step towards addressing these concerns. Maritime studies on emissions in the fuel supply chain and its use in stages like - Well to ship's rail and ship's rail to exhaust may yield quantifiable results. In the present case of the harbor tug, taking f_i as per Fig.4 and the useful work represented by the combined power of the two engines in kW; an emission measure parameter defined by Eqn.49 is calculated for natural gas and diesel options at each load condition and presented in Table 35. The results show the net effective emission efficiency is better for gas engines. There are two important deductions from this Table 35 (also from Table 32) - emission reductions in terms of % reduction from diesel engines and in terms of quantity (Kg) reduction from diesel engines. GHG % reduction possible from the use of natural gas lean burn engines, in comparison to diesel engines is maximum at lower power conditions, which is about 34.5% at Idling. This % emission reduction advantage gradually reduces to 22% at 100% power. Higher GHG quantity (Kg) reduction, over diesel engines, is evident from load ranges at and below 30% of power. Since the harbor tug is operated for about 96% of its time at lower loads, there is a high potential for natural gas as fuel for harbor tugs. The concept of electric propulsion, which enables operation of engines at their maximum power, while the tug is operated at 30 $\sim$ 40% of its maximum power, is an interesting area of study [ABB [1]]. Considering the issues of transport work in assessing energy efficiency of service vessels, possibly we can import ideas from rocket technology. Thrust Specific Fuel Consumption (TSFC) is used in rocket science [NASA [34]] as a measure of fuel efficiency of the flight engines. It is defined as:

$$TSFC = \frac{\text{Fuel mass flow rate per hour}}{\text{Thrust}} \qquad \textbf{[50]}$$

Such a relation for a vessel can integrate propulsion and hull efficiencies and may show combined efficiency. There is a scope to enhance and standardize this proposed approach by use of EED$_{sv}$ and TSFC (Eqn.50) for service vessels. This may facilitate comparison of different service vessels for energy and emission efficiency.

ACKNOWLEDGMENTS. We would like to thank Mr. Avinash Godey for his inputs on the General Arrangement drawings for the harbor tug, Professor RP Gokarn for his review and comments, Mr. Naresh Maniar and other reviewers for their suggestions and support in bringing out this paper. This work was supported by a grant from the Ministry of Shipping, Government of India. Special thanks to Fedora-Linux, Python, LATEX , TikZ, GNU Project, Matplotlib, gnuplot, SCILab, Eclipse, spyder, Emacs-Auctex, GIMP, CTAN, pgfplots and Google. This paper is typeset using LATEX PNAS stylesheet sourced from www.pnas.org. We also thank Ms. Vidyadhari and Mr. Varun Suman for helping in editing the final paper. We are thankful to Robert Allan Ltd., Herbert Engineering corp, Jensen Maritime Consultants and Technology Associates inc for their comments and critique, which has immensely benefitted the paper.

