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June 2004

Water Injection System for Emissions Reduction Tested on the MV *Cabot*

Test Plan and Test Results

Transport Canada
Transportation Development Centre
Environment Canada
Emissions Research and Measurement Division

TP 14272E

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WATER INJECTION SYSTEM FOR EMISSIONS REDUCTION TESTED ON MV *CABOT*
TEST PLAN AND TEST RESULTS

by
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16. Abstract

This report describes the field-testing of a water injection system (WIS) to reduce oxides of nitrogen (NOx) emissions on the MV *Cabot*. The primary objectives were to verify emissions inventories and compliance with future regulatory limits as well as to demonstrate the feasibility of installing affordable emissions reduction technology on marine vessels. The emissions tests were conducted in accordance with ISO 8178-4-E3 protocol using both marine diesel oil (MDO) and intermediate fuel oil (IFO).

The emissions tests demonstrated the effectiveness of a low-cost WIS for reducing NOx emissions in marine diesel engines. The WIS reduced NOx at the expense of an increase in both particulate matter (PM) and carbon monoxide (CO) when using IFO. NOx reductions varied between 10 and 30 percent, and were most effective with increased water injection above 50 percent engine load. The tests showed that the engines emitted NOx levels of 12 g/kWh at 75 percent load and a water-to-fuel (W/F) ratio of 50 percent.

The test results showed no negative impact of the WIS on engine operation. Further testing and development of the WIS are required to realize optimal emissions reduction potential and to determine the impact of water injection on fuel consumption and engine operational performance as well as the impact of fuel quality on emissions.

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16. Résumé

Le présent rapport décrit l'essai en service d'un système d'injection d'eau (WIS, *water injection system*) destiné à réduire les émissions de NO_x (oxydes d'azote) du NM *Cabot*. Cet essai avait comme objectifs de valider les inventaires des émissions et de vérifier la conformité de celles-ci aux nouvelles limites réglementaires, ainsi que de démontrer la faisabilité de doter les navires d'une technologie de réduction des émissions peu coûteuse. Les essais de contrôle des émissions ont été réalisés conformément au protocole ISO 8178-4-E3, alors que le moteur brûlait soit du carburant marin (MDO, *marine diesel oil*) soit du mazout intermédiaire (IFO, *intermediate fuel oil*).

Les essais de contrôle des émissions ont démontré qu'il est possible, avec un système d'injection d'eau à faible coût, de réduire les émissions NO_x des moteurs diesel de propulsion marine. Dans le cas de l'IFO, le WIS a mené à une réduction des émissions de NO_x, mais au prix d'un accroissement des émissions de particules et de monoxyde de carbone (CO). Les taux de réduction des NO_x variaient de 10 % à 30 %, et ils atteignaient leur maximum lorsque la charge du moteur était portée à plus de 50 %. Les émissions mesurées de NO_x atteignaient 12 g/kWh à une charge de 75 % du moteur, lorsque le rapport eau-carburant (E/C) était de 50 %.

Les essais n'ont révélé aucun effet négatif de l'injection d'eau sur le fonctionnement du moteur. Il faudra en outre réaliser d'autres essais et poursuivre la mise au point du WIS pour réaliser tout le potentiel de réduction des émissions du système et pour déterminer l'effet de l'injection d'eau sur la consommation de carburant et le rendement du moteur, de même que pour établir l'effet de la qualité du carburant sur les émissions.

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Executive Summary

The Transportation Development Centre of Transport Canada, in collaboration with Environment Canada's Emissions Research and Measurement Division, conducted emissions tests onboard the OCEANEX RoRo vessel MV *Cabot* operating between Montreal, Quebec, and St. John's, Newfoundland. The main goal of the tests was to demonstrate and evaluate the effectiveness of a water injection system (WIS) to reduce diesel engine emissions. The primary objectives were to verify emissions inventories and compliance with future regulatory limits as well as to demonstrate the feasibility of installing affordable emissions reduction technology on marine vessels. The tests also provided an opportunity for Canada to share information on emissions program and technology developments with U.S. regulatory authorities. This may lead to developing joint emissions reduction initiatives for existing marine vessels.

The issue of reducing oxides of nitrogen (NOx) from ships is of prime interest to Marine Safety, the regulatory body of Transport Canada. The international regulations incorporated under International Maritime Organization (IMO) / Marpol 73/78, Annex VI, propose to limit airborne emissions, primarily NOx and SOx (oxides of sulphur), from marine vessels. Canada is committed to ratifying the 1997 IMO Protocol in 2005. Transport Canada is currently incorporating the provisions of MARPOL Annex VI into the Canada Shipping Act and would implement and enforce the IMO rules through Port-State control.

The emissions tests demonstrated the effectiveness of a low-cost WIS for reducing NOx emissions in marine diesel engines. The emissions tests were conducted with both marine diesel oil (MDO) and intermediate fuel oil (IFO), and the data allowed an investigation of the effect of fuel quality on engine emissions. The WIS effectively reduced NOx at the expense of an increase in both particulate matter (PM) and carbon monoxide (CO) when using IFO. NOx reductions varied between 10 and 30 percent, and were most effective with increased water injection above 50 percent engine load. This corresponds to a NOx emissions value of 12 g/kWh at 75 percent load and a water-to-fuel (W/F) ratio of 50 percent. This does not allow us to conclude that these values are the upper emissions reduction limits for the WIS technology because of the unequal excess water distribution among cylinders. Both NOx and PM are load dependent, with lower emissions at higher loads; CO, in turn, increases with load when running on IFO. Both the W/F ratio and fuel quality affect PM production. When using high (1.5 percent) sulphur fuel, PM increases with water injection; however, with MDO, PM remains constant. Water injection (regardless of fuel quality) has no impact on fuel consumption or carbon dioxide (CO_2) production.

On the engine operation side, the impact of the water is primarily to saturate the engine's combustion air supply as well as to lead to direct water droplet carryover into the cylinders. A noticeable effect was the greater reduction of the exhaust gas temperatures of cylinders nearest the point of injection. This was ascribed to the unequal distribution of the water along the length of the air manifold. Key considerations are location, method of spray atomization, and water droplet distribution. The ship's staff also expressed concerns regarding engine operation and turbocharger surging during water injection. Injection timing adjustments and turbocharger matching may need to be considered for permanent engine operation with the WIS operating at high W/F ratios. Further testing and development of the WIS are required to realize optimal emissions reduction potential and to determine the impact of water injection on fuel consumption and engine operational performance as well as the impact of fuel quality on emissions.

Sommaire

Le Centre de développement des transports de Transports Canada, en collaboration avec la Division de la recherche et de la mesure des émissions d'Environnement Canada, a mené des essais de contrôle des émissions gazeuses à bord du navire roulier NM *Cabot* de la société OCÉANEX, qui assure la liaison entre Montréal, Québec et St. John's, Terre-Neuve. Le principal objectif de ces essais était de démontrer et évaluer l'efficacité d'un système d'injection d'eau (WIS, *water injection system*) en tant que moyen de réduire les émissions de moteurs diesel. Ils visaient à valider les inventaires des émissions, à vérifier la conformité de celles-ci aux nouvelles limites réglementaires, et à démontrer la faisabilité de doter les navires d'une technologie de réduction des émissions peu coûteuse. Les essais ont aussi été l'occasion pour le Canada d'échanger de l'information sur les programmes de réduction des émissions et sur les progrès technologiques accomplis dans ce domaine avec les organismes de réglementation américains. Ces échanges pourraient mener à la mise en place d'initiatives communes pour réduire les émissions produites par les navires existants.

La question de la réduction des émissions d'oxydes d'azote (NO_x) générées par les navires intéresse au plus haut point la Direction générale de la sécurité maritime, l'organisme de réglementation de Transports Canada. Les règlements internationaux énoncés dans l'annexe VI de la convention Marpol 73/78, adoptée par l'Organisation maritime internationale (OMI), proposent de limiter les émissions atmosphériques, principalement les NO_x et les SO_x (oxydes de soufre), produites par les navires. Le Canada s'est engagé à ratifier en 2005 le protocole de 1997 de l'OMI. Transports Canada a donc commencé à intégrer les dispositions de l'annexe VI de la convention Marpol à la *Loi sur la marine marchande* du Canada, et entend appliquer les règlements de l'OMI au moyen du contrôle des navires par l'État du port.

Les essais de contrôle des émissions ont démontré qu'il est possible, avec un système d'injection d'eau à faible coût, de réduire les émissions de NO_x des moteurs diesel de propulsion marine. Les essais ont été réalisés à l'aide de carburant marin (MDO, *marine diesel oil*) et de mazout intermédiaire (IFO, *intermediate fuel oil*), et les données recueillies ont permis d'étudier l'effet de la qualité du carburant sur les émissions du moteur. Dans le cas de l'IFO, le WIS a mené à une réduction des émissions de NO_x, mais au prix d'un accroissement des émissions de particules et de monoxyde de carbone (CO). Les taux de réduction des NO_x variaient de 10 % à 30 %, et ils atteignaient leur maximum lorsque la charge du moteur était portée à plus de 50 %. Cela correspond à des émissions de NO_x de 12 g/kWh à une charge de 75 % du moteur, avec un rapport eau-carburant (E/C) de 50 %. Mais on ne peut conclure que ces valeurs sont représentatives de la performance optimale de la technologie WIS, en raison de la répartition inégale de l'excès d'eau entre les cylindres. Les émissions de NO_x et de particules dépendent de la charge du moteur : plus la charge est élevée, plus les émissions sont faibles; en revanche, lorsque le moteur brûle de l'IFO, plus la charge est élevée, plus les émissions de CO augmentent. Par ailleurs, le rapport E/C et la qualité du carburant influent sur la production de particules. Ainsi, avec un carburant à forte teneur en soufre (1,5 p. 100), l'injection d'eau mène à une augmentation des émissions de particules; toutefois, lorsque le moteur brûle du MDO, les émissions de particules demeurent constantes, avec ou sans injection d'eau. Enfin, l'injection d'eau (peu importe la qualité du carburant) n'a aucun effet sur la consommation de carburant et sur les émissions de dioxyde de carbone (CO_2).

Pour ce qui est du fonctionnement du moteur, le principal effet de l'eau est de saturer l'air d'admission, ce qui fait que des gouttelettes d'eau sont directement acheminées dans les cylindres. Un autre effet de l'eau a été remarqué : une diminution plus prononcée des températures des gaz d'échappement des cylindres se trouvant le plus près du point d'injection. Cet effet a été attribué à la répartition inégale de l'eau dans le collecteur d'air. Parmi les grands facteurs à prendre en compte figurent le lieu d'injection, la méthode de vaporisation de l'eau et la distribution de la taille des gouttelettes. Des membres de l'équipage du navire ont également fait part de certaines préoccupations concernant le fonctionnement du moteur et le pompage du turbocompresseur lors de l'injection d'eau. Il y aurait peut-être lieu d'améliorer la synchronisation de l'injection d'eau et le raccordement du turbocompresseur au moteur avant d'équiper en permanence un moteur d'un WIS à rapports E/C élevés. Il faudra en outre réaliser d'autres essais et poursuivre la mise au point du WIS pour réaliser tout le potentiel de réduction des émissions du système et pour déterminer l'effet de l'injection d'eau sur la consommation de carburant et le rendement du moteur, de même que pour établir l'effet de la qualité du carburant sur les émissions.

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1. Introduction

Public awareness with regard to harmful emissions is increasing. Governments and industry are under growing pressure to curb the rise of vehicle emissions. Heavy-duty diesels in both on-road and construction equipment contribute significantly to ambient air pollutants. These emissions include oxides of nitrogen (NOx), carbon monoxide (CO), carbon dioxide (CO_2), unburned hydrocarbons (THC), and particulate matter (PM). These emissions are of concern for a number of reasons, including detrimental effects to human health[1] and to the environment, where they contribute to smog, acid rain, and global warming. In particular relevance to this project, the emissions of NOx and PM are strongly associated with diesel combustion. Diesel-fuelled vehicle emissions are a significant source of PM. Particle sizes of less than 10 microns (PM10 and PM2.5) have been declared toxic by governments in Canada and the U.S.

Canada, as a member of International Maritime Organization (IMO) and a signatory of the Montreal Protocol, has committed to the reduction of gaseous emissions that contribute to global warming and local atmospheric pollution. Ships are responsible for a portion of the man-made air pollution contributing to environmental degradation. It is PM, NOx, and CO_2 that are of primary concern with regard to health and environmental effects.

The international regulations incorporated under IMO/MARPOL, Annex VI, propose to limit airborne emissions such as NOx and oxides of sulphur (SOx) from marine vessels. Recent IMO discussions on climate change have also focused on greenhouse gas emissions such as CO_2 and health-related emissions such as PM. IMO MARPOL Annex VI was ratified in May 2004, by 15 member nations representing 50 percent of the world's combined commercial shipping tonnage. It will enter into force in 2005. Annex VI will apply to all new ships (or major retrofits) built after January 1, 2000, with engines rated greater than 130 kW.

Marine vessels contribute to air pollution through the exhaust generated from both their main and auxiliary engines. Though the contribution of this source to the overall pollution burden is relatively small (approximately 16 percent of the world's total NOx emissions according to some estimates), the impact on local air sheds has the potential to be significant. In Vancouver, Canada, for example, the port experiences over 8000 annual marine vessel movements. In an effort to control these emissions, IMO has negotiated standards for NOx and has initiated discussions on similar controls on PM. Adding to this international effort, participants of IMO can apply to have specific locations identified as "special designated areas" requiring more stringent emissions regulations for marine vessels.

Shipbuilders and manufacturers of marine vessel engines have responded to the demands to reduce vessel emissions by improving the operation of the engines and by incorporating emissions control technologies in the design of new vessels. Selective catalytic reduction (SCR), fuel emulsions, water injection systems, and a number of engine modifications are a sample of the technologies being employed.

2. Objective

The NOx Emissions Reduction Trials aimed to demonstrate and evaluate various diesel engine emissions reduction technologies for the reduction of exhaust emissions. The trials were conducted on the MV *Cabot* by Transport Canada's Transportation Development Centre (TDC) with support from Environment Canada's Emissions Research and Measurement Division (ERMD). The primary objectives were to verify emissions inventories and compliance with future regulatory limits as well as to demonstrate the feasibility of installing affordable emissions reduction technology on marine vessels. The tests also provided an opportunity for Canadian and U.S. regulatory authorities to share information on program and technology developments. This may lead to developing joint emissions reduction initiatives for existing marine vessels.

To meet these objectives, TDC installed a water injection system and an engine data acquisition system on the port engine of the MV *Cabot*. ERMD installed a mobile sampling unit and analyzer bench to collect and analyze exhaust emissions from the diesel engine operating under real-world conditions.

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[1] US Environmental Protection Agency. Office of Mobile Sources. Regulatory Announcement "New Emission Standards from Heavy Duty Diesel Engines Used in Trucks and Buses." EPA 420-F-97-016. 1997.

