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Real Time Ship Exhaust Gas Monitoring for Compliance to SO_x and NO_x Regulation and CO₂ Footprint

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ABSTRACT: IMO MARPOL Annex VI regulation has been set for global application to reduce the negative consequences of ship gas emissions SO_x, NO_x, and CO₂. To enforce the regulation, real time gas emission monitoring system is in need. The system in this paper consists of a microcontroller, gas analyzers, sensors and Iridium radio module. The data acquired from the sensors and gas analyzer is transmitted using a microcontroller over the Iridium satellite to the ground station for real-time compliance check. Real time monitoring system expedites the checks by the ground station in enforcing the regulation. Ultimately, this application enables engine manufacturers, ship-owners and Administrations to ensure in real time that all applicable marine diesel engines are in compliance with the limiting values determined by IMO MARPOL Annex VI.

1 INTRODUCTION

The increasing number of ships operating on the sea has increased the awareness of IMO (International Maritime Organization), the primary regulatory agency made of 170 Member States tasked with developing regulations for the control of pollution from international shipping activities. IMO created the IMO MARPOL Annex VI regulation to limit the emission of SO_x, NO_x, and CO₂ from the ships. Tier II of the regulation has been enforced since 1st January 2011. Since the regulation requires the ship owner to keep complying throughout the time, there is a need for IMO to have a tool to enforce the regulation. The tool must have the sensors performance compliance as have been detailed by IMO. The tool of such has been developed by many to cater the need of ship owners, but not for the enforcement by IMO. Therefore, IMO lacks of a system that enables it to monitor the ship gas emission in real time from distance. Furthermore, the ships to be monitored travel to many different parts of the world and this require wide data transmission coverage. That is why; satellite communication is suitable for this application.

In this paper, the monitoring of SO_x, NO_x, and CO₂ follows the 2009 Guidelines for Exhaust Gas Cleaning Systems, and Chapter 6.4 Direct Measurement and Monitoring Method of the NO_x Technical Code (2008). Meanwhile, the limit value stated at IMO MARPOL Annex VI regulation 13 and regulation 14 are described in the figures below.

Figure 1. SO_x, NO_x, and CO₂ emission limit

Figure 1. SO_x, NO_x, and CO₂ emission limit (continued)

This paper offers the solution of the lack of technology mentioned above. The illustration of this solution can be found in the Figure 2 below. Important

parameters for compliance are measured by sensors that give electrical signal output of various types. After that, the data value from the sensors is collected by the microcontroller (data acquisition system). The microcontroller processes the data calculation and output the value useful for end-user such as SO_x, NO_x and CO₂ emission. This end-user data is stored in the local memory of the microcontroller. Thereafter, the end-user data is transmitted through the Iridium satellite, from the location of the marine diesel engine being monitored to the any place on earth. In this case, the ground station (headquarter in Figure 2.) of the country shall get the data for law enforcement. This end-user data obtained by the ground station is then stored and used accordingly for monitoring purposes. Ultimately, the aim of this solution is to be the standard for IMO to enforce the IMO MARPOL Annex VI.

Figure 2. Overview of the System

2 PARAMETERS MEASUREMENT

The parameters required for compliance refer to the independent variables identified in the 2009 Guidelines for Exhaust Gas Cleaning Systems, and Chapter 6.4 Direct Measurement and Monitoring Method of the NO_x Technical Code (2008). These independent parameters are listed in Table 1 as follows.

Table 1. Independent parameters for compliance calculation

Symbol	Term	Unit
q_{maw}	Intake air mass flow rate on wet basis ^	kg/h
q_{mad}	Intake air mass flow rate on dry basis ^	kg/h
q_{mf}	Fuel mass flow rate ^	kg/h
c_{SO2d}	Concentration of SO ₂ in the exhaust in	ppm

c_{NOd}	Concentration of NO in the exhaust gas in dry basis ^	ppm
c_{NO2d}	Concentration of NO ₂ in the exhaust gas in dry basis ^	ppm
c_{CO2d}	Concentration of CO ₂ in the exhaust gas in dry basis ^	ppm and (% V/V)
c_{COd}	Concentration of CO in the exhaust gas in dry basis ^	ppm
p_b	Total barometric pressure ^	kPa
R_a	Relative humidity of the intake air ^	%
T_a	Intake air temperature determined at the engine intake ^	K
T_{SC}	Charge air temperature ^	K
PAH_w	Polycyclic Aromatic Hydrocarbon concentration of wash water ^	µg/L
$Turbidity_w$	Turbidity of the wash water ^	FNU or NTU
pH_w	pH of the wash water ^	1