References

1. ABB, Tor Arne Myklebust, A. K. A. (2010). *Azipod VI series product introduction, Doc. no. 3AFV6019310 Draft A / 12th March 2010 and Parallel hybrid propulsion for AHTS, ABB.* ABB Oy, Marine, Retrieved on 19th Aug 2013 from - http://www05.abb.com/global.
2. AEMO (2010). *Operating Procedures, Gas Quality Guidelines - Doc Ref: 224235 (2010).* Australian Energy Market Operator Ltd.(AEMO), Retrieved on 20th May 2013 from http://www.aemo.com.au/.
3. Ahmed, T. (2010). *Reservoir Engineering Hand book.* ISBN 978-1-85617-803-7, Gulf Professional Publishing, Elsevier, 30 Corporate Drive, Suite 400, Burlington, MA 01803, USA.
4. Airliquide (2013). *Website of Air liquide Group.* Airliquide, 75321 Paris Cedex 07, Retrieved from - http://encyclopedia.airliquide.com/, on 20th May 2013.
5. ANL (August 26, 2010). *The Greenhouse Gases, Regulated Emissions and Energy use in Transportation Model, GREET 1.8d.1.* Argonne National Laboratory, Argonne, IL, USA.
6. Bengtsson et al., Selma Bengtsson, K. A. E. F. (2011). *Life cycle assessment of marine fuels - A comparative study of four fossil fuels for marine propulsion.* ISSN 1652-9189, Report No. 11:125, Chalmers University of Technology, Gothenburg, Sweden.
7. Blumberg et al., Katherine O Blumberg, M. P. W. C. P. (2003). *Low Sulfur Gasoline and Diesel: The key to lower vehicle emissions.* Available online [Aug 26, 2013] at: http:/www.unep.org/pcfv/pdf/publowsulfurpaper.pdfâĂŐ (2003).
8. CARB (2002). *California Air Resources Board - Rule making 2002-02-21 Appendix D Methane Number and Fuel Composition consider Ammendments.* California Air Resources Board (CARB), 1001 'I' Street, Sacramento, CA 95814, US.
9. Caterpillar (2007). *Application and Installation Guide - Gas Engine Emissions, G3600, G3500, G3400, G3300.* Caterpillar inc, USA, 100 North East Adams Street, Peoria, Illinois USA.
10. CCNR/OCIMF (2010). *International Safety Guide for Inland Navigation Tank-barges and Terminals.* ISBN 978-2-7466-2185-5, CCNR/OCIMF, Retrieved from - http://www.isgintt.org.
11. CIMAC (2006). *Information about the use of LNG as Engine Fuel- Position Paper dec-2008.* CIMAC Lyoner Strasse 18, 60528 Frankfurt, Germany, Retrieved from - http://www.cimac.com.
12. Cooper, D. (31st May, 2002). *Representative emission factors for use in 'Quantification of emissions from ships associated with ship movements between port in the European Community'.* IVL Swedish Environmental Research Institute Ltd for Entec UK Ltd., Retrieved on 26th Aug 2013 from - http://projects.dnv.com/.
13. Dag Stenersen, M. (2011). *Gas Fuelled ships - LNG-Fuelled Engines and Fuel Systems for Medium- Speed Engines in Maritime Applications, GTS Technical Seminar Series, 2011-09-28.* MARINTEK, Marine Technology Centre, Otto Nielsens veg 10, NO-7052 Trondheim, Norway.
14. Downie, N. A. (1997). *Industrial Gases, pp 268,269 & 317.* ISBN 0-751-40352-0, Kluwer Academic Publishers, 101 Philip Drive, Norwell, MA 02061 USA.