3. Emissions Standards

The national marine emissions standards being adopted by Canada are those established by the IMO in MARPOL Annex VI. Transport Canada (i.e., the Canadian National Administration) is on record for stating that it will ratify the IMO proposal by 2005. MARPOL Annex VI applies only to NOx and specifies sulphur limits in marine fuels. There are currently no standards proposed for PM, THC or CO. The NOx standards for new marine diesel engines are shown in Table 1.

Table 1. NOx Emissions Limits (g/kWh)

Engine Speed (n)		
N ≥ 2000 rpm	2000 > n ≥ 130 rpm	N < 130 rpm
9.8	4.5 × n exp – 0.2	17.0

Annex VI requires that all new ships (or major retrofits) built after January 1, 2000, with engines rated greater than 130 kW comply with the NOx standards. In anticipation of this, the majority of marine engine manufacturers had made internal engine modifications or developed NOx after-treatment systems, allowing their engines to meet the proposed limits. These NOx emissions reduction systems have been installed on all new vessels. Existing ships needing retrofits will also have to comply with the proposed limits. IMO Annex VI was recently ratified when 15 member nations representing 50 percent of the world's combined commercial shipping tonnage accepted the MARPOL convention. It will enter into force in 2005. Canada, as a signatory to IMO, implements and enforces the IMO rules through Port-State control under the Canada Shipping Act.

Implementing the standards in an effective way requires a program of certification and compliance. Currently, marine surveyors periodically inspect marine equipment immediately after installation and then once every five years. This inspection, however, does not require engines to be tested every five years, and verification to standards is obtained from a review of the Engine Parameter Log Book. The test procedures for demonstrating compliance are set out in the IMO MARPOL NOx Technical Code.[2] The key to achieving Port-State control approval is the ability to monitor NOx on a continuous basis in order to demonstrate in situ compliance.

There is a general belief that the provisions of Annex VI lack sufficient stringency. Once it enters into force, more stringent sulphur and NOx limits may well be imposed. There is growing support among member states for a revision of the protocol, especially with regard to lower sulphur limits. IMO protocol allows for special SOx emissions control areas (SECAs), such as the Baltic Sea, where more stringent rules apply. Several countries (e.g., Sweden) have adopted innovative approaches to encourage ship owners to reduce emissions through a program of differential port fees. Canada could adopt this designation for sensitive environmental areas. Sulphur is a critical component of marine fuels in that it not only affects the formation of photochemical smog but also has an impact on SOx, NOx, and PM production.

In January 2003, the United States the Environmental Protection Agency (EPA) published Tier 1 standards[3] for Category 3 marine engines (e.g., those above 30 L/cylinder) used on the larger ocean-going marine vessels. These Tier 1 standards (Table 2) are equivalent to IMO Annex VI NOx standards and apply to marine diesel engines installed on new vessels. Future Tier 2 standards for Category 3 engines are proposed that envisage a reduction of 20 percent for NOx, CO, and HC. PM is not addressed by either IMO or EPA standards for Category 3 marine engines. The European Union currently accepts IMO regulations, but if by the end of 2006 IMO does not introduce stricter standards, the EU will propose limits in alignment with EPA Tier 2 Standards.

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[2] www.imo.org/conventions/MARPOL

[3] U.S. Environmental Protection Agency, Final Regulatory Support Document: Control of Emissions from New Marine CI engines Above 30 Liters per Cylinder, EPA420-R-03-004, January 2003.

Table 2. EPA Tier 1 Emissions Standards for Marine Engines

Cylinder displacement Litres/cylinder	HC + NOx g/kWh	PM g/kWh	CO g/kWh	Implemetation date
2.5 < displ. < 5.0	7.2	0.20	5.0	2007
5.0 < displ. < 15.0	7.8	0.27	5.0	2007
15 < displ. < 20.0 power < 3300 kW	8.7	0.50	5.0	2007
15 < displ. < 20.0 power > 3300 kW	9.8	0.50	5.0	2007
20.0 < displ. < 25.0	9.8	0.50	5.0	2007
25.0 < displ. < 30.0	11.0	0.50	5.0	2007
displ. > 30.0	17.0 (IMO)			2004

The EPA will announce final Tier 2 standards for engines exceeding 30 L/cylinder by April 2007. The proposed Tier 2 limits are 13.3 g/kWh NOx, 3.0 g/kWh CO, and 0.4 g/kWh HC.

4. Test Methodology

The emissions test program is focused on conducting a number of field trials onboard the RoRo vessel MV *Cabot* operating between Montreal, Quebec, and St. John's, Newfoundland. The trials measured the impact of a water injection system (WIS) on the reduction of exhaust gas emissions, primarily NOx. The test cycle was designed to adhere to the ISO 8178-4-E3 protocol while still conforming to the normal operation of engines in the field. The trials were designed to be conduced on a non-interference basis and under steady-state operation. The test plan considered the vessel operating regimes (engine speed and load) and matched them with the ISO 8178-4-E3 protocol prior to testing. A number of preliminary tests without water injection were carried out to collect data on engine operation, engine duty cycle, and emissions profile, and to determine the vessel route. A formal WIS emissions trial with water injection at discrete load settings was conducted on the MV *Cabot* during the week of March 14-21, 2004.

5. Emissions Measurement Protocol

The emissions measurement protocol specifies the measurement of emissions in terms of the test set-up, instrumentation, accuracy, and test duration. The test procedures for demonstrating compliance to emissions norms are outlined in the NOx Technical Code and are based on ISO 8178. A series of dedicated emissions tests were conducted in accordance with the ISO 8178-4-E3 protocol. The tests were done with and without water injection at various load configurations with the engine running on both marine diesel oil (MDO) and intermediate fuel oil (IFO). The tests were carried out with the engines operating in a steady-state condition. Emissions measurements were taken at 25, 50, and 75 percent engine load and a range of water injection volumes (water/fuel ratios). The time of each test configuration was approximately 30 minutes. Baseline emissions measurements for each load condition were taken prior to the activation of the WIS.

ERMD provided the primary emissions analyzer and sampling system for the WIS trials. A portable mini-dilution system (ECOM) was installed onboard the vessel to measure NOx, HC, CO, CO_2, O_2 and PM emissions. The ECOM system is designed for a marine application and conforms to ISO 8178-4-E3 requirements with respect to accuracy, test set-up, instrumentation, and test duration. The WIS emissions trial followed ISO 8178-4-E3 as set out in Table 3. Since the candidate engine operates at maximum 85 MCR (maximum continuous power rating), only modes 2, 3 and 4 were tested.

Table 3. Propeller Cycle – ISO 8178-4-E3

Mode	% Rated Engine Speed	% Engine Load
1	100	100
2	90	75
3	80	50
4	63	25

6. Water Injection System

The Water Injection System (WIS) was designed and developed by TDC. The concept of using water for emissions reduction has been explored extensively for a number of decades. Water introduced into the combustion process lowers the peak combustion temperature, which inhibits the formation of NOx. The WIS tested on the MV *Cabot* is based on combustion air humidification through water injection into the combustion air stream. The amount of water injected is expressed in terms of a mass water-to-fuel ratio (W/F). Table 4 indicates the range of flow rates injected at each load condition.

Table 4. Range of Water Injection

Load % MCR	Fuel Rate (kg/h)	Min. W/F ratio (flow rate in %)	Max. W/F ratio (flow rate in %)
25	278.71	16.30%	137.48%
50	557.41	8.15%	68.74%
70	780.37	5.82%	49.10%
75	836.12	5.43%	45.83%
80	891.86	5.09%	42.96%
85	947.60	4.79%	40.43%

Water is injected into the intake air manifold immediately after the air cooler through a set of injection nozzles as shown in Figure 1. The nozzles inject a finely atomized spray into the combustion air. The nozzles are sized for different flow rates, depending on the water demand computed by the controller as a function of W/F. There is one water injection branch for each bank of the V-12 engine.

The WIS module is skid-mounted and installed near the MV *Cabot*'s V-12 engine as shown in Figure 2. It comprises a computer-based controller, solenoid valves, nozzles, piping, and a single continuous-speed, multi-stage centrifugal water pump with a rated capacity of 2.28 m^3/h at 350 psi. The nozzles operate between 90 and 200 psi and, within this pressure range, are capable of delivering the required water flow rates to the engine at different load settings.

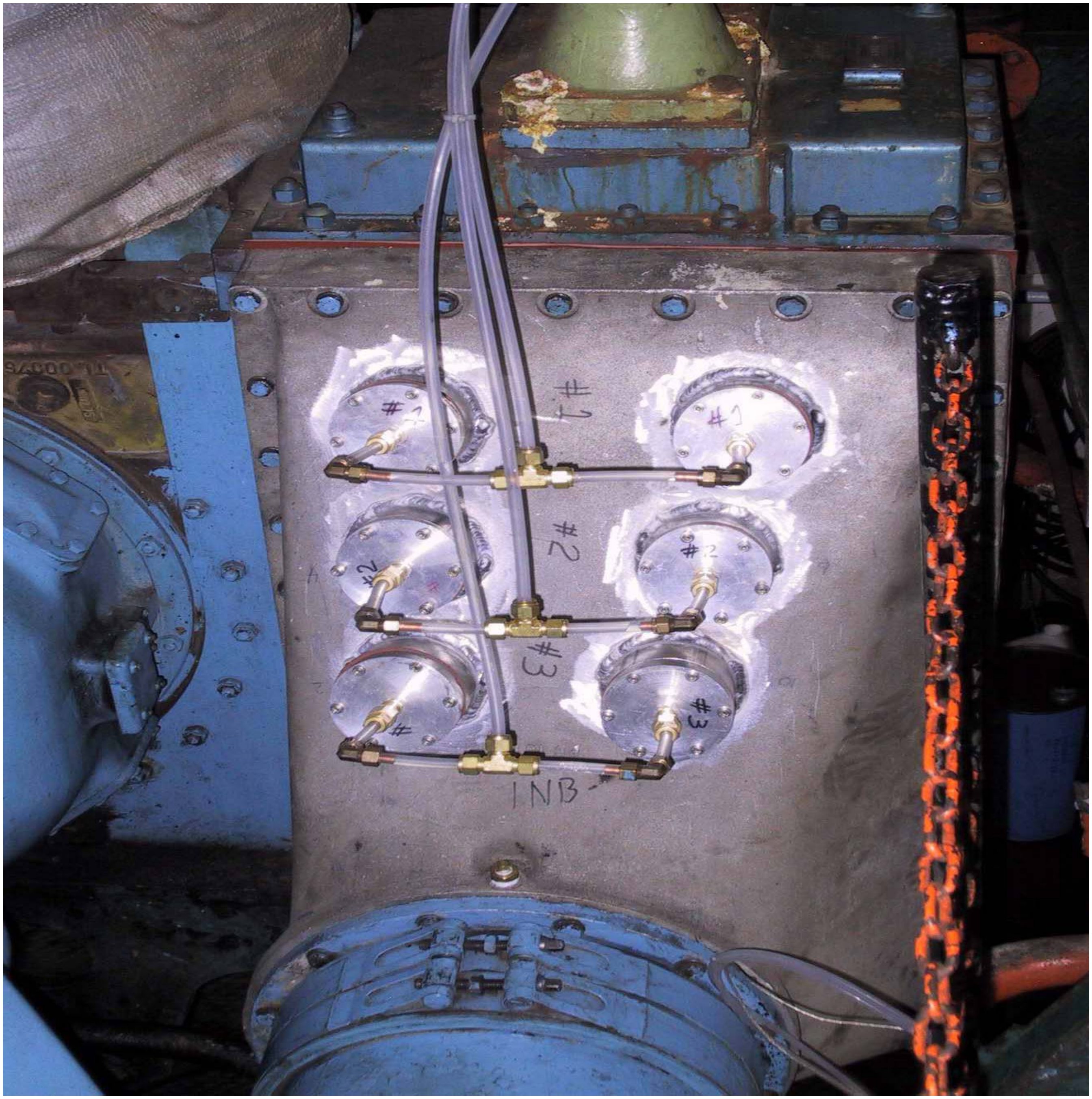

Figure 1. Water Injection Nozzles

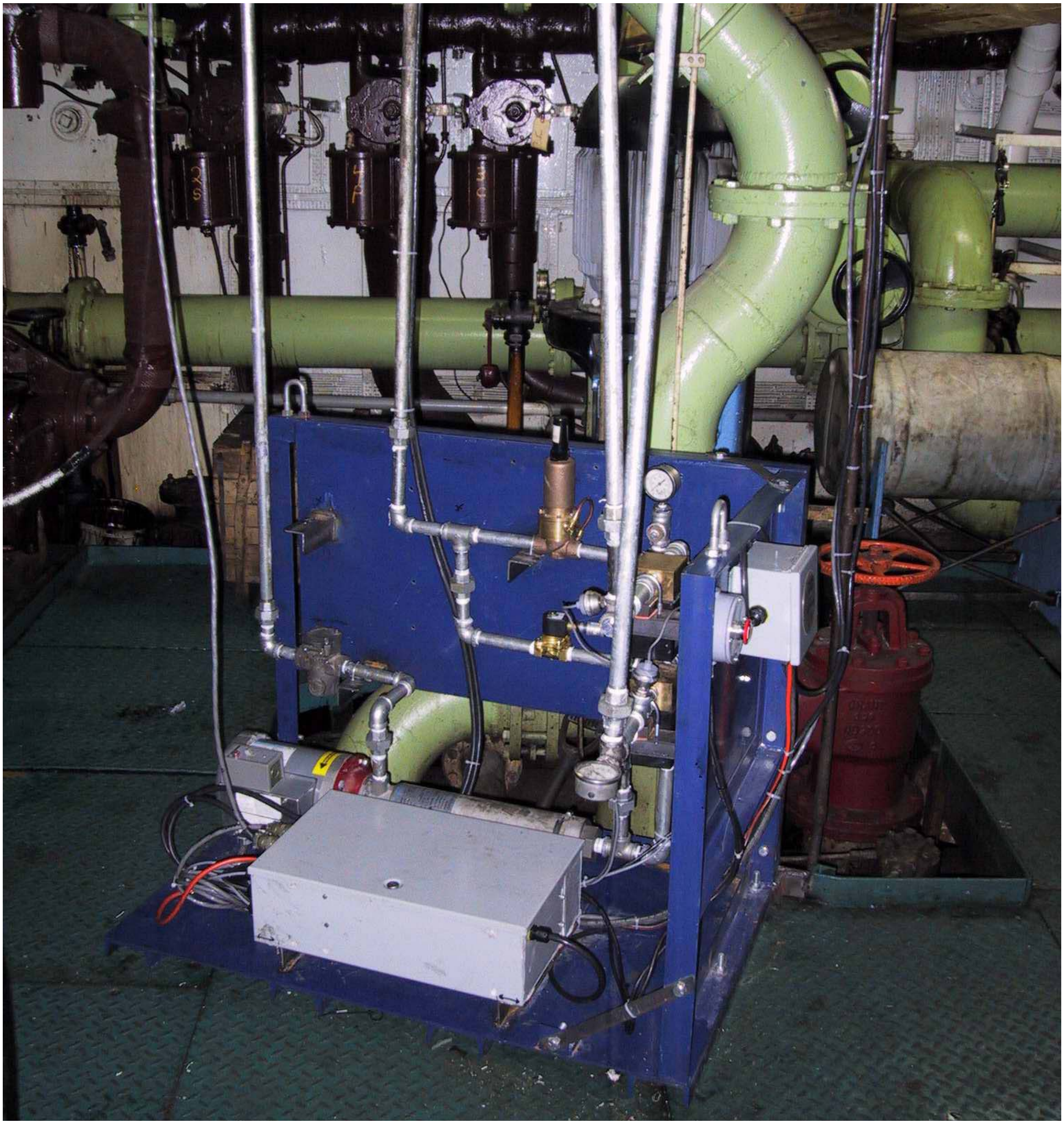

Figure 2. WIS Module

The WIS controller has been implemented in a microcontroller on the CPU card in the Firing Pressure Remote Transmitter (FPRT). This allows for simultaneous control and monitoring of engine operation, emissions measurements, and water injection. A control algorithm uses measured fuel flow, rpm, and fuel rack position as inputs into the WIS main controller, with output as required water flow rate. The WIS incorporates the following features:

- Calculation of the correct amount of water injected into the air manifold as a function of the engine load, measured fuel flow, and fuel rack position.
- Injection of water through spray nozzles into the air manifold.
- Monitoring, shutdown, and fail-safe interlocks to ensure safe operation.