T_w	Temperature of the wash water ^	K
P_{aux}	Declared total power absorbed by auxiliaries fitted for the test and not required by ISO14396 *	kW
P_m	Maximum measured or declared power at the test engine speed under test condition *	kW
W_{ALF}	H content of fuel *	% m/m
W_{BET}	C content of fuel *	% m/m
T_{SCRef}	Charge air reference temperature *	K
W_F	Weighting factor **	1
u	Ratio of exhaust component and exhaust gas densities **	1
T_b	Temperature of water vapor after cooling bath of the analysis system **	°C

^ Require sensor or gas analyzer to measure

* Obtained from the manufacturers Technical File

** Obtained from NOx Technical Code (2008)

The parameters above will be used for calculation using the following formulas below which are adjusted specifically for incomplete combustion and compression ignition engines with intermediate air cooler. Calculating gas_x in equation (1) is our goal.

$$gas_x = \frac{\sum_{i=1}^n (q_{mgas_i} \cdot W_{Fi})}{\sum_{i=1}^n (P_i \cdot W_{Fi})} \quad (1)$$

$$P = P_m + P_{aux} \quad (2)$$

$$q_{mgas} = u_{gas} \cdot c_{gas} \cdot q_{mew} \cdot K_{hd} \quad (\text{for NO}_x) \quad (3)$$

$$q_{mgas} = u_{gas} \cdot c_{gas} \cdot q_{mew} \quad (\text{for others}) \quad (4)$$

$$q_{mew} = q_{maw} + q_{mf} \quad (5)$$

$$c_{gas} = c_w = k_{wr2} \cdot c_d \quad (6)$$

$$k_{wr2} = \frac{1}{1 + \alpha \cdot 0.005 \cdot (c_{CO2d} + c_{COD}) - 0.01 \cdot c_{H2d} + k_{w2} - \frac{P_r}{P_b}} \quad (7)$$

$$\alpha = 11.9614 \cdot \frac{W_{ALF}}{W_{BET}} \quad (8)$$

$$c_{H2d} = \frac{0.5 \cdot \alpha \cdot c_{COD} \cdot (c_{COD} + c_{CO2d})}{c_{COD} + 3 \cdot c_{CO2d}} \quad (9)$$

$$k_{w2} = \frac{1.608 \cdot H_a}{1000 + (1.608 \cdot H_a)} \quad (10)$$

$$H_a = \frac{6.22 \cdot p_a \cdot R_a}{p_b - 0.01 \cdot R_a \cdot p_a} \quad (11)$$

$$p_a = (4.856884 + 0.2660089 \cdot t_a + 0.01688919 \cdot t_a^2) \cdot \frac{101.32}{760} \quad (12)$$

$$K_{hd} = \frac{1}{1 - 0.012 \cdot (H_a - 10.71) - 0.00275 \cdot (T_a - 298) + 0.00285 \cdot (T_{sc} - T_{SCRef})} \quad (13)$$

The table below lists the information for parameters in the equations above that is not found in Table 1.

Table 2. Parameters information

Symbol	Term	Unit
gas_x	Specific emission of gas	g/kWh
P_i	Uncorrected brake power on individual	kW

	mode
q_{mgas}	Emission mass flow rate of individual gas g/h
c_x	Concentration in the exhaust (with suffix of the component nominating, d=dry or w=wet) ppm/% (V/V)
K_{hd}	Humidity correction factor for NO _x for diesel engines 1
q_{mew}	Exhaust gas mass flow rate on wet basis kg/h
k_{wr2}	Dry to wet correction factor for the raw exhaust gas 1
c_{H2d}	Concentration of H2 in the exhaust gas in dry basis ppm
p_r	Water vapour pressure after cooling bath of the analysis system kPa
p_a	Saturation vapour pressure of the engine intake air determined using a temperature value for the intake air measured at the same physical location as the measurements for p_b and R_a kPa
H_a	Absolute humidity of the intake air (g water / kg dry air) g/kg

3 GAS ANALYZER AND SENSORS SELECTION

The gas analyzer is prescribed in Appendix 3 of NO_x Technical Code (2008) and also point 6 Emission Testing of 2009 Guidelines for Exhaust Gas Cleaning Systems. CO, CO₂, and SO₂, should be measured by non-dispersive infrared (NDIR) absorption type. NO, NO₂ should be measured by chemiluminescent detector (CLD) or heated chemiluminescent detector (HCLD). Appendix 8 point 2.1.1 of the NO_x Technical Code (2008) however, mentions that other systems or analyzers can be used as long as it is approved by the Administration and yield equivalent results to the advised equipment. The specification and arrangement of the gas analyzers shall follow the Appendix 3 and Appendix 4 of the NO_x Technical Code (2008).