15. Edgar Cuipers, S. N. (May 17, 2005). *INTERCHANGEABILITY presentation.* Technical conference for Natural Gas Council's (NGC) white papers, Washington USA, Retrieved on 26th Aug 2013 from - http://www.cre.gob.mx/documento/1234.pdf.
16. E+EOCW (2013). *Get Involved.* admin., Retrieved August 23, 2013, from Energy + Environment Web site: http://eeocw.org/get-involved/index_html.
17. EERE (May, 2005). *Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems - A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions.* EERE, US Dept. of Energy, Retrieved on 26th Aug 2013 from - http://www.transportation.anl.gov/.
18. Fukuzawa et al., Yorihiro Fukuzawa, Y. K. H. S. H. E. K. T. (2001). *Development of High Efficiency Miller Cycle Gas Engine.* Mitsubishi Heavy Industries, Ltd. Technical Review Vol.38 No.3 (Oct. 2001), Available online [Aug 26, 2013] at: http://www.mhi.co.jpâĂŐ.
19. GIIGNL (2011). *LNG Custody Transfer,Third edition - version 3.01.* International Group of Liquefied Natural Gas Importers, 58, rue du Rocher 75008 Paris.
20. Ginzburg, P. (2006). *ANG storage as a technological solution for the "Chicken-and-egg" problem of NGV refuelling infrastructure development.* 23rd World Gas Conference, Amsterdam 2006, Retrieved on 26th Aug 2013 from - http://www.apvgn.pt.
21. GPSA (2004). *Engineering Data Book - Volumes I & II.* Gas Processors Suppliers Association, 6526 East 60th Street, Tulsa, Oklahoma 74145.
22. Guo, B. and Ghalambor, A. (2005). *Natural Gas Engineering Handbook.* ISBN 0-9765113-3-9, Gulf Professional Publishing Company, 2 Greenway Plaza, Suite 1020, Houston, TX 77046.
23. Hall, K. R. and Yarborough, L. (June 18, 1973). A new equation-of-state for z-factor calculations. *Oil and Gas Journal*, page pp. 82âĂŞ92.
24. Howarth et al., Robert W Howarth, R. S. A. I. (2012). *Venting and leaking of methane from shale gas development: response to Cathles et al. Climatic Change - DOI 10.1007/s10584-012-0401-0.* This article is published with open access at Springerlink.com, Retrieved August 23, 2013, from - http://www.eeb.cornell.edu/.
25. IPCC (August 2013). *IPCC Fourth Assessment Report: Climate Change 2007.* IPCC, Retrieved on August 23, 2013 from - http://www.ipcc.ch/.
26. Judd et al., RW Judd, D. G. R. H. D. B. J. I. M. A. (1998). *The use of Adsorbed Natural Gas Technoloy for Large Scale Storage.* BG Technology, Gas Research and Technology Center, Loughborough, UK, Retrieved on 23rd Aug 2013 from: http://www.web.anl.govâĂŐ.
27. Kidnay, A. J. and Parrish, W. R. (2006). *Fundamentals of Natural Gas Processing.* ISBN-978-0-8493-3406-1, CRC Press - Taylor & Francis Group, 6000 Broken Sound Parkway NW, Suite 300, Boca Raton, FL 33487-2742.
28. Kirchgessner et al., David A Kirchgessner, R. A. L. R. M. C. M. R. H. T. M. S. (1997). *Estimate of Methane Emissions from the US Natural Gas Industry.* Available as - Chemosphere, Vol. 35, No.6, pp. 1365-1390, 1997 Published by Elsevier Science, Retrieved August 23, 2013, from -