The water demand at each load condition is determined in terms of W/F ratio. The water flow rate is regulated by a proportional solenoid valve (PSV) that controls the pressure and thus the flow to the nozzles. The PSVs are controlled by a primary control loop consisting of a proportional/integral (P/I) controller acting on feedback from pressure transducers and a demand signal from the WIS controller. The position of the solenoid valves sets the operating pressure to obtain the desired water flow rate. This mechanism allows the system to control the set flow rates to the nozzles when the engine is operating at various load conditions. Separate On/Off solenoid valves are installed to control the flow to each set of nozzles.

A fresh-water storage tank with a capacity of 400 tons provides the main water supply to the vessel. The vessel also has a 15-ton water storage tank located in the engine room, which is used for general washing and to supplement the boilers and expansion tanks. The WIS was directly connected to this tank as illustrated in Figure 3.

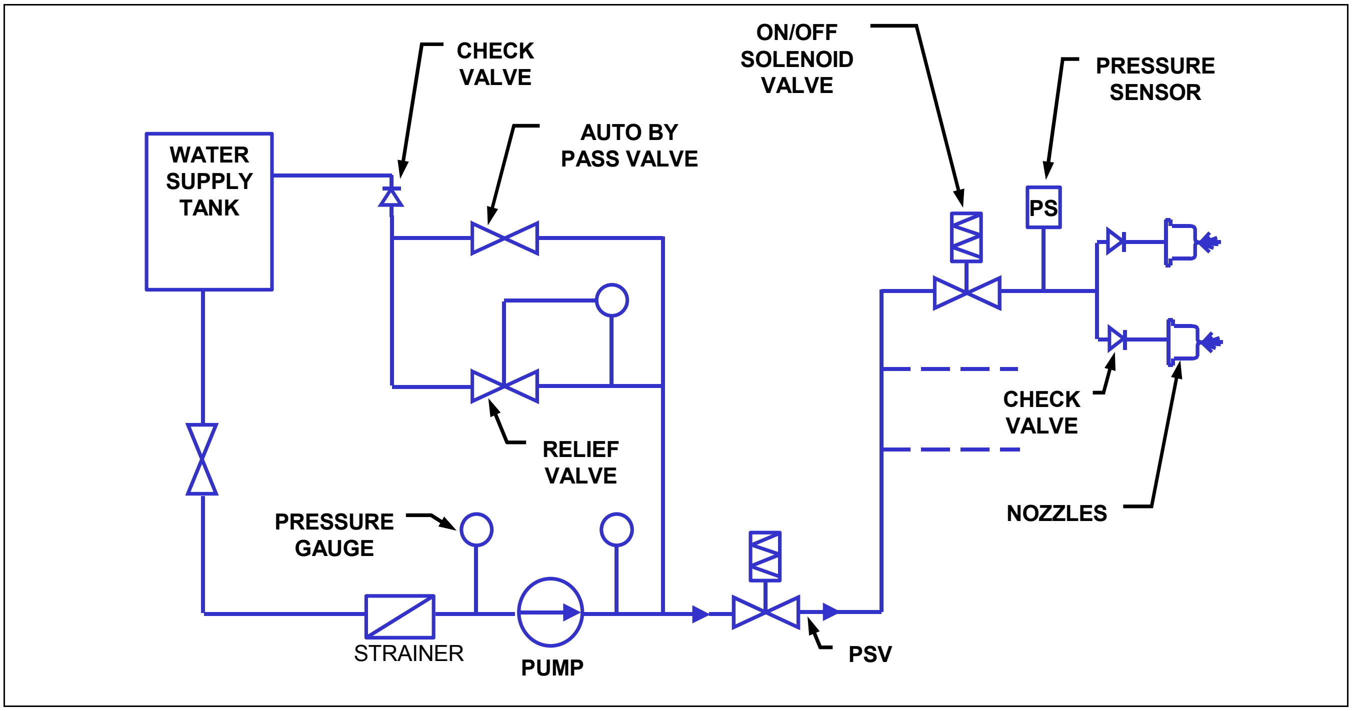

Figure 3. WIS Schematic

7. Engine Data Logging System

The core of the data logging system is the FPRT (Figure 4), a specialized data acquisition/conversion unit built around two Motorola 68HC16Z1 CPUs running at 20 MHz. A CPU card and analogue card share the bulk of the system circuitry and allow interconnection of the various external signals to the unit. Most external sensors consist of pressure, temperature and timing interface devices. Special water-cooled piezoelectric sensors allow the measurement of cylinder pressure curves in continuous mode.

Cylinder pressure curves are sampled at a rate of 100 kHz. Each cylinder pressure curve is captured in turn and synchronized to the engine rotation with a precision of better than 0.1 degrees. Following the capture of a cylinder pressure curve, all engine auxiliary channels are captured. These consist mainly of charge air pressure and temperature, exhaust temperatures, fuel rack setting, cooling water inlet and outlet temperatures, and engine fuel flow rate. A total of 37 auxiliary channels are scanned following the capture of each cylinder pressure curve. Following capture, digital filtering of the pressure curves is applied and the pressure curve and auxiliary data are packed in a serial message called a stream, which is transmitted to a data reception PC located in the engine control room. On average, a complete stream is captured and transmitted every 0.8 seconds, providing an update rate of approximately 1.25 Hz for the auxiliary channels.

Data received on the engine control room PC can be displayed using a special software package called FPDS (Firing Pressure Display Software). The FPDS also forwards the incoming data on to the PC hard disk for future processing. Processing of the recorded data allows retrieval of additional information from the cylinder pressure waveforms, such as peak cylinder pressure, indicated work, thermodynamic constants, etc. In addition, correlations among auxiliary channels such as rack and charge air pressure can be established using thermodynamic or physics principles.

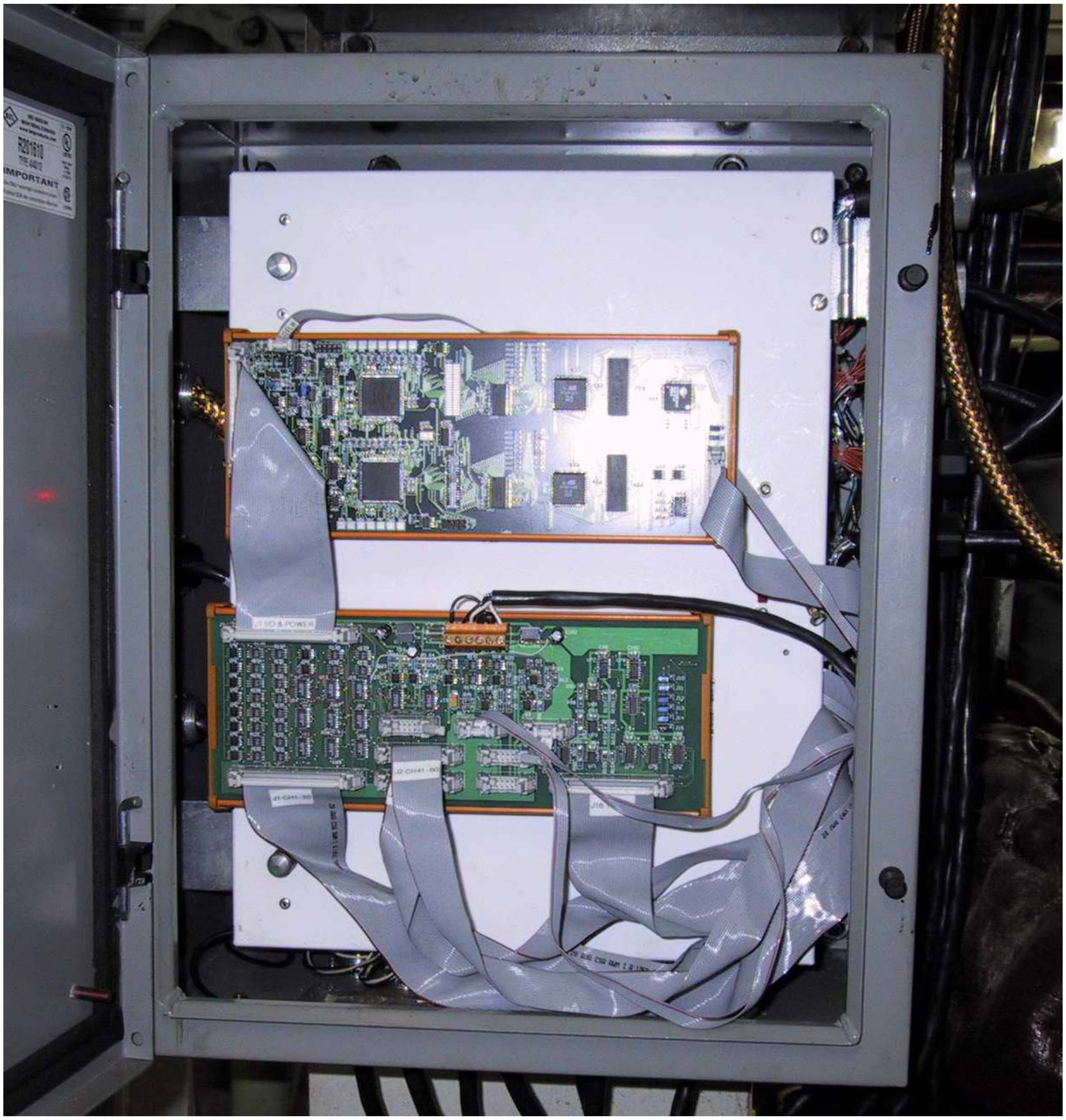

Figure 4. FPRT Controller

7.1 Measurements and Sensors

Combustion Pressure

The pressure inside the combustion chamber of the engine is measured using water-cooled piezoelectric Dytran 2204M2 pressure transducers (Figure 5). A special interface card powers the sensors and provides temperature compensation, amplification and conditioning of the pressure signal. Cylinder combustion pressures are sampled at a 100 kHz rate with a precision of 10 bits. The accuracy is within 1 percent of the actual pressure and the resolution is 0.1 percent.

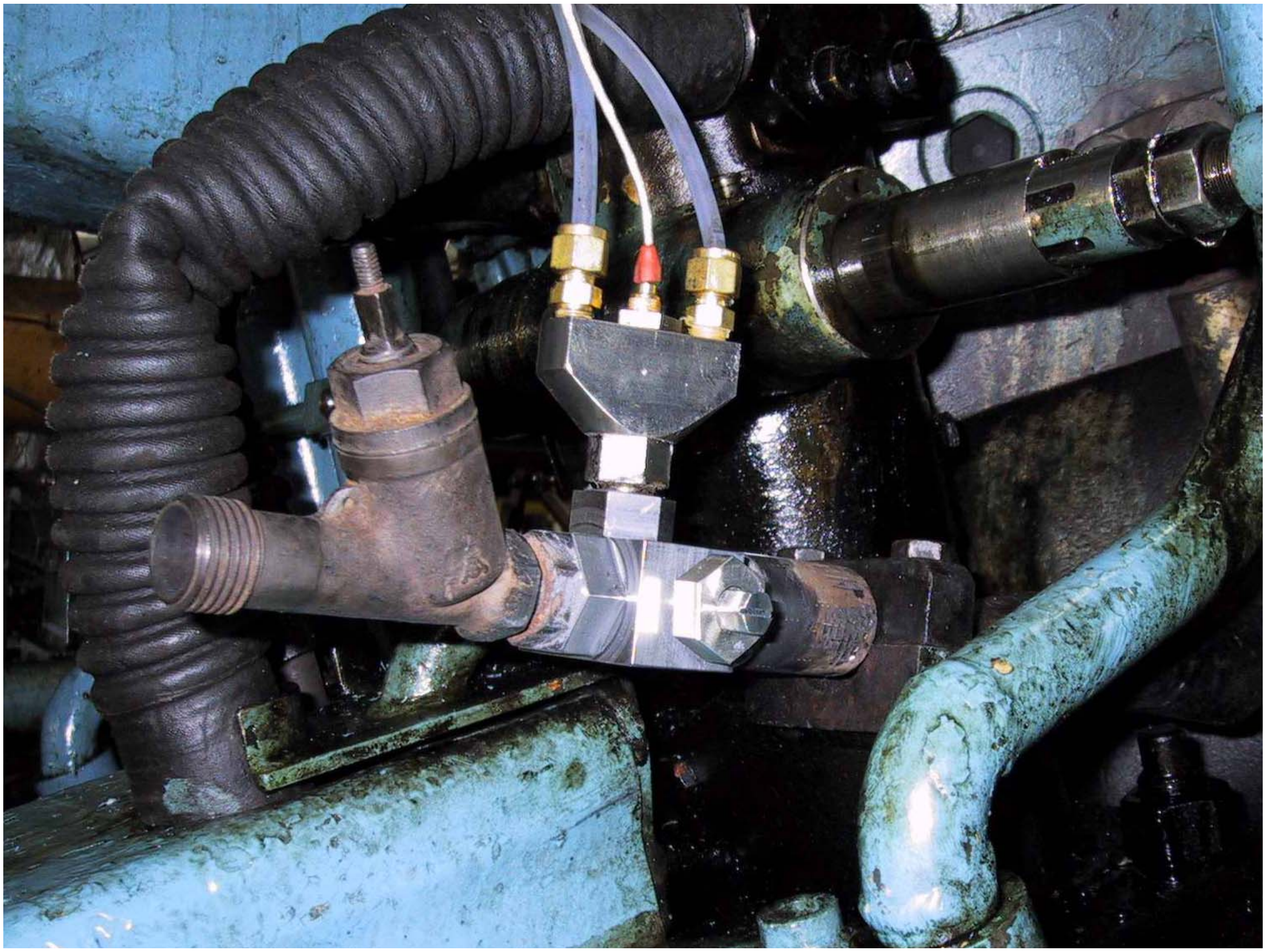

Figure 5. Water-Cooled Piezoelectric Sensors

Fuel Flow

Fuel mass flow (kg/h) is measured by fuel flow meters installed in both the supply and return lines to the engine. Continuous direct fuel flow measurements using an acoustical Coriolis effect type sensor are made using two MASS1200 flow meters with their MASS6000 signal converter. The output of each flow meter is then subtracted from one another using a processing unit. The accuracy of the system is within 1 percent of the actual flow.