In measuring exhaust gas concentration; there are two types of gas analyzer, dry basis and wet basis. The dry basis gas analyzer requires the removal of water molecule H₂O from the sample gas before entering the gas analyzer. The removal or gas conditioning cools the sample gas temperature to less than 4°C. Depending on the gas conditioning method, the dry basis gas analyzer often removes small part of NO₂, SO₂, and some hydrocarbon. Thus the reading will be less accurate.

The wet basis gas analyzer on the other hand, measures the sample gas in high temperature of 180-200°C and does not require removal of H₂O. Thus it has higher accuracy compared to the dry basis side.

The suffix w in c_w and c_d in the equation (6) and other equations for gas concentration denote this dif-

ference. The suffix w is meant for wet basis gas analyzer while the suffix d is meant for dry basis gas analyzer. Since the concentration that we need is in wet basis, therefore there is a correction factor that we shall calculate for dry basis gas analyzer.

In order to maximize the cost efficiency for end-users while maintaining the performance of the gas analyzer, this paper uses NDIR dry basis gas analyzer to measure SO₂, CO₂ and including the NO, and NO₂.

The sensors selection refers to the parameters listed in Table 1. The sensors specification shall follow the Appendix 4 of the NO_x Technical Code (2008) for compliance.

The differences that come in the sensor selection are from the marine diesel engine performance to be measured. Different marine diesel engine gives different requirement for the sensors. This paper refers to Daihatsu 6DK-26 for the sensors selection. This Daihatsu 6DK-26 has 6 cylinders, 1570kW with exhaust turbo charger and intermediate air cooler. Therefore, readers are advised to adjust the sensors according to the marine diesel engine that is used.

4 IRIDIUM RADIO MODULE SELECTION

Iridium is selected mainly because of its widest coverage compared to the same service that other offers. It is applicable to this project which requires this level of coverage. Iridium has 66 active satellites in its constellation and it covers most of the area on earth including the North and South poles.

Iridium offers voice and data messages in different application. The Iridium module used in this paper is Iridium 9602 Short Burst Data (SBD) transceiver. The data is sent to email for testing purposes. Iridium 9602 does not come with the data transfer hardware interfacing, and therefore third party ready interface product is used.

5 EQUIPMENT SETUP

This setup considers vast variety of engine, where different engine requires different kind of sensors to serve the engine performance. Hence, the setup is so much flexible such that when the sensors are replaced to adjust to the engine, the same data acquisition and transmission system can still be used.

The schematics to describe the equipment setup can be found in Figure 3 below. The equipment is arranged utilizing several slave microcontrollers (slave MC) and one master microcontroller (master MC). The slaves collect the data from various sensors and a gas analyzer and store it in its local microSD memory card. Thereafter, this data is sent for calculation to the master by using XBee radio communication module. After the calculation is done,

the data is stored in the master microSD memory card. The data is also displayed on the screen attached to the slave and master microcontrollers. This data is then transmitted by the master microcontroller to the Iridium 9602 which will be forwarded to the Iridium Gateway, the gateway for data transceiving at Iridium satellite. In the next step the data is sent from Iridium Gateway to end user application.

Programming of the software is done on the Arduino platform, the Arduino Web IDE. The language for Arduino Web IDE programming is C++

Figure 3. Data acquisition and transmission arrangement

6 CONCLUSIONS AND DISCUSSION

The development of the system has gone through detailed analysis of the parameters required for measurement in order to fulfill the compliance. It is to be noted that for engine owner or engineers responsible for the engine compliance shall understand each of the parameters mentioned in Table 1 and 2. The selection of equipment such as sensors and gas analyzer requires detailed analysis of their performance as well.

The system developed in this paper provides the flexibility for IMO to install to ships for law enforcement. On the other side, this flexibility also gives the ship owner the advantage to monitor the exhaust gas on their ships. Through the future application of Tier III and also awareness on the global

warming effect, this system is expected to come in place to make everything easier for many parties.

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