http://www.epa.gov/ttnchie1/ap42/ch14/related/methane.pdf.

29. Marcogaz (2009). *Guidelines for Industrial Gas Installations-UTIL-IGI-07-15 D399 Rev.08/10/09.* Marcogaz, Technical Association of the european natural gas industry, Retrieved on 26th Aug 2013 from - http://www.marcogaz.org.
30. MATHESON (2010). *The BTU Accuracy Connection to Profitability and How to Achieve Improvements.* MATHESON, Equipment Technology Center, http://www.mathesongas.com/.
31. Menon, E. S. and Menon, P. S. (2011). *Gas Pipeline Hydraulics, pp 20 ∼ 23.* ISBN 978-1-4669-7671-9, Trafford publishing, North Americal and International, www.trafford.com.
32. Menon, V. and Komarneni, S. (1998). Porous adsorbents for vehicular natural gas storage: A review. *Journal of Porous Materials*, Kluwer Academic Publsihers, Netherlands(5):43–58.
33. Mokhatab et al., Saeid Mokhatab, W. A. P. J. G. S. (2006). *Handbook of Natural Gas Transmission and Processing.* ISBN 987-0-12-386914-2, Gulf Professional Publishing, Elsevier, The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK.
34. NASA, G. R. C. (2013). *Basics of Thrust Specific Fuel Consumption.* portal of Glenn Research Center, NASA, USA, Available online [Aug 26, 2013] at: https://www.grc.nasa.gov/.
35. OECD (2001). *Vehicle Emission Reductions, European conference of ministers of transport, Volume 425, pp 34.* ECMT Publications - OECD Publication, 2, rue Andre Pascal, 75775 Paris Cedex 16, France.
36. Pelkmans et al., L Pelkmans, D. D. K. G. L. (2001). *Emissions and fuel consumption of natural gas powered city buses versus diesel buses in real- city traffic.* VITOâĂŤFlemish Institute for Technological Research (Belgium), Available online [Aug 26, 2013] at: http://citeseerx.ist.psu.edu/.
37. Pilusa et al., T J Pilusa, M. M. M. E. M. (February 18, 1974). Reduction of vehicle exhaust emissions from diesel engines using the whale concept filter. *Aerosol and Air Quality Research, 12: 994âĂŞ1006, 2012*, ISSN 1680-8584, Taiwan Association for Aerosol Research.
38. Podolski et al., Walter F Podolski, S. A. M. D. K. S. A. G. F. V. C. D. E. L. J. D. B. L. K. R. H. P. L. E. B. K. H. G. M. I. G. J. S. R. D. S. P. J. L. C. E. B. J. M. W. M. K. (1999). *Energy Resources, Conversion and Utilization, Perry's chemical Engineers' Handbook.* ISBN 0-07-049841-5, McGrawHill Publishing.
39. RICE (2012). *Natural gas fired and Reciprocating Internal Combustion Engine (RICE) AOS.* PS Memo# 98-006, Interoffice communications, Colorado Department of Public Health and Environment - Air Pollution Control Division, Retrieved on August 23, 2013 from - http://www.colorado.gov.
40. Robert Allan et al., Robert G Allan, F. A. A. T. (2013). *Discussion on the paper Eswara et al. SNAME AM 2013.* Robert Allan Ltd., Vancouver, Canada.
41. Rolls-Royce (2012a). *Marine engine and propulsion programme 2012 product catalouge, General conditions for Marine engines, Gas Engines.* Rolls Royce, Retrieved from - http://www.rolls-royce.com/.
42. Rolls-Royce, O. M. H. (April 19, 2012b). *The 'Environship Concept' - System Solutions Wave Piercing Technology.* Rolls-Royce Marine, Retrieved on 23rd Aug 2013 from - http://www5.nho.no/download/vh.pdf.
43. Rouquerol et al., Rouquerol J, D. C. F. D. E. J. H. N. P. J. R. K. S. K. U. (1994). Recommendations for the characterization of porous solids. *Pure Applied Chemistry,ISSN electronic 1365-3075*, 66(8):1739–1758.
44. Sherway, R. A. and Jewett.Jr., J. W. (2012). *Physics for Scientists and Engineers, Volume 1.* ISBN 978-1-133-95415-6, Cengage Learning, USA, 10650 Toebben Drive, Independence, KY 41051.
45. Sinor, J. (1991). *Comparison of CNG and LNG technologies for transportation applications - Report June 1991-December 1991 - NREL Colorado.* NREL Colorado / J.E. Sinor Consultants Inc, 15013 Denver W Pkwy Golden, CO 80401, United States.
46. Solar et al., Cecilia Solar, A. G. B. A. V. K. S. (2010). *Natural Gas - Adsorption of methane in porous materials as the basis for the storage of natural gas.* ISBN 978-953-307-112-1, Published by SCIYO, Croatia, www.sciyo.com.
47. Speight, J. G. (2007). *NATURAL GAS A Basic Handbook.* ISBN 978-1-933762-14-2, Gulf Professional Publishing Company, 2 Greenway Plaza, Suite 1020, Houston TX 77046, USA.
48. Starling et al., K E Starling, E. R. D. J. H. H. R. G. M. (1995). *Method for Improving Natural Gas Energy Density at Ambient Temperatures.* American Chemical Society.
49. Sutton, R. P. (September 22 - 25, 1985). Compressibility factors for high-molecular-weight reservoir gases. *60th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers, Las Vegas*, SPE Paper(14265).
50. USCG (April 19, 2012). *CG-521 Policy Letter - Equivalency determination design criteria for natural gas fuel systems.* USCG, http://www.uscg.mil/hq/cg5/cg521/âĂŐ.
51. USEPA (2013). *Overview of Greenhouse Gases - Methane.* United States EPA, Retrieved from - http://www.epa.gov/.
52. USEPA (7th November 2011). *Emission Factors for Greenhouse Gas Inventories.* United States Environmental Protection Agency, Retrieved on 26th Aug 2013 from - http://www.epa.gov/.
53. Van der Linden et al., Wilco van der Linden, K. V. L. B. J. C. V. B. K. W. N. (2010). *Innovation in Tug Design.* ITS 2010, Vancouver, Canada, Retrieved from - http://towmasters.files.wordpress.com/.
54. Wik, C. and Hallbaeck, B. (2008). *Reducing emissions using 2-stage turbo charging.* Wartsila Technical Journal 01.2008, Available online [Aug 26, 2013] at: http://www.wartsila.com/âĂŐ.