Engine Speed

Special hardware was developed to allow precise timing information measurement on the engine. A stainless steel (non-magnetic) band to which were attached 18 steel blocks at very precise intervals (better than 0.08 degrees) was mounted on the engine flywheel (Figure 6). The steel blocks provide the magnetic reluctance variations required by Hall effect magnetic sensors mounted on the engine block. Shorter block spacing at the band junction provides slightly shorter pulse duration at the output, indicating to the FPRT the completion of a complete revolution of the engine. The rpm information is derived from the measurement of pulse frequency from the Hall effect sensor.

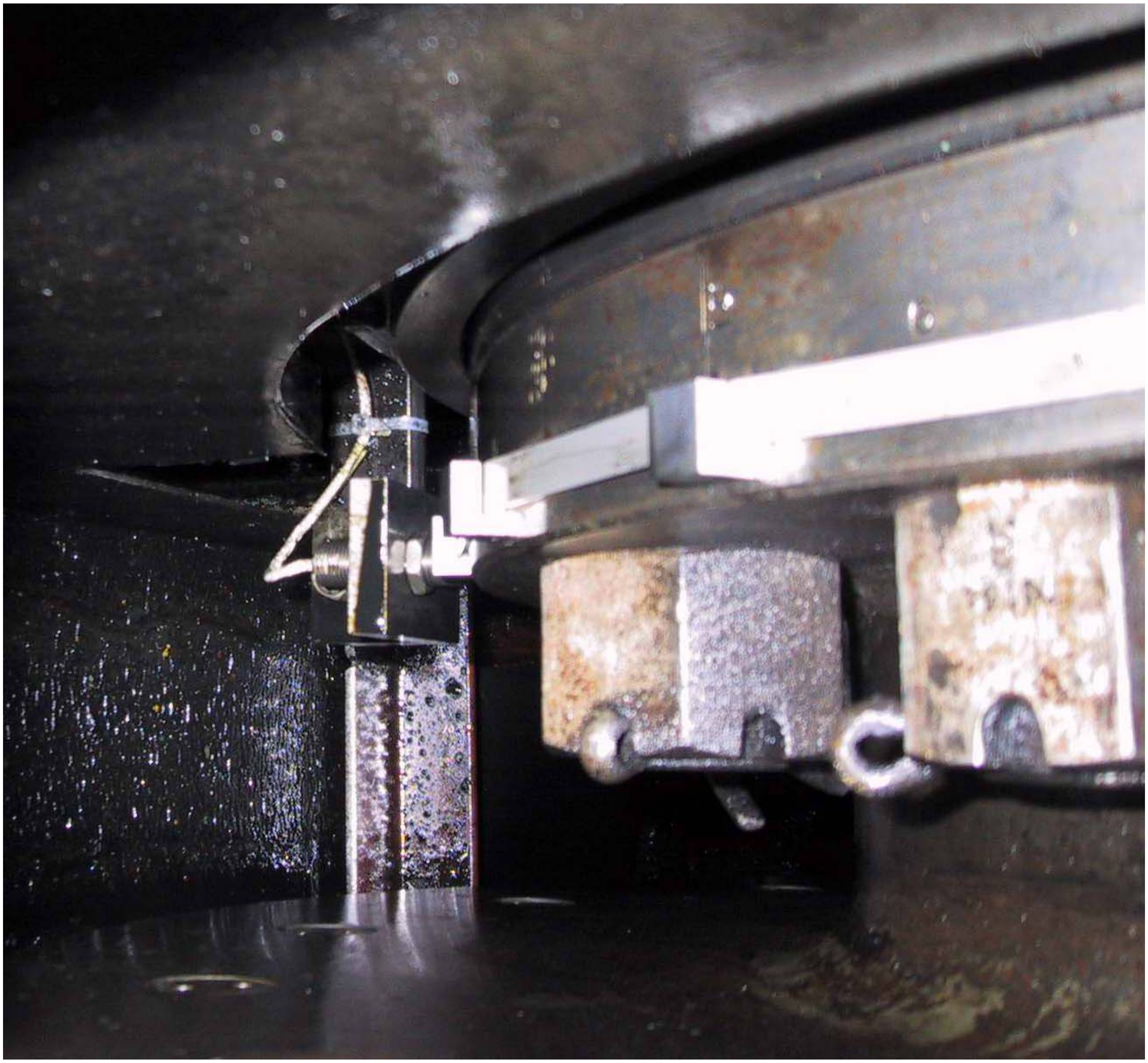

Figure 6. Engine Speed Sensor

Engine Power

Indicated engine power is calculated from the cylinder pressure curves, in combination with the engine instantaneous combustion chamber volume derived from precise crankshaft angle measurement. The brake power is then calculated by subtracting the friction power from the indicated power.

Fuel Rack Position

An angular displacement transducer (Figure 7) measures the fuel rack position with accuracy better than 0.1 mm.

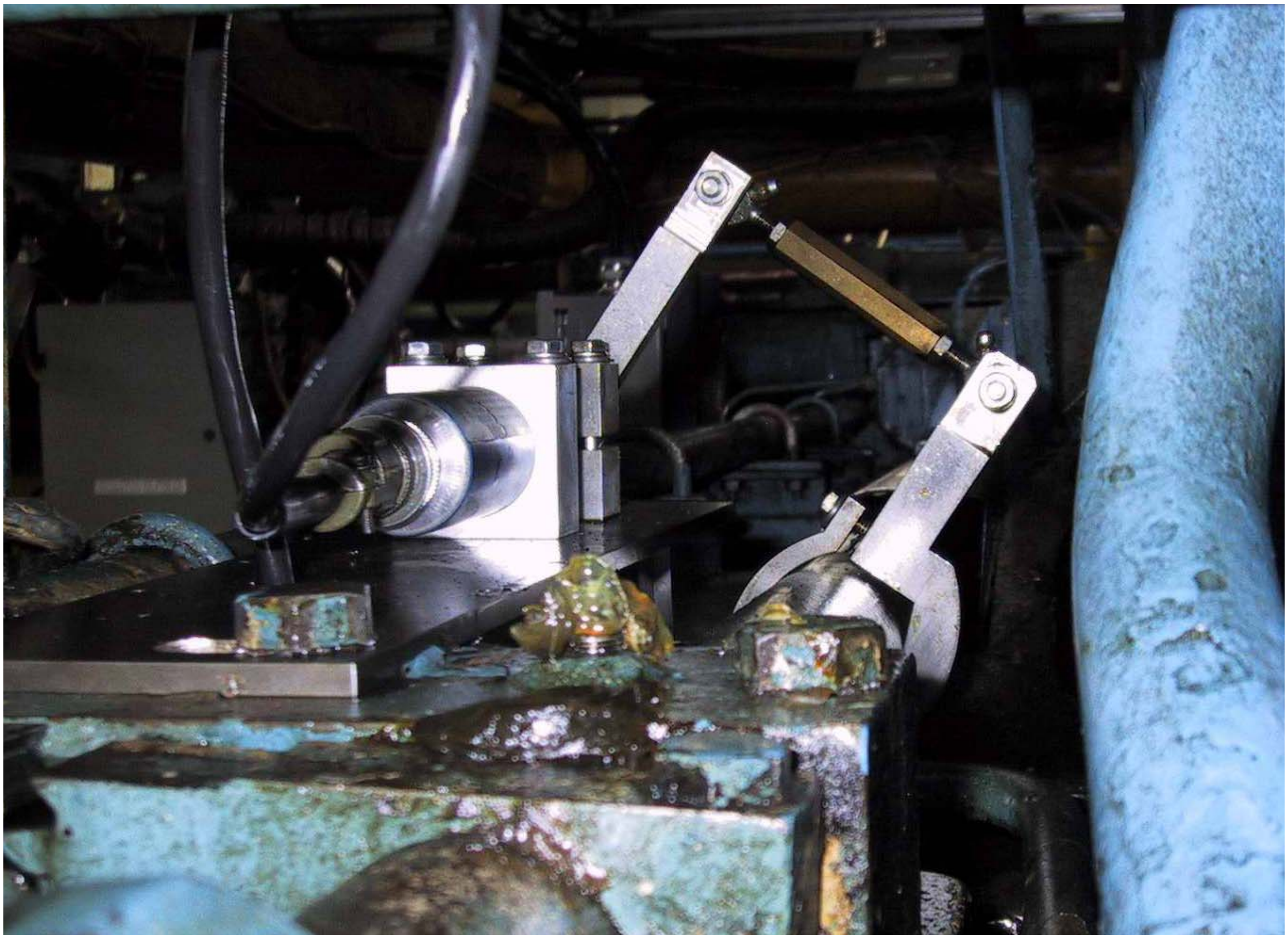

Figure 7. Fuel Rack Position Sensor

Additional Temperature and Pressure Measurements

Additional measurements include:

- Individual exhaust temperatures *(Sensor: Type K thermocouples, Output: ºC)*
- Turbo temperatures *(Sensor: Type K thermocouples, Output: ºC)*
- Exhaust pressure *(Sensors: Intertechnology 211-B-UN, Output: kPa)*
- Charge air temperature *(Sensor:Thermo-Kinetics R11-D100A3, Output: ºC)*
- Engine cooling water temperature *(Sensor: Thermo-Kinetics R11-D100A3, Output: ºC)*
- Charge air pressure *(Sensors: Intertechnology 211-B-UM, Output : kPa)*

- Combinator position *(Q408 Action Instruments Isolation Interface + 10 bits ADC)*
- Propeller pitch *(Q408 Action Instruments Isolation Interface + 10 bits ADC)*
- Vessel location *(Global Positioning System [GPS] receiver)*

7.2 Communication Link Between the FPRT and the Emissions Sampling/Analysis System

The portable SMART multi-gas analyzer (Figure 8) was used to continuously sample raw emissions constituents at a rate of 1 Hz. The SMART 2000 system analogue outputs were directly connected to the engine data logging system.

Figure 8. Portable Emissions Analyzer (SMART)

In addition, a Horiba MEXA-720 NOx & A/F Ratio analyzer (385950) and a smoke meter for continuous measurement of NOx and opacity were installed. The intent was to undertake long-term monitoring of the impact of the WIS on the engine emissions. These two systems have an analogue output, which could also be connected to the engine data logging system. The outputs from these systems are as follows:

System	Output	Units
Horiba MEXA-720 NOx & A/F Ratio analyzer	Analog Output: 0 – 5 V DC Serial Interface: RS-232C	NOx: 0 – 3,000 ppm (for lambda >1) A/F: 9.5 – 200 Lambda: 0.65 – 13.7 O_2: 0 – 25 Vol%
Bosch RT100 Smoke meter	Serial Interface: RS-232C	

In contrast, there was no permanent electronic connection between the engine data logging system (FPRT) and the main ECOM mini-dilution emissions sampling and analysis system that were used during the WIS trials. The emissions measurements from the ECOM system and the engine parameters recorded by the data logging system were synchronized during the time of data acquisition. All parameters from the engine data logging system were recorded automatically at 1 Hz during the sample period – e.g., fuel flow, engine load, engine speed, and engine power – and were correlated with the emissions measurements.

8. Vessel

The MV *Cabot* is one of three ice-class RoRo containerships operated year-round by the Montreal-based commercial shipping company Oceanex. The vessel was built in 1979 and has a gross rate tonnage of 14,597. The ship is powered by two twin Pielstick PC2.5 V12 engines each rated at 5365.5 kW MCR. The MV *Cabot* runs between Montreal, Quebec, and St. John's, Newfoundland, covering approximately 2200 nautical miles. The ship has a cargo capacity of 644 TEU, but a typical voyage load is about 550 TEU (85 percent capacity) on average, composed primarily of 40-foot containers. The test vessel and engine are described in Table 5.

Table 5. Test Vessel – Engine Specifications

Vessel Name	MV Cabot
Ship Description	RoRo Container
Gross Tonnage	14,600 GWT
Main Engine Description	12PC 2.5V Engine,
Manufacturer	Pielstick
Bore and Stroke	Bore 400 mm, Stroke 460 mm
Fuel Quality	Marine diesel oil (MDO) and IFO 180 cSt
Number of Cylinders	V-12
MCR and Speed	5.37 MW at 500 rpm

8.1 Operating Profile

The MV *Cabot* makes weekly round trips between Montreal and St. John's (see Figure 9). The outbound voyage departs from Montreal and takes approximately 2½ days of steaming time, depending on the weather and season. The inbound voyage from St. John's takes roughly the same time. The total operating time for the engines is about 137 hours per trip. Over an average year, the vessel does 48 weekly round trips, for a total engine operating time of 6,600 hours per year. The engines are usually operated at equal load levels in a combinator mode at a constant speed around 500 rpm. In this mode, the ship's speed is controlled by varying the pitch of the propellers. Although capable of 18 kn, the typical average speed for voyages is about 16.5 kn. The engines are well-balanced during operations and maintained regularly with new parts and components to achieve optimal efficiency. The engine thermal efficiency is calculated at approximately 48 percent,[4] which falls into the expected range of 45 to 50 percent for medium-speed engines.

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[4] Based on IFO @ 42 GJ/t and MDO @ 39 GJ/t.