Discussion by Robert Allan Ltd.

Robert G. Allan P.Eng, FSNAME , Fuzz Alexander P.Eng (Visitor),CIMarE, Allan Turner P.Eng, (Visitor), CIMarE

1. The opening section covering the chemistry of natural gas is interesting, and while pertinent to the paperâĂŹs title it could better have been included as an Appendix rather than leading the entire paper. For potential LNG fuelled tug applications the vast majority of this information is of little or no relevance to LNG storage on an LNG fuelled vessel.
2. Section 2.1. correctly notes that in doing assessments one needs to consider the net usable energy content (LHV) of the fuel as against the total energy content (HHV). But it isnâĂŹt necessary to convert engine manufacturerâĂŹs data to an HHV basis for comparison as long as the difference is accounted for. Using LHV data and applying the appropriate correction factor (generally fixed at LHV = 89 to 90% of HHV) gets the same result. For liquid fuels the adjustment factor is much broader, ranging from perhaps 91% to about 94% of HHV, but typically the LHV value is readily available or can be easily calculated from fuel composition.

Reply:

(a) *The data of Engine efficiency at each loading condition is provided to show likely variation from quoted figures. The data is used to draw important conclusions in the paper.*

3. Paper Section 2.2 is based on publicly available fuel price information but here is where things become misleading. The typical distillate (MGO/MDO) and residual (HFO) fuels are priced in $/metric tonne and are representative of fuel available in ports worldwide. Other than adding bunkering delivery costs (about plus 1 to 2 %) the fuel cost used is reasonably representative of fuel delivered for on-board consumption. So these liquid fuel prices can be used as reasonably representative of $/energy unit of liquid fuel on-board. However for natural gas fuels the indicated price is not at all representative of the delivered cost of fuel energy and should not be used as the basis for arriving at a representative $/energy unit of natural gas fuel on-board. The indicated natural gas price is a reference price of gaseous fuel at an arbitrarily fixed pipeline location (probably Henry Hub in Louisiana) and is only relevant to USA pipeline gas pricing - it is not at all representative of worldwide gas pricing delivered to a vessel. If this gas fuel is to be delivered and stored as LNG there is the added cost (and emissions) of liquefaction plus the added cost (and emissions) of transport and distribution to on-board the vessel. All these additional gas costs are very significant and could easily result in an on-board gas fuel cost of $10/MMBTU to $15/MMBTU as against the $4.06/MMBTU used to portray

natural gas pricing in the paper. As a result the gas price comparisons to liquid fuels are very misleading and infer economic advantages that likely cannot realistically be achieved.

Reply:

(a) *The discussion raises valid points. However, we did not have reliable and realistic prices at the time of drafting the document. Now, with your input, we have revised our calculations and have reproduced the fuel costs with reference to natural gas pricing of 10$/MMBtu and 15$/MMBtu.*

4. Section 2.3 uses a typical load profile for a harbor tug which is indeed representative, but it should be noted that there are very large variations, and the actual load profile is a very critical factor in doing an economic or emissions comparison of gas vs. liquid fuelled vessels. The authors' use of Van der Linden's load profile is somewhat unconventional, as they have assumed engine shutdown in the "standby/loiter" condition whereas the engines most typically would be at idle. Load profile should be calculated into a "load factor" and applied to an amount of annual operating hours (typically 2500-3500 hrs/year). The load profile shown in Tables 14 & 15 is somewhat misleading as the sum of operating time does not add up to 100%, a result of the authors' assumption that the engines are off in the standby/loiter condition. Overall the end result of the calculations does not change, but it would be clearer to the reader if the load profile was adjusted to add up to 100% and an assumed amount of operating hours was defined. Overstating operating hours is a common way to show savings in fuel consumption which in reality are not achievable!

Reply:

(a) *The authors thank you for this important input. The paper has been updated as advised.*

5. Sections 2.4 and 2.5 compare operating costs for CPP and FPP tug configurations which do not unfortunately reflect the real world. A tug fitted with CPP would normally have a "combinator" control system whereby pitch and rpm vary together through some pre-programmed combination to give the desired thrust performance. In our long experience we have never encountered a tug with CPP running at constant rpm. The engine fuel consumption curves for CPP should not be materially different than for FPP applications, and might well be marginally better than FPP, with more versatility in operating the engine at its most economical condition. This same argument applies to Sections 3.1 and 3.2 which consider CPP vs. FPP for a liquid fuelled vessel, and is also carried into the emissions comparisons in Section 4, portraying a disadvantage to CPP that is not necessarily applicable to tugs.

Reply:

(a) *We do not have access to the combinator graphs for a CPP propulsion system of a harbor tug. This is a limitation to our analysis on CPP operation. However, in absence of a combinator graph, we have adopted a pure constant rpm at prime mover condition. This is indicative of engine performance at a pure CPP condition, which we feel would give the reader a better understanding of gas engine behavior. The calculations are relevant in providing beneficial data (by way of gas consumption and emission quantification) to readers interested in the gas engine as a electric generator and also to the ocean going ships which may adopt constant rpm of prime mover for propulsion. We appreciate your comments and have included a remark in the beginning of the analysis, indicating that the CPP operation depicted in the paper may not apply to a harbor tug. We hope this would clear any misconception.*

6. The paper fails to discuss the relative capital costs of a conventional diesel-powered tug vs. the gas-fuelled tug. The reality is that while indeed one may need to have tug of 35 metres in length to accommodate the LNG system, the same power of tug with simple diesel engines could be 10 metres or more shorter, and cost a great deal less. That cost delta must be paid for through fuel savings, which may or may not be possible depending on the operation. The costs of tanks and the LNG components alone are considerable, but one also must build a very much larger tug to accommodate them. The business case for LNG must include evaluation of both CAPEX and OPEX, unless a significant subsidy is applied in favor of the lower emission fuel.