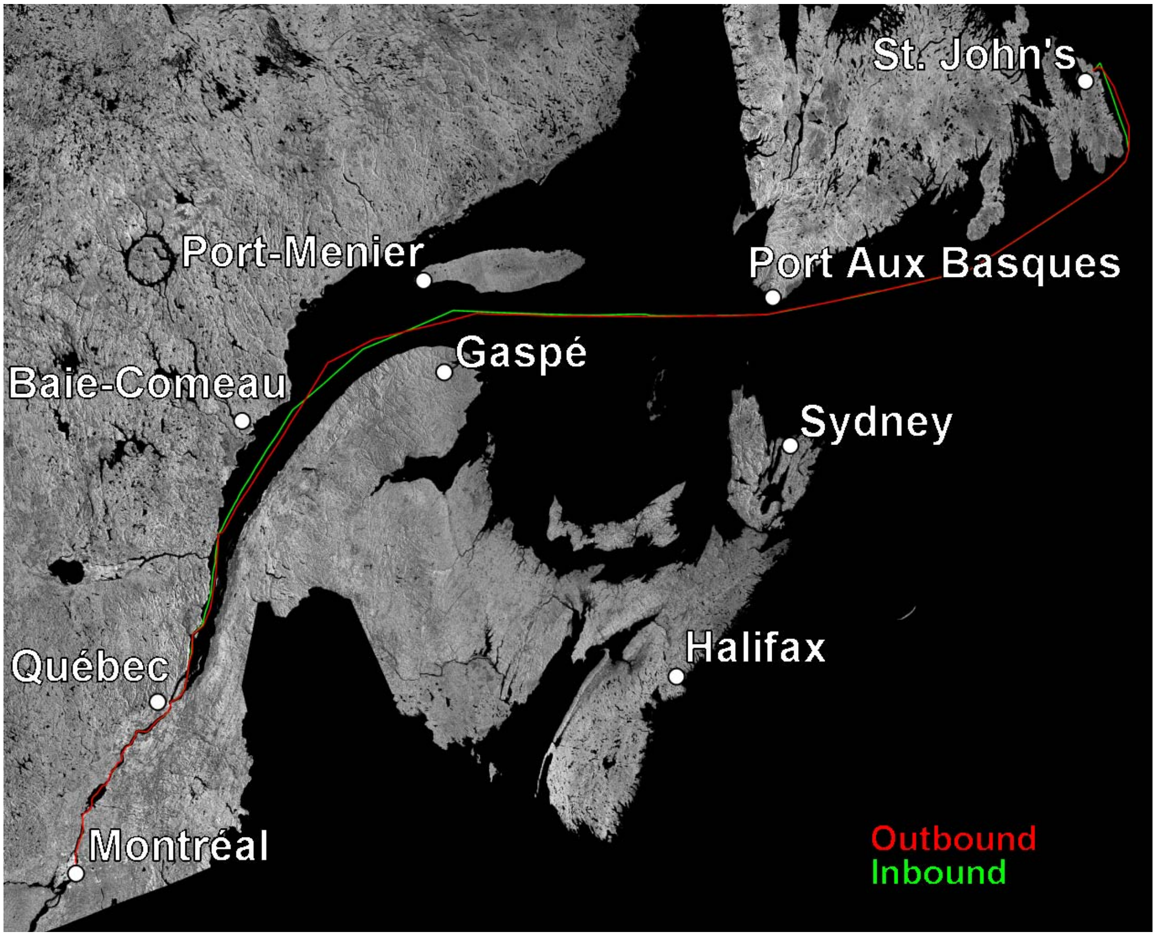

Figure 9. MV *Cabot* Route

8.2 Fuel

The MV *Cabot* engines consume IFO 180 cSt fuel oil as the primary fuel for 98 percent of the time and MDO when near port. IFO 180 is a common mid-grade marine fuel oil, also known as "marine bunker", which is a blend of mostly heavy or residual fuel oil and some MDO. This fuel meets British Standards Institute specifications of a maximum 180 cSt viscosity at 50°C and has a density of about 0.97 kg/L. The calorific value of IFO 180 is assumed to be 42 GJ/t, similar to that of heavy fuel oil. The sulphur content of the IFO fuel used on the *Cabot* averages just under 1.5 percent or 15,000 ppm. Many commercial marine operators try to use IFO 180 since it is perhaps the cheapest fuel blend that ensures reliable engine performance and meets local environmental restrictions. Many ports have maximum allowances for sulphur in fuels. For example, fuel sulphur levels in Toronto and Montreal are restricted to a maximum of 1.5 percent.

The optimum engine fuel consumption is achieved over a load range of 82 to 86 percent MCR.[5] The main engine fuel consumption is approximately 200 tonnes of IFO 180 and 4 tonnes of MDO fuel per trip. This translates into an overall fuel consumption rate of approximately 220 g/kWh. In port areas, the engines are operated on MDO alone, but this amounts to about 2 percent of the total fuel use for a voyage. MDO has a density of 0.866 kg/L and an assumed heating value of 39 GJ/t.

The fuel properties (as per the sample supplied to ERMD) can be found in Table 6.

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[5] On a typical trip, the average load recorded was 9,900 kW (2 engines), which is roughly 85 percent of MCR.

Table 6. Test Fuel Properties

Fuel Property	MDO	IFO
Density (kg/m^3)	0.866	0.978
Carbon, mass (%)	86.49	87.63
Sulphur, mass (%)	0.394	1.3
Nitrogen, mg/kg	N/A	0.29
Flash point (ºC)	57.8	76.5
Kinematic Viscosity (cSt) @ 40ºC	1.3 – 4.1	418.8

The typical sulphur content of MDO is about 0.5 percent or 5000 ppm. The U.S. EPA has issued a final notice of rule making for marine diesel fuel, limiting sulphur content to 500 ppm in 2007 and 15 ppm in 2012. These limits apply to the smaller Category 1 and Category 2 marine diesel engines under 30 L/cylinder. In contrast, the EPA is not proposing any legislation for lower sulphur limits for the larger Category 3 ocean-going vessels beyond those specified under IMO Annex VI.

8.3 Engine Emissions

Onboard emissions testing was conducted by ERMD on marine vessels operating in Canadian waters to establish an emissions inventory. The 1992 stand (sample) of ships showed that the expected range of average uncontrolled NOx emissions for vessels with medium-speed engines was in the range 10 to 22 g/kWh. Actual uncontrolled NOx emissions for the MV *Cabo*t have been measured by Environment Canada in limited performance tests.[7] Environment Canada test data shows that the MV *Cabot*'s NOx emissions ranged from 15 g/kWh at the highest load to 24.8 g/kWh when operating at low load when entering the port. It is standard practice for the MV *Cabot* to operate the engines near 85 percent MCR for the greater part of the 137 hour round trip. Based on previous emissions tests, the uncontrolled measured NOx emissions were calculated at 16.0 g/kWh. This translates into a total NOx emissions inventory of 1025 tonnes per year.

Baseline engine NOx emissions from diesel engines are measured on the test bed and do not generally tend to increase appreciably over the life of an engine, since they are largely based on the combustion temperature-time profile. PM and HC emissions are very much dependent on engine maintenance and tend to increase with time. NOx emissions, however, are affected by water injection or other emissions reduction technologies. Engines equipped with these systems also require changes to fuel injection timing and other engine adjustments, which change the NOx emissions profile of the vessel.

Consequently, to demonstrate compliance, a direct means of measuring in-use NOx emissions is recommended. Online continuous NOx measurements would serve as a reference mark relative to emissions limits. Continuous monitoring of emissions would permit the vessel owner to operate the emissions reduction system more effectively and thus achieve emissions limits, taking into consideration the ship's operating profile, engine duty cycle, and fuel quality.

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[6] On a typical trip, the average load recorded was 9,900 kW (2 engines), which is roughly 85 percent of MCR.

[7] Environment Canada, *Engine Exhaust Emissions Evaluation of the CABO*T (ERMD Report #00-12), Dec. 2000.

9. Emissions Measurement System

The emissions analyzer and sampling system consisted of a portable mini-dilution system (ECOM) capable of taking detailed emissions measurements of NOx, THC, CO, CO_2, O_2 and PM. The engine parameters were simultaneously recorded by a dedicated data logging system at 1 Hz. The engine was instrumented to measure power, fuel flow, engine speed and rack, as well as various engine temperatures and pressures.

In addition, two portable continuous emissions multi-gas analyzer systems (SMART 1500 & 2000) were used to measure NOx, CO, O_2, CO_2, and THC. A Horiba MEXA-720 NOx & A/F Ratio analyzer (385950) was also installed in the raw exhaust gas stream to measure NOx and O_2.

The portable SMART 2000 emissions analyzer was connected to the engine data logging system (sampling at 1 Hz) and provided continuous emissions and engine data during the trial. The data acquisition system recorded both engine performance data and regulated emissions (e.g., NOx, THC, CO, CO_2, O_2).

The ECOM is a discrete sampling system designed for a marine application for collecting gaseous and particulate emissions samples. It was developed by ERMD and correlated to a full exhaust emissions dilution and sampling system that is employed for the certification of engine emissions according to Environment Canada and U.S. EPA test protocols. The ECOM analyzer was installed in the dilute exhaust stream and required 15 minutes to sample the constituent gases. The ECOM system recorded detailed emissions measurements of NOx, THC, CO, CO_2, O_2 and PM. The emissions constituents were then analyzed as follows:

• Carbon Monoxide	Non-Dispersive Infrared Detection (NDIR)
• Carbon Dioxide	Non-Dispersive Infrared Detection (NDIR)
• Oxides of Nitrogen	Electro-chemical as well as direct insertion zirconia ceramic sensor
• Total Hydrocarbons	Non-Dispersive Infrared Detection (NDIR)
• Particulate Matter	PM2.5 and PM10 Gravimetric Procedure
• Opacity	Bosch Smoke Meter

The duration of the individual tests was dependent on the sampling time required for the PM filter collection. To ensure repeatability of the data, two PM samples were taken simultaneously during the 15 minute period allocated to PM collection. The emissions measurements were conducted during steady-state engine operation in conjunction with each engine load configuration (e.g., 25, 50, and 75 percent) and for varying W/F injection volumes.

9.1 Mini-Dilution Sampling System

The primary function of the mini-dilution system was to collect a known quantity of raw exhaust (partial flow) from the exhaust system of an engine and mix this with a known quantity of ambient dilution air so that a particulate sample could be obtained. Diluting the raw exhaust with ambient air while maintaining a constant temperature and flow velocity conditions the sample and minimizes condensation, a major obstacle to PM collection in the field. This technique was used in order to determine average weighted emissions rates over defined periods of operation. Figure 10 represents a schematic flow diagram of the raw sample once it enters the emissions sampling and analysis system.

For vehicle applications, the engine functions under various speed and load conditions. As a result, the volume of exhaust varies, as does the concentration of the pollutants. However, for marine application, the engine operation is typically at steady state. In order to accurately measure emissions under these conditions, isokinetic or proportional sampling is not required. This is accomplished by establishing a flow rate of the dilution air that permits the collection of a “dry” PM sample with sufficient mass on the collection media.

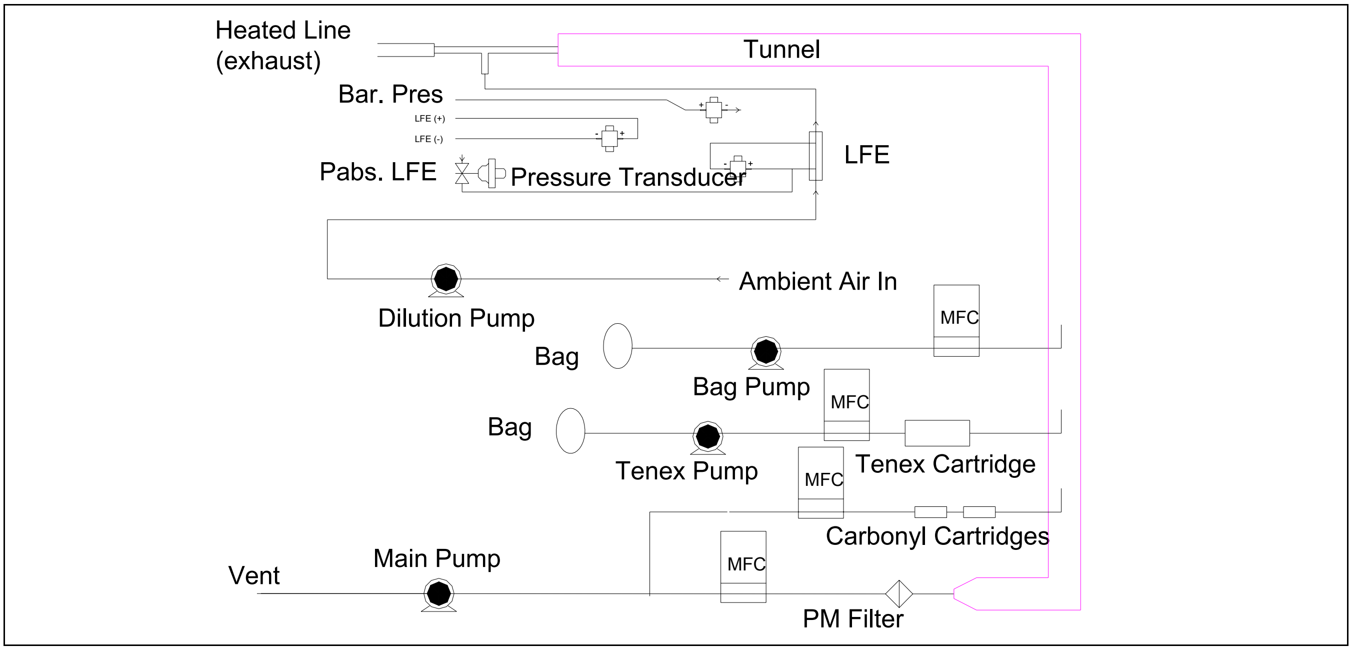

Figure 10. Schematic Flow Diagram of the Sampling System

9.2 Analyzers

The emissions analyzers and associated reference calibration gas were set up in a location in close proximity to the test engine.

9.3 Data Acquisition

The outputs from the two analyzers and the Horiba NOx sensor were recorded on notebook computers. This data was analyzed post-test and combined with the fuel and air flow data collected by the Transport Canada system in order to report the mass emissions rates.

10. Sampling Set-Up

The set-up involved installing the mini-dilution system and analyzer bench with associated calibration gases in the engine room of the vessel. Figure 11 shows the ECOM mini-dilution tunnel system installed in the engine room of the MV *Cabot*.

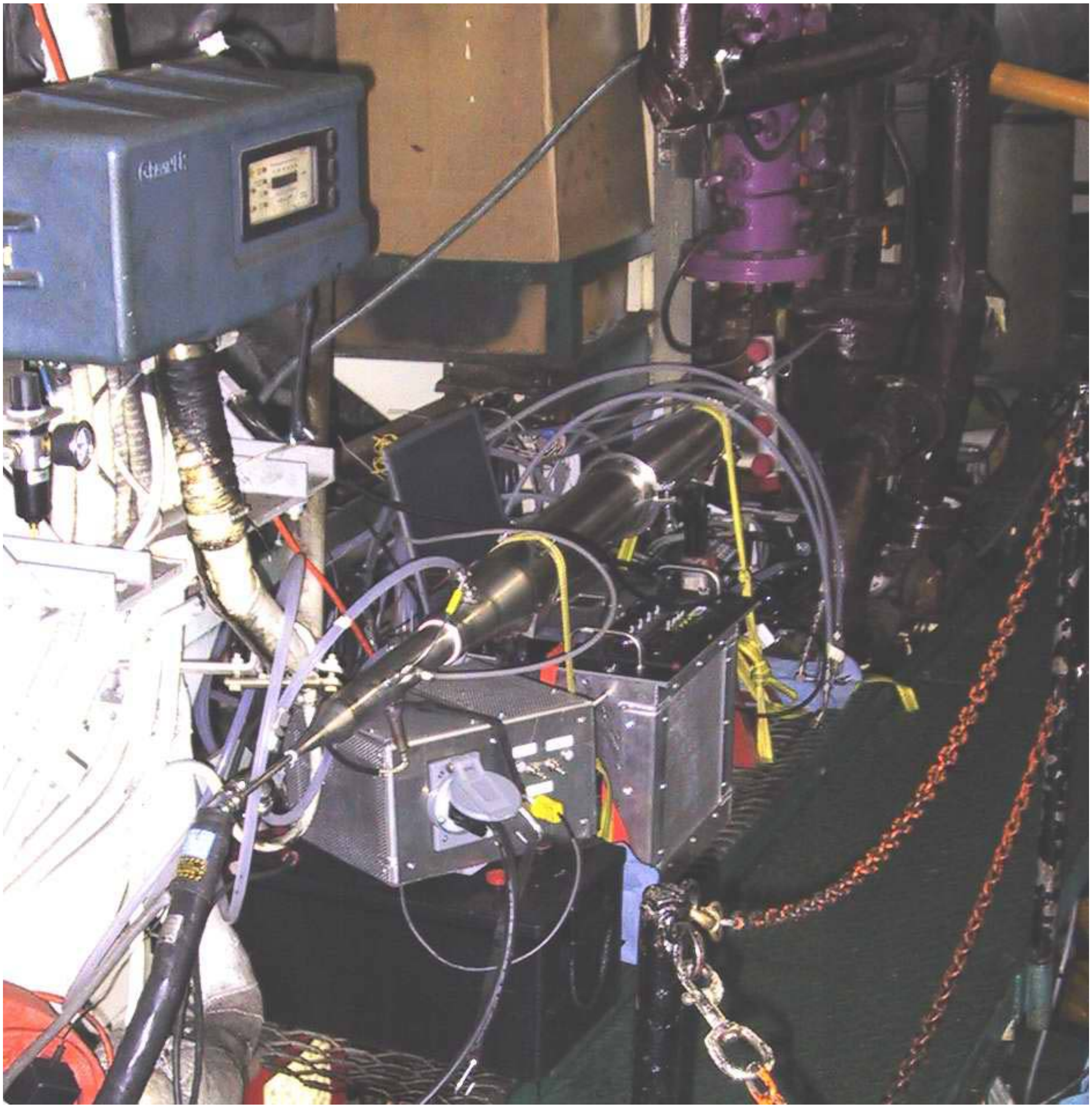

Figure 11. Portable Mini-Dilution Tunnel

10.1 Heated Line and Exhaust Probe

A 25 ft. length of heated line connected the exhaust probe to the dilution tunnel. The exhaust probe was 3/8 inch stainless steel tubing, which had concentric holes located along its length. The probe was inserted perpendicular to the exhaust flow and traversed ¾ of the exhaust duct diameter. The probe was connected to the heated line with a Swagelock™ fitting**.**

11. Emissions Test Procedures

11.1 Pre-Test Calibration

Prior to shipping the mini-dilution system to the site location, the following activities were undertaken at ERMD test facilities:

Sampling System Correlation

The ECOM mini-dilution system was installed into the heavy-duty engine test cell at ERMD. The system was then operated in parallel with the full-size dilution system and analyzer bench. The two sampling systems were compared over both steady-state operation of the engine and the transient cycle used for certification of new on-road engines. The ERMD full-size emissions collection apparatus in the program utilizes a constant volume sampling (CVS) system that dilutes the engine exhaust during the test with filtered ambient air from the test cell. A schematic of a Test Cell is shown in Figure 12. This system allows measurement of the true mass of the gaseous and PM emissions from the engine or vehicle during operation. The design of this sampling and analytical system for engine emissions follows the protocol of the CFR Title 40 Part 86.

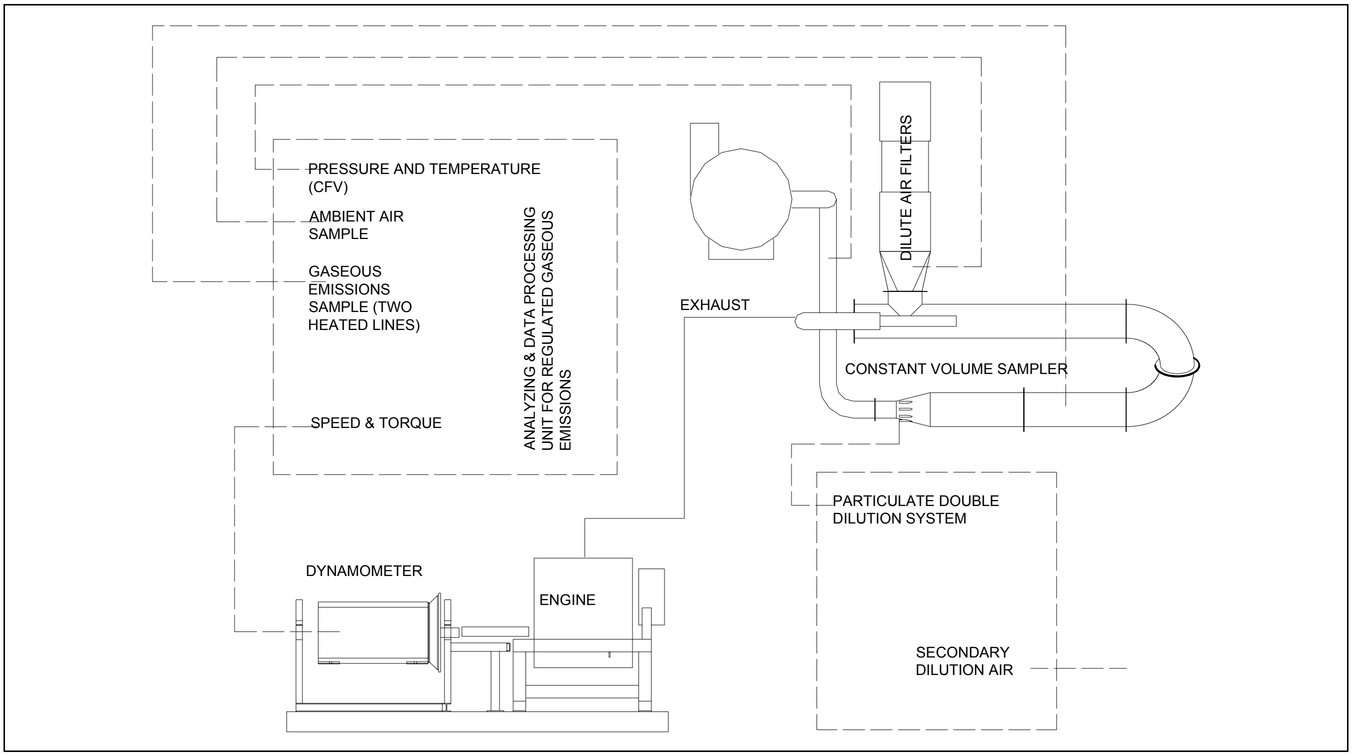

Figure 12. Test Cell Schematic

The total volume of raw exhaust was transferred from the engine/vehicle exhaust manifold to the CVS through a steel exhaust pipe. The raw exhaust was then diluted with HEPA-filtered laboratory ambient air within the dilution tunnel. The dilute exhaust was passed through a critical flow venturi. Data obtained from temperature and pressure sensors located upstream of the venturi and downstream of the sampling zone allowed for correction of the volumetric flow rate to ASME standard conditions (i.e., 273 K, 101.325 kPa). Dilution air was filtered through a set of filters (bag, activated carbon and HEPA) to increase PM measurement accuracy.

During the comparison testing, a sample probe was installed in the raw exhaust transfer pipe and the ECOM sample was extracted from there. A continuous flow of the diluted exhaust was collected from the CVS through in-line sampling probes and directed to the analyzers through heated filters, pumps and sample lines. In each case, the emissions data was corrected for background air concentrations.

Instrument Calibration Checks

The SMART and ECOM analyzers were calibrated using a commercial reference gas, which is a mix of the target compounds found in the exhaust constituents. All flow controllers were calibrated against a dry-gas calibration tool.

11.2 On-Site System Operation and Test Verification

System verification and testing started once the mini-dilution system and sensors were installed, allowed to warm up, and verified to be functioning correctly as read on the computer. New filters were installed in each of the filter holders.

System verification consisted of a leak check of the mini-dilution system, verification of the system flows, and calibration of the analyzers.

12. Emissions Tests

12.1 MV *Cabot* Sea Trials – Engine Emissions Tests

Emissions from the engines were measured at a point where the two banks of the 12 V Pielstick PC2.5 engine combine into a single exhaust uptake. The temperature of the exhaust gas before the turbocharger was in the range of 350 to 370°C. The economizer inlet exhaust temperature was 325°C, but this fell to about 240°C at the economizer outlet. At maximum continuous rating, the exhaust gas flow rate was 3.54 tonnes per hour per cylinder. The stainless steel probes were inserted into the exhaust ducting after the economizer, and a sample line was led to the mini-dilution tunnel. Coinciding with the dilute exhaust measurements, ERMD also collected raw exhaust data from the Horiba MEXA-720 NOx & A/F Ratio analyzer (385950) and measured the opacity using the selected smoke meter. Once the vessel was operating at the desired test condition (engine speed and load), the test team initiated the test. The following steps were followed:

1. TDC personnel notified the ERMD test team that the engines were at the selected operating condition.
2. ERMD test team provided a signal to the engine data logging system that emissions sampling had been initiated (via an electronic connection activated by a switch at the ERMD bench).
3. The engine power, fuel flow, etc. was automatically logged by the engine data logging system and was correlated with the emissions sampling done by the ERMD test team.
4. Initial raw exhaust measurements of CO_2 and O_2 concentrations were taken and used to determine exhaust gas flow rate.
5. Dilution rate was set on the ECOM system and verified.
6. Dilute exhaust emissions measurements for each test condition were obtained over a 15-minute period. Two PM samples were taken simultaneously to ensure repeatability of data.

The tests were carried out with the engines operating in a steady-state condition. Emissions measurements were taken at each load setting (e.g., 25, 50, and 75 percent engine load) and for a range of water injection volumes. The WIS system was operated over a range of water volumes at each of the specified load conditions. The time of each test configuration was approximately 30 minutes. Emissions measurements were taken with the propulsion engines operating at the conditions specified under the ISO 8178-4-E3 protocol.

12.2 Test Results

Emissions tests were conducted at a steady-state engine operating condition with the WIS in operation. Baseline emissions measurements for each load condition were taken prior to the activation of the WIS. The engine was operated on both MDO and IFO. Field tests showed that NOx and PM emissions are dependent on load, fuel quality and higher W/F ratio. It is evident that fuel quality has an effect on emissions. In the case of IFO 180 cSt the fuel effect of the entrained nitrogen is not insignificant. It has been reported that fuel-bound nitrogen (0.4 percent) in residual fuel produces a 22 percent increase in NOx over distillate fuel.[8] This is illustrated in Figures 13 and 14, when comparing the specific NOx emissions at 50% load for both MDO and IFO. In general, NOx decreases with increasing engine load and W/F ratio. The rate of NOX reduction is more pronounced at higher loads and higher W/F ratios with the engine burning IFO 180 cSt.

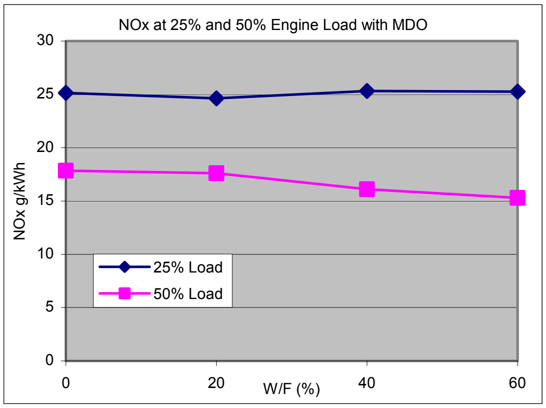

Figure 13. NOx as a Function of W/F Ratio and Engine Load with MDO

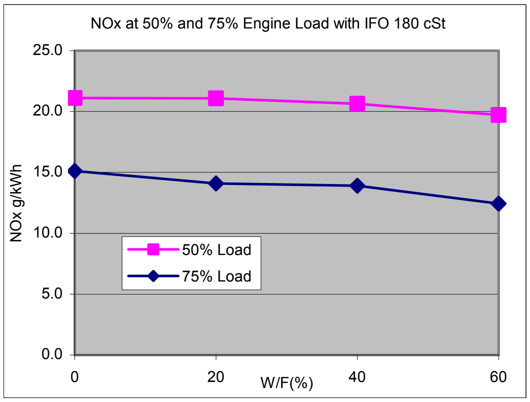

Figure 14. NOx as a Function of W/F Ratio and Engine Load with IFO

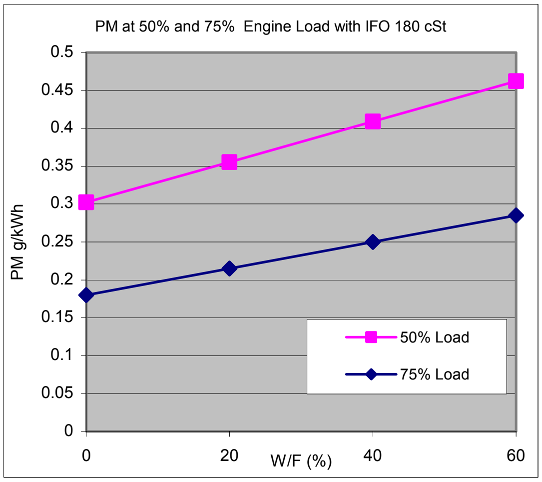

Figure 15. PM as a Function of W/F Ratio and Engine Load with IFO

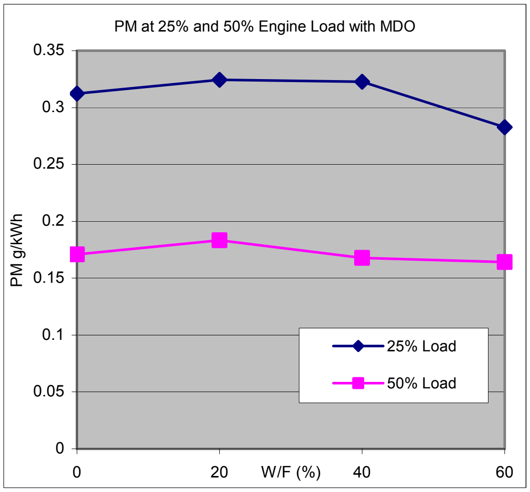

Figure 16. PM as a Function of W/F Ratio and Engine Load with MDO

As illustrated in Figures 15 and 16, PM production is very dependent on fuel quality, and increases with W/F ratio. A 60 to 70 percent increase above baseline was measured when using IFO 180 cSt at high W/F ratios. In contrast, when the engines were operating on MDO, the PM values remained constant. This increase is attributed to the high sulphur content (about 1.3 percent) as well as the higher concentrations of asphaltenes in the fuel. The addition of water to the combustion process results in greater PM formation. On one hand, the lower cylinder temperatures promote the formation of soot, SOx and sulphates during combustion; on the other, they inhibit PM oxidation, which is more efficient at higher temperatures.