Reply:

(a) *It has been rightly pointed out that we have not addressed the issues of the cost of natural gas equipment, their installation and if any, additional increase in tug overall lengths to accommodate natural gas. However, we have tried to work out a reduced endurance scenario, in trying to limit natural gas fuelled design to that of a traditional diesel propelled tug. We have primarily focussed on fuel costing, emissions and introduction to storage and terms of gas engines. This paper is a primer on natural gas options and we intend to work on a paper in future, which would discuss construction and machinery installation of a gas fueled harbor tug.*

7. The report states "GHG emission reduction per kW power is not significant for natural gas and diesel options at 100% power. Notable GHG reduction from the use of natural gas is evident only at load ranges below 30% of power requirement". We recommend that the authors revisit this statement as it is contrary to information provided by engine manufacturers for modern lean burn engines.

Reply:

(a) *We intended to convey the meaning that % GHG gains over diesel engine is misleading. We should be more concerned about quantity reductions of emissions in kg or MT. Our environment is impacted by the quantity of GHG emissions and therefore in switching over to natural gas engines, our primary concern should be to achieve the best environmental performance rather than comparitive reduction from diesel engines. Kindly note the following:*
There are two ways to evaluate these results, namely

   i. *in terms of % reduction from diesel engines and*

   ii. *in terms of quantity (Kg) reduction from diesel engines.*

GHG % reduction possible from the use of natural gas lean burn engines, in comparison to diesel engines is maximum at lower power conditions, which is about 34.5% at Idling. This % emission reduction advantage gradually reduces to 22% at 100% power. Higher GHG quantity (Kg) reduction, over diesel engines, is evident from load ranges at and below 30% of power. In order to bring this clarity into the paper, we have modified the sentence in the paper to convey the intended meaning.

Discussion by Herbert Engineering Corp.

E. Van Rynbach, S. Schilling, Herbert Engineering Corp.

1. The author's are to be congratulated for preparing a very thorough paper on this topic. The paper provides useful background information on the chemistry of LNG, which is not commonly presented in such a complete form in maritime related papers. It is important for persons involved with LNG fueled ships to have an understanding of the properties and characteristics of natural gas. As explained in the paper the properties of natural gas can vary significantly depending on the source of the gas and this affects how it is specified for purchase, the delivery receipts, the fuel consumption rates of the engines and how much energy is available from a fixed volume or weight of LNG.
2. Tables 30 and 31 give useful data for comparing total GHG effects of gas engines versus diesel fuel engines and how the Global Warming Potential can be significantly impacted by the amount of methane slip from the gas engines. Can the author's comment on the range of methane slip expected from different engine types and also on the time dependency of the GWP of the methane slip and whether the 20 yr or 100 yr value is preferred for doing such GHG comparisons. The GHG emissions

improvements in Table 33 would be quite different if the 20 yr GWP is used.

Reply:

(a) *The government regulators such as US EPA, CARB are using 100 year GWP scale. The choice of GWP scale is often debated at international forums. We have used both scales for comparison, with a foresight, that if there is a shift to 20 year scale, the likely scenario should not be very disadvantageous. The calculations show that methane slip could be a spoil sport. Consider (revised paper) GHG emissions by methane - 100 year scale in FPP operation produced about 28MT equivalent. In a 20 year scale for the same operation, it is 80.7 MT. This difference is disadvantageous for gas engines, when compared to diesel operations. Our calculations indicate that diesels have an advantage in the scenario, only where GHG emissions are concerned; with about 7.4% or about 13 MT improvement over gas engines for a harbor tug in a year (3500 running hours) of operation.*

(b) *Methane slip, for the lean burn engine that we have assessed, the manufacturer claims best in the class performance. That is the engine used in the analysis has the least methane emissions for any type of gas engines. A dual fuel engine or other gas engine is likely to produce more methane emission. However, NO_x reductions achievable with other gas engines are more or less likely to be the same as evaluated in the paper. The bottom line is that gas engines reduce NO_x effectively, SO_x and PM emissions also reduce as natural gas has no sulphur content in it. The issues with GHG reduction should be assessed case by case using the respective load profile.*

3. Table 32 on pg 15 compares emissions for the harbor tug per month based on propulsion system and fuel type (gas versus diesel fuel). The NOx difference between gas and diesel fuel of about 8 or 9 to 1 seems excessive. The NOx emission of the gas engines is shown in Figure 12 as between 1.4 and 2 g/kWh, which is a little less than the IMO Tier 3 requirement of 2 g/kWh. At a minimum the diesel fuel engines for construction now would meet IMO Tier 2 and if in the US, EPA Tier 3, so the NOX emissions would be less than 8 g/kWh per IMO and less than 6 g/kWh per EPA. This means the NOx from the diesel fuel engines would be on the order of 3 to 4 times the gas engines and not eight times.