A similar increase in CO with water injection was measured when operating on IFO. CO formation is due to incomplete combustion and appeared to increase dramatically with water injection when burning heavy fuel. There was no CO increase at 50 percent load when operating with MDO and water injection (see Figure 17).

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[8] EPA420-R-004, January 2003

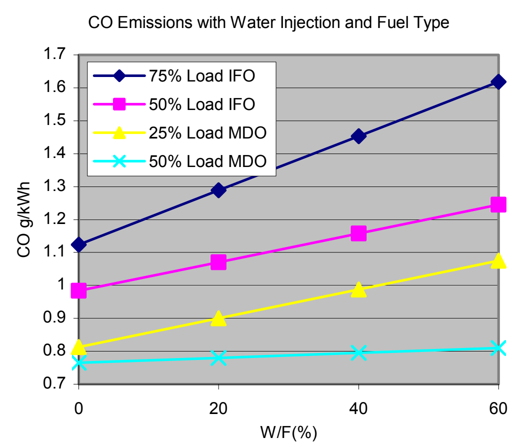

Figure 17. CO Test Results with MDO and IFO

When examining the overall effect of water injection on NOx reduction, it is evident that the major NOx reductions (in the range of 30 percent) are made when operating at higher W/F ratios and above 50 percent load as shown in Figure 18. A maximum NOx reduction of 30 percent could be achieved at 75 percent MCR and 100 percent W/F ratio.

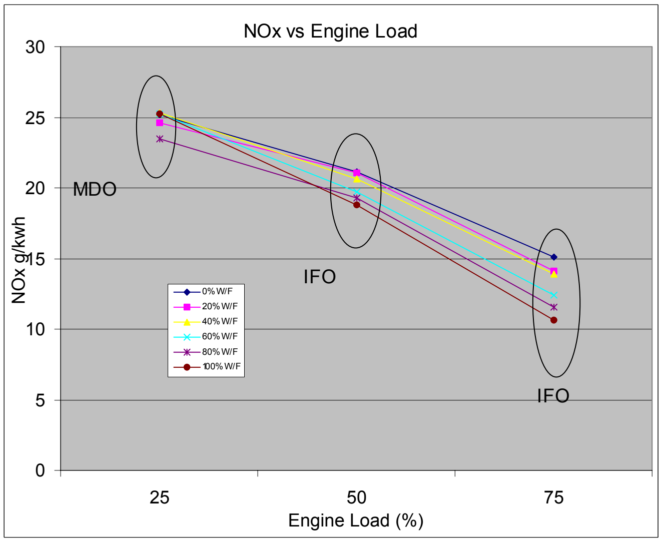

Figure 18. NOx Reduction as a Function of W/F Ratio and Engine Load

Table 7 gives specific emissions at 75 percent load.

Table 7. Emissions (g/kWh) at 75% MCR with IFO 180 cSt

WIS W/F	Fuel Flow kg/h	Engine Power kW	SFC kg/kWh	CO	NOx	CO_2	PM
0	851	3923	0.217	1.07	15.1	637	0.180
.20	850	3899	0.218	1.17	14.1	649	0.215
.40	847	3834	0.221	1.28	13.9	662	0.250
.60	850	3847	0.221	1.38	12.4	674	0.285
.80	843	3903	0.216	1.48	11.5	687	0.320
1.00	845	3876	0.218	1.59	10.7	699	0.355

Note: The shaded area represents projected values.

The general trend is an increase in CO and PM and a decrease in NOx with increasing W/F ratios. The tests show that PM production is very fuel dependent and increases with W/F ratio. Fuel consumption and CO_2 are not affected greatly by water injection. The WIS effectively reduces NOx emissions at the expense of an increase in PM and CO when operating on IFO 180 cSt. Tables 8, 9, 10, and 11 detail the results from the WIS tests on the MV *Cabot*, conducted March 15-22, 2004.

Table 8. Emissions Rates (g/kWh) at 25% MCR and MDO

Test Run	WIS water-fuel ratio	WIS water kg/h	Fuel flow kg/h	Engine power kW	SFC kg/kWh	CO	NOx	CO_2	PM	NOx ppm average contin.
1	0	0	258.8	1250.2	0.207	1.53	25.1	687.1	0.312	1456.6
2	.20	50.9	254.5	1247.5	0.204	1.57	24.6	705.9	0.324	1423.8
3	.40	101.64	254.1	1251.7	0.203	1.61	25.3	724.8	0.323	1391.0
4	.60	156.24	260.4	1282.8	0.203	1.65	25.3	743.7	0.283	1358.2

Table 9. Emissions Rates (g/kWh) at 50% MCR and MDO

Test Run	WIS water-fuel ratio	WIS water kg/h	Fuel flow kg/h	Engine power kW	SFC kg/kWh	CO	NOx	CO_2	PM	NOx ppm average contin.
1	0	0	534.8	2606.8	0.205	0.91	18.3	632.8	0.204	1458.4
2	.20	104.92	524.6	2555.5	0.205	1.01	17.6	646.7	0.183	1360.5
3	.30	157.14	523.8	2550.1	0.205	1.07	16.7	653.7	0.179	1311.6
4	.45	251.33	558.5	2694.4	0.207	1.15	15.8	664.1	0.168	1238.2
5	.55	294.20	534.9	2585.5	0.207	1.21	15.4	671.1	0.164	1189.3

Table 10. Emissions Rates (g/kWh) at 50% MCR and IFO 180 cSt

Test Run	WIS water-fuel ratio	WIS water kg/h	Fuel flow kg/h	Engine Power kW	SFC kg/kWh	CO	NOx	CO_2	PM	NOx ppm average contin.
1	0	0	528.5	2433.5	0.217	0.71	21.1	605.3	0.314	1805.9
2	.30	157.59	525.3	2482.2	0.212	0.73	21.1	620.5	0.356	1732.6
3	.40	209.32	523.3	2452.5	0.213	0.74	20.6	625.5	0.392	1708.2
4	.50	264.10	528.2	2510.5	0.210	0.75	20.9	630.6	0.418	1683.7
5	.60	318.66	531.1	2539.3	0.209	0.75	19.7	635.7	0.534	1659.3

Table 11. Emissions Rates (g/kWh) at 75% MCR and IFO 180 cSt

Test Run	WIS water-fuel ratio	WIS water kg/h	Fuel Flow kg/h	Engine Power kWw	SFC kg/kWh	CO	NOx	CO_2	PM	NOx ppm average contin.
1	0	0	851.4	3923.5	0.217	1.07	15.1	637.2	0.184	1340.5
2	.20	170.02	850.1	3899.5	0.218	1.17	14.1	649.7	0.197	1266.1
3	.40	339.0	847.5	3834.8	0.221	1.28	13.9	662.2	0.236	1191.7
4	.45	379.8	844.0	3836.4	0.220	1.30	12.7	665.3	0.372	1173.1

The results of the tests were measured both in kilograms per brake horsepower-hour and in kilograms per metric tonne of fuel. These results can then be used to calculate overall emissions per vessel round trip, based on the specific route profile and operating conditions.

12.3 Discussion of Test Results

As stated in Section 2, the main goal of the tests was to demonstrate and evaluate the effectiveness of a WIS to reduce diesel engine emissions. Water added to the combustion process reduces the maximum combustion temperature and thus leads to lower NOx formation. Data on water-based emissions control technologies suggest that this method has the potential to reduce uncontrolled NOx emissions by more than 50 percent.[9]

One of the findings of these tests was the effect of water injection on PM emissions. PM formation under normal operation is primarily due to incomplete combustion of the fuel. The addition of water tends to aggravate the problem. While water reduces NOx formed at high temperatures, it inversely increases PM formation, which is normally reduced through oxidation at high cylinder combustion temperatures. Another key factor contributing to the production of PM is the use of IFO as the primary fuel for engine operation. IFO is inherently high in sulphur and metal oxides, which leads to an increase in PM in comparison with distillate fuels such as MDO. The challenge lies in reducing PM production while simultaneously reducing NOx emissions. Designers of new engines have adopted a holistic approach incorporating in-cylinder technologies such as controlling the timing and rate of injection, cylinder swirl and increased compression ratios. For a retrofit application, these solutions are limited and the best compromise would be to control the fuel quality when operating in critical environmental areas.

13. Impact of Water Injection on Engine Operation

13.1 Knocking

Knocking occurs in a cylinder when combustion occurs instantaneously instead of gradually as fuel is injected in the cylinder. Typically, this would occur when fuel atomization is poor or when compression pressure or temperature is too low to ignite the injected fuel immediately. Knocking appears as a dramatic and sudden increase in cylinder pressure and temperature, occasionally resulting in audible impact noise outside of the engine. Knocking induces shock waves in the combustion chamber that can result in localized temperature peaks and high instantaneous loads on the various engine components.

The engine under study is instrumented with piezoelectric sensors monitoring the pressure inside each combustion chamber. The piezoelectric sensors are located at the end of a long tube leading to the combustion chamber. The tube connecting the pressure sensor to the cylinder head is a resonant element that distorts the pressure wave measured by the pressure sensor. The tube acts as a resonant element that can be roughly modelled as a second order system (equivalent to a mass and spring resonant system). Any transient signal present in the cylinder will excite this resonant element and these oscillations can be monitored by performing a Fourier analysis of the pressure waveforms measured with the piezoelectric sensor. The more severe the knocking, the more severe the resonance will be in the tube. Due to similar construction for all the cylinders, the resonance frequency is identical for all the cylinders. In the Average Power Density Spectrum (APDS) of the pressure waveform of each cylinder, the resonance frequency is around 2.5 kHz, and the resonance appears in all the recorded data with or without water injection. This resonance is induced mainly by the ignition event in the cylinder power cycle, but is more significant when knocking occurs.

No definite relationship could be established between cylinder knocking and water injection. Some of the cylinders exhibited increased knocking in the presence of water injection, whereas other cylinders showed a reduction of knocking with water injection. Although it can be clearly established that water injection has an impact on cylinder knocking, the nature of that impact is sometimes beneficial and other times detrimental. It was, however, observed that in general, the impact of water injection on knocking was less significant at high engine loads.

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[9] US Environmental Protection Agency. Final Regulatory Support Document: "Control of Emissions from Marine Engines" EPA 420-F-97-016. 1997

Figure 19 shows the APDS of cylinder #1. The amplitude of the power density is shown in different colours.

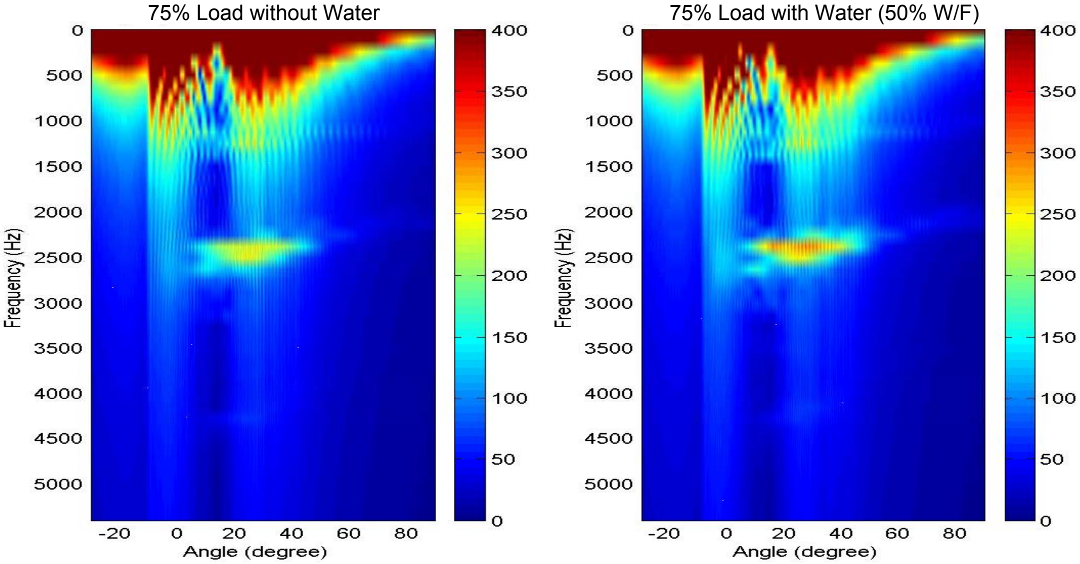

Figure 19. Average Power Density Spectrum of Cylinder #1

13.2 Scavenge Temperature

During the tests performed on the MV *Cabot*, the charge air coolers were maintained in operation. During normal operating conditions, charge air exits from the air cooler at a temperature between 40ºC and 50ºC. Higher temperatures increase the specific volume of the charge air to the point where the flow rate falls below the surge line of the compressor, inducing surging. This phenomenon puts a lower limit on acceptable charge air temperature, normally maintained around 45ºC.

Atomization of water in the air manifold has a direct impact on charge air temperature and humidity. Finely atomized water offers large surface areas in contact with the charge air, and a large area promotes evaporation. At the same time, the heat necessary to evaporate the atomized water has to be drawn from the charge air. The amount of water vapour that can be held by the charge air (saturated vapour) is highly dependent on its temperature. The higher the charge air temperature, the higher the amount of water vapour it can hold. As water is atomized in the air manifold, water droplets start to evaporate, drawing heat from the charge air and therefore inducing a drop in air temperature. The drop in temperature reduces the amount of water vapour that the air can hold. A balance is reached when the amount of water evaporated reaches the maximum water vapour concentration allowable at the final charge air temperature after evaporation.

The final temperature is determined by the amount of heat needed to evaporate the water to reach the saturation point. Once the saturation point is reached, no further evaporation of water is possible and any excess water present in the manifold will remain in its liquid state and will be entrained by the air stream toward individual cylinders. Suspended water droplets in the air stream will eventually coalesce on various surfaces inside the manifold on their way to the cylinders. Condensation on engine surfaces will be more significant at points furthest from the point of water injection.

During the tests on the MV *Cabot*, a relatively constant charge air temperature drop of 20ºC was observed during the water injection cycles, for any W/F ratio of more than 20 percent. Thermodynamic calculations show that the heat loss corresponding to a 20º temperature drop of the charge air at 75 percent engine load corresponds exactly to the amount of heat necessary to evaporate the quantity of water corresponding to 20 percent W/F ratio.