Reply:

(a) *The calculations in the paper have produced a considerable difference in NOx emissions between gas and diesel engines. The final % reduction possible with gas engines is about 88 ∼ 89 % over diesel engines. This is inline with the claims made by gas engine manufacturers. For example, a major European builder, advocates NOx reductions up to 90% by changing over to natural gas engines.*

(b) *Guidebook by EMEP Task Force on Emission Inventories (EMEP, 2001), whose emission factors are used in the present evaluation, are mostly taken directly from Lloyds Register Engineering Services (1995) and IPCC (1997). This is a valid authentic reference, but considering the more recent IMO type II diesel engines, they emit about 20% less NOx and could meet Tier II requirements.*

(c) *It is also important to note in this context that diesel engines or gas engines' makers, show emission values for compliance to environmental norms. These values are calculated using standard test cycles like ISO 8178, at test bed conditions. Some are determined by parent engine classes and over-all the effort is to simplify and present environmental compliance by the engines.*

(d) *Our effort to quantify emissions should be viewed as, in a practical sense, the emissions possible in a harbor tug operation. These values offer an explanation to the hidden meanings to the statements that engine manufacturers use. Such an assessment would be useful in future, considering the importance of the regulatory frame works, to assess choices of fuel and engines for maritime vehicles. This analysis alone may not be sufficient, to prove environmental compliance with statutory bodies.*

4. Tables 33 and 34 provide useful guidance on the overall impact on emissions and pollution for the change to gas fueled engines from diesel fueled engines. However, Table 33 can be unclear as to meaning. It seems what the authors are trying to say is that there are emissions gains from using natural gas (reductions in the indicated pollutant), however the use of positive numbers gives the impression these are increases in emissions from gas, not decreases. Perhaps it would have been clearer to indicate the improvements from using gas as negative numbers like Table 34? It should be noted that the colors will not be reproduced in the final printed transactions.

Reply:

(a) *Thank you for the feedback. We have effected the changes as advised in the paper.*

Discussion by Professor RP Gokarn

(Professor retired, department of Naval Architecture & Ocean Engineering, IIT Kharagpur, India)

1. The authors must be commended for a well-timed paper since (as they point out) “gas fueled ships are much sought (after) in the maritime industry today”. The discussion on the properties of Natural Gas and the measures of its quality as a fuel, viz. heating value, Wobbe Index, Methane Number and flame speed, is very informative, particularly since the paper gives in detail the procedures for calculating these parameters from the composition of the gas. The paper also gives a useful list of national and international guidelines and codes for the use of gaseous fuels in ships. There is an exhaustive consideration of emissions from the use of Natural Gas as a fuel.
2. The definition of volumetric efficiency in Section 1.9.1 is misleading unless the pressures and temperatures are given of the two volumes of gas being compared.

Reply:

(a) *Thank you for the feedback. We have added an explanation to volumetric efficiency in the paper.*

3. The calculation of fuel cost following Eqn. [38] is not immediately clear, and one has to search through the paper to find what some of the numbers mean: 1800 is apparently the power of the engine in kW, but what is 8.624? From Eqns. [34] - [38], it appears to be the SFGC in MJ per kW hr, but the value for this is shown as 7500 kJ per kW hr in Table 11. Other calculations are similarly difficult to understand, e.g. those in Eqns. [43] and [44].

Reply:

(a) *Explanation to the calculation of equations 38 - The equations 34 to 37 are substituted in Eqn.38. 8.624 is the value of SFGC (shown in Eqn. 36) of gas engine in FPP operation at NSR.*

(b) *The calculations show “for the tug operated with FPP (variable shaft rpm). One engine at NSR consumes $66.31 in one hour, for natural gas pricing at 4.06$/MMBtu. When computed for natural gas pricing at 10$/MMBtu, the value would be 163.33 $/hr”.*

4. In the description of the storage arrangements for Natural Gas fuel, there appears to be some confusion between IMO Independent Tanks Type C, ASME Pressure Vessels and ISO LNG Tanks. An IMO Type C Tank is not normally double layered but the ISO LNG Tank is. The pressure and temperature at which the Natural Gas will be stored should have been stated. There is no mention of any insulation arrangements. The system to deal with the 'boil-off' has also not been considered.