This analysis indicates that any quantity of injected water below 20 percent W/F will be nearly entirely evaporated. Any amount of water above 20 percent W/F will remain suspended in the air stream until it coalesces on internal surfaces. Water reaching individual cylinders will therefore be a mixture of saturated air and suspended water microdroplets.

When operating at 75 percent load and injecting W/F ratios ranging from 20 to 40 percent, the scavenge temperature drop remains relatively constant at 20°C (see Figure 20). The same energy is required to vaporize 20 percent W/F of water at 20°C as to cool the air from 40°C to 20°C at 75 percent load. Therefore, at 30 percent and 40 percent W/F ratio, the scavenge temperature drop is the same as for 20% W/F.

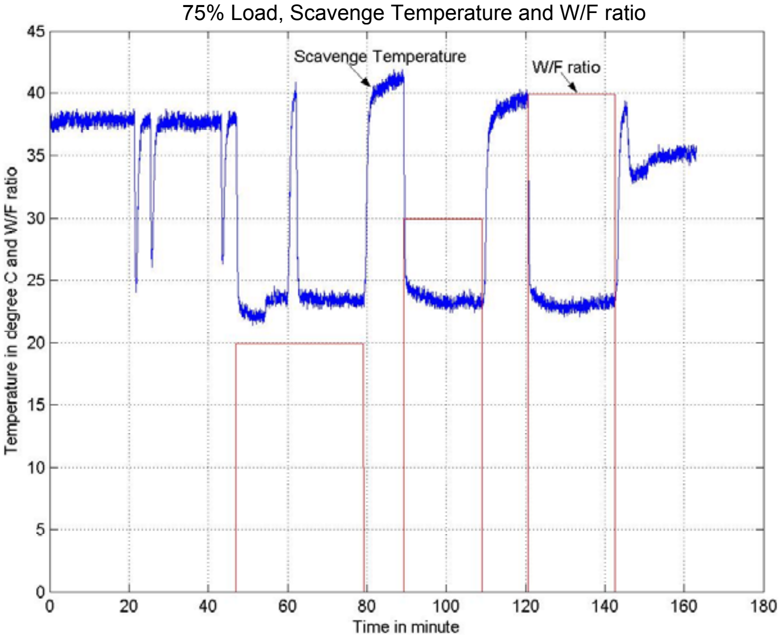

Figure 20. Scavenge Temperature and W/F Ratio at 75% Load

13.3 Effect of W/F on the Shift of the Maximum Pressure Angle (MPA)

The main effect of injected water is to reduce combustion temperatures and delay ignition. A delayed ignition and lower combustion temperatures will delay the point at which the maximum combustion pressure is reached. This effect is more pronounced at low loads, where the temperatures and pressures are lower, than at higher loads, as shown in Figure 21.

At both 25 and 50 percent load, the shift of MPA increases with W/F ratio. However, at 75 percent load there is almost no shift of MPA with increasing W/F ratios. It was also observed that for cylinders #6 and #12 (adjacent to the water injection point) at 25 percent load, the shift of MPA with increasing W/F ratio increased more than for all the other cylinders. This is attributed to the unequal distribution of water among the cylinders located along the air manifold. Water is more highly distributed to the cylinders nearest the point of water injection. This is consistent with the assumption that suspended water will coalesce more for cylinders located farthest from the injection point.

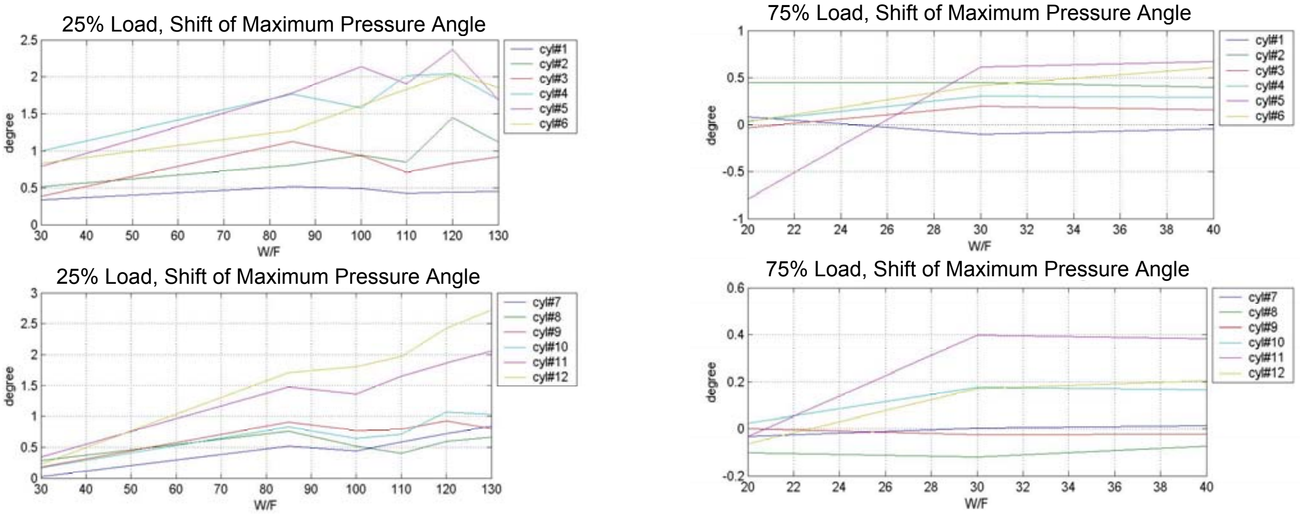

Figure 21. Maximum Pressure Angle as a Function of W/F Ratio

13.4 Effect of W/F on Exhaust Temperature

One of the most direct mechanisms relating water injection to exhaust temperature is through a reduction of charge air temperature resulting from the evaporation of part of the atomized water. A drop in charge air temperature is matched by a similar drop in exhaust temperature. Thermodynamics calculations show that vapour saturated air behaves much like pure air and can be modelled by ideal gas laws such that the relationship $PV^{\gamma} = K$ holds. For air, gamma (γ) = 1.4, whereas for low concentrations of water vapour in air (20 percent W/F ratio), gamma is in the range of 1.39, very close to the value for pure air. During compression, such a small change in polytropic coefficient has virtually no impact on the final compression pressure and temperature.

The maximum water vapour concentration in the charge air is determined by its temperature. It was observed during the trials that, beyond 20% W/F ratio at 75% engine load, there is no further drop in charge air temperature. It has further been observed that cylinders nearest the injection point exhibit exhaust temperature drops in the range of 20ºC at maximum W/F ratio, whereas those farthest away from the injection point show exhaust temperature drops in the range of 5ºC that remain virtually constant, whatever the W/F ratio beyond 20%. Significant combustion temperature drops and hence exhaust temperature drops, must therefore result from more important contributions than those of water vapour-related polytropic coefficient variations alone.

The only mechanism that can account for such large reductions in exhaust temperatures must be the evaporation of excess water suspended in the charge air and drawn into the cylinder during the induction cycle. During the compression cycle, turbulence and energy from the compression contribute to evaporate the excess liquid water, resulting in significant compression pressure and temperature drops at the end of compression. This in turn results in lower combustion temperatures and hence lower exhaust temperature. This effect is more pronounced in those cylinders in which a large amount of excess liquid water is present.

Figure 22 shows the port side relative exhaust temperatures at 75% load. In order to facilitate the comparison of exhaust temperature variations among cylinders, the exhaust temperatures have been offset to match the mean temperatures of the cylinders without water injection. This is visible in the fact that all the cylinders exhaust temperatures are at 355ºC before water injection. This is the only modification made to the exhaust temperature data for the purposes of this graph.

It is clear that as W/F ratio increases the reduction rate of the exhaust temperature increases as well. The reduction rate of cylinder #6 located near the point of water injection is much higher than others located farthest away from the injection point. This indicates that cylinder #6 is getting more water droplets in comparison to the other cylinders. It can also be observed that the exhaust temperature reduction for cylinder #1 remains virtually constant regardless of W/F ratio beyond 20%. It is clear from this data that the water distribution among cylinders is not equal.

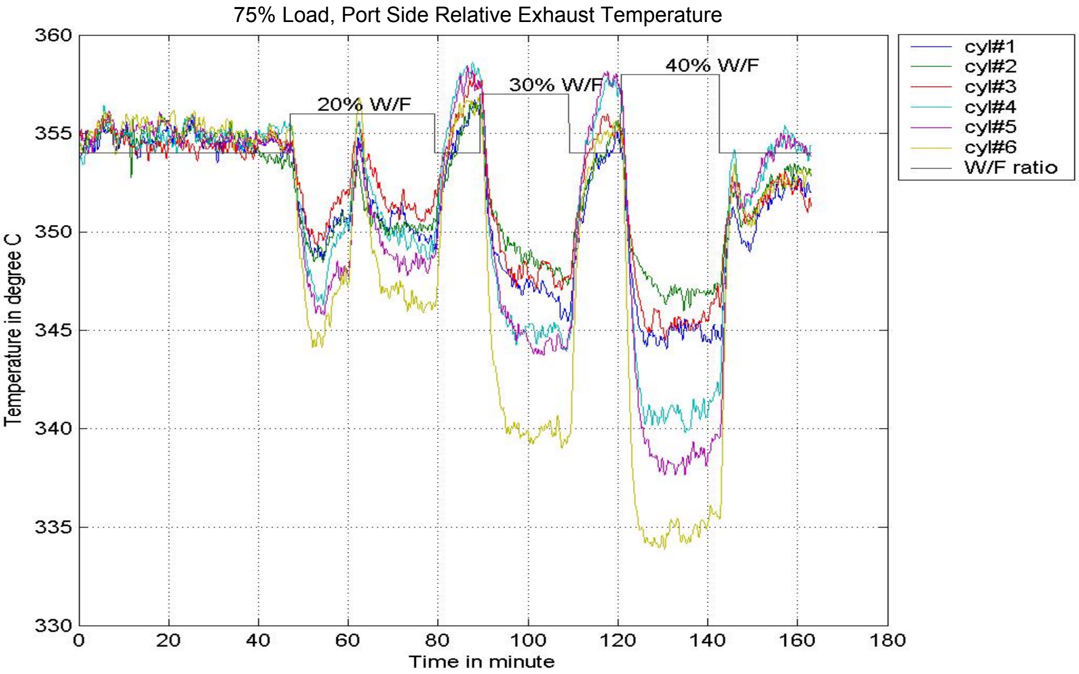

Figure 22. Port Side Relative Exhaust Temperature at 75% Load

13.5 Presence of Water in the Lubricating Oil

Water injected in the charge air manifold eventually reaches individual cylinders in the form of water vapour intermixed with suspended water droplets of very small diameter. It has been shown that cylinders located closest to the injection point receive far more excess water than those located farthest away. In addition, at low engine loads, engine dynamics generate lower air speeds in the manifold, lower charge air density, and lower combustion temperatures. These factors contribute to allow a significant amount of liquid water to coalesce on cylinder walls, eventually ending up in the engine crankcase, where it mixes with the lubricating oil. At high loads, the combustion dynamics will tend to reduce water ingress into the engine sump.

For the purposes of the trials, the engine was equipped with an on-line water detection sensor that monitors moisture content in the oil. Dissolved water content is measured as the percentage of water relative to the saturation level at the temperature considered, 100 percent corresponding to the maximum amount of water that can be suspended in oil before the onset of coalescence. The dissolved water content in the oil is expressed in units of Maximum Water in Oil Saturation (MWOSL). The MWOSL was monitored continuously during the trials. Without water injection, normal MWOSL readings of around 2 percent were measured. With the engine running at 25 and 50 percent load at maximum W/F ratio, MWOSL readings of 6 to 7 percent were measured. However, at 75 percent load and maximum W/F ratio, MWOSL readings of only 4.4 percent were measured. These observations confirm the mechanisms involved in the formation of water/oil emulsion. It should be noted that MWOSL reached a maximum level during operation with water injection. This indicates that prolonged operation with water injection would not result in higher MWOSL readings.

The water content in the engine lubricating oil is a function of engine load and W/F ratio. It was noted that the highest percentage of water recorded is well below the alarm threshold of 30%. The engine lube oil is periodically passed through a centrifugal separator to remove water and solid impurities. Consequently, the impact of water injection on lube oil water content is not considered critical.

13.6 Fuel Consumption

The analysis of the normalized Indicate Power (Indicate Power / Fuel Flow Rate) at different engine load and different W/F ratio showed that water injection had no impact on fuel consumption.

13.7 Impact of Water Injection on Engine Intake Components

One positive benefit of water injection is the prevention of carbon buildup on the cylinder walls and the piston crown, and the generally clean condition of the inlet air manifold. Water appears to dislodge oil and carbon deposits through mechanical or capillary action. Capillary action allows the water to seep underneath deposited oil films and dislodge them due to water's lower viscosity. There is concern that mechanical action may in part be responsible for the ability of the injected water to dislodge deposits from the charge air conduits and cylinder head intake components. Further investigation would be required to verify this conjecture since the instrumentation deployed during the trials did not allow to resolve this issue, which only became apparent during the tests.

14. Conclusion

The emissions tests demonstrated the effectiveness of a low-cost water injection system (WIS) for reducing NOx emissions in marine diesel engines. The emissions tests were conducted with both MDO and IFO, and the data allowed an investigation of the effect of fuel quality on engine emissions. The WIS effectively reduced NOx at the expense of an increase in both PM and CO when using heavy fuel. NOx reductions varied between 10 and 30 percent, and were most effective with increased water injection above 50 percent engine load. This corresponds to a NOx emissions value of 12 g/kWh at 75 percent load and a W/F ratio of 50 percent. This does not allow us to conclude that these values are the upper emissions reduction limits for the WIS technology due to the unequal excess water distribution among cylinders.

Both NOx and PM are load dependent, with lower emissions at higher loads; CO in turn increases with load when running on heavy fuel. Both W/F ratio and fuel quality affect PM production. When using high (1.5 percent) sulphur fuel, PM increases with water injection; however, with MDO, PM remains constant. Water injection (regardless of fuel quality) has no impact on fuel consumption or CO_2 production. The THC resolution of the portable multi-gas analyzer was at set at 1 ppm. All THC readings were less than 1 ppm for all runs.

On the engine operation side, the impact of the water is primarily to saturate the engine's combustion air supply as well as to lead to direct water droplet carryover into the cylinders. A noticeable effect was the greater reduction of the exhaust gas temperatures nearest the point of injection. This is ascribed to the unequal distribution of the water along the length of the air manifold. Key considerations are the location, method of spray atomization, and water droplet distribution. The ship's staff also expressed concerns regarding engine operation and turbocharger surging during water injection. Injection timing adjustments and turbocharger matching may need to be considered for permanent engine operation with the WIS operating at high W/F ratios. Further testing and development of the WIS are required to realize optimal emissions reduction potential and to determine the impact of water injection on fuel consumption and engine operational performance as well as the impact of fuel quality on emissions.