Reply:

(a) *LNG is accommodated in the tank room shown in the General Arrangement figure using EN 13458 pressurized cryogenic tank. The tank consists of inner and outer tanks, with the annular space under vacuum and with perlite insulation. We have made a correction regarding the tank type in the paper.*

5. In Section 4, and equivalence ratio have been used without being defined. It is stated that from Fig. 13 it can be seen that Carbon dioxide emissions are maximum at but the range of in the figure is 1.5-2.0.

Reply:

(a) *CO2 emissions graph has been curtailed to show variation of CO2 emissions in the operation zone only. In trying to focus on the brevity, the graph at lambda = 1 is curtailed. However, the essence of mentioning that CO2 emission is maximum at lambda = 1 is that, in this condition, air and fuel are in stoichiometric ratio and combustion is stable and hence very less or no carbon monoxide is formed. (All the carbon is oxidized to carbon dioxide and hence the maximum carbon di-oxide formation.).*

Discussion by Technology Associates, Inc

Anil Raj PE, President, TA Inc

1. The paper shows the relative reductions of pollutant reductions using natural gas as fuel. Table 32 quantifies the obvious. Reductions of upto 35% GHG, 51% CO2, and 88% in NO_x are attractive. However operators and owners, though more conscious now of the need to reduce emissions, do not get paid extra in charters hire rates or cargo tariff because the vessel is more environmentally friendly. In a commercially competitive market the end users are not conscious enough to pay extra to help the environment. Thus the key factors from an Owner's perspective are:
   (a) How much more does a natural gas fueled vessel cost to build, assuming all other parameters are the same?
   (b) How more does it cost to operate and maintain over the life cycle?
   (c) Will the Owner be able to recover his extra capital and operating costs in a reasonable period from the savings in fuel costs?
   (d) Is the supply infrastructure there to fuel his vessel, not only in the intended port of operation, but other ports where it may have a home, or call on?
2. After the recent KYOTO protocol of UNFCCC (United Nations Framework Convention on Climate Change) and subsequent IMO resolutions at the 63rd session of MEPC, the following (MEPC.212(63), MEPC.213(63), MEPC.214(63), MEPC.215(63)) have mandated that: The CO2 reduction level (grams of CO2 per tonne mile) for the first phase is set at 10%. This will be tightened every five years to keep pace with technological developments of new efficiency and reduction measures.Âă The reduction rate is calculated from a reference line representing the average efficiency for ships built between 2000 and 2010. Reduction rates have been established until the period 2025 to 2030 by when a 30% reduction is mandated for applicable ship types. (or) In other words, MARPOL 73/78, ANNEX-VI, from 1^{st} January 2013, mandates for all new ships,
   (a) Energy Efficiency Design Index (EEDI)
   (b) Ship Energy Efficiency Management Plan (SEEMP).

   These values require a minimum energy efficiency level per capacity mile (example: Tonne-mile). The level is expected to be tightened incrementally every five years.

Reply:

(a) *At this stage, we have not sought to work out comprehensively on the design, construction and the cost estimates. Possibly, in continuation, we would get the opportunity to work on those aspects.*

(b) *We have worked out a price advantage amounting to $0.1554 million per year (3500 running hours basis, natural gas price of 15$/MMBtu, MGO prices of 968.8$/MT) or about 30% savings in fuel costs presently over Marine Gas Oil for a harbor tug operation. Hopefully, accounting for regular price variations, we can estimate the cost recovery on additional investment.*

(c) *Looking into the future, maritime industry will have to develop and incorporate energy efficiency and emission efficiency into design. The first step in this direction has been implemented for larger ships through EEDI by the IMO. We have made a suggestion in the paper for energy efficiency and emission efficiency separately for service vessels. Service vessels are much varied in design and employment compared to larger vessels. They have different power demands and load profiles and any index meant for them must be practical and should consider defining a transport work equivalent. We have tried to account for load profiles in the emission efficiency index by using time-weighted summation of an index at each load point. We feel that such an approach is technically correct and practical. Also, a TSFC parameter (Thrust specific fuel consumption) as used in flight engines (NASA), is suggested for energy effciency index. This is an applicable parameter for fuel efficient design of some service vessels.*