

Gaseous and Particulate Emissions Using Isobutanol-Extended Fuel in Recreational Marine Two-Stroke and Four-Stroke Engines

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ABSTRACT

Biologically derived isobutanol, a four carbon alcohol, has an energy density closer to that of gasoline and has potential to increase biofuel quantities beyond the current ethanol blend wall. When blended at 16 vol% (iB16), it has identical energy and oxygen content of 10 vol% ethanol (E10).

Engine dynamometer emissions tests were conducted on two open-loop electronic fuel-injected marine outboard engines of both two-stroke and four-stroke designs using indolene certification fuel (non-oxygenated), iB16 and E10 fuels. Total particulate emissions were quantified using Soxhlet extraction to determine the amount of elemental and organic carbon. Data indicates a reduction in overall total particulate matter relative to indolene certification fuel with similar trends between iB16 and E10. Gaseous and PM emissions suggest that iB16, relative to E10, could be promising for increasing the use of renewable fuels in recreational marine engines and fuel systems.

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INTRODUCTION

Ethanol, as an E10 blend, has been the primary alternative fuel in use in the United States due in part to cost effective fermentation and production processes, government subsidies, and congressionally mandated usage volumes. Additionally, local production of biologically derived feed-stocks for ethanol production may reduce reliance on fossil fuels [1].

The congressionally mandated Renewable Fuels Standard has established targets for the quantity of alternative fuel produced each year in the U.S, and requires 36 billion gallons by the year 2022 [2]. At the same time, consumption of finished gasoline has continued to decline since 2007, leading to a barrier known as the blend wall.

Recognizing the impending barrier, which would effectively limit the amount of ethanol production beyond E10, a waiver request for E15 was submitted to the U.S Environmental Protection Agency (EPA). In 2010, EPA approved the first of two partial waiver requests allowing for the use of E15 in model year 2007 and newer passenger vehicles, followed by a second partial waiver for model year 2001 - 2006 passenger vehicles [3]. However, E15 is not a direct replacement for gasoline, and several issues with respect to compatibility with

engines, fuel system components and the potential for misfueling have limited the large scale introduction of E15 into the marketplace [4].

To that end, ethanol-extended fuels, particularly fuels with greater than 10 vol% ethanol, create a number of concerns for recreational marine engines and boat fuel systems. Outboard engines, on average, are used approximately 35 hours per year and are operated on a very aggressive duty cycle compared to automotive engines [5]. Most built-in boat fuel tanks are vented directly to the atmosphere which allows for moisture to enter the fuel system during daily diurnal temperature changes. The environment in which the engines are operated means it is more likely for water or salt water to enter the fuel system. Moreover, the long storage periods, particularly in northern climates, result in a greater chance for ethanol extended fuels to phase-separate.

The way in which recreational marine engines are operated and stored during the off season creates an ideal harsh testing environment for verifying the performance of alternative fuels.

With increased energy density, isobutanol has the potential of moving beyond the blend wall as it can be blended at 16 vol% while maintaining equivalent oxygen content of E10 fuels. A

number of laboratory and field studies using iB16 in recreational marine engines indicate similar gaseous exhaust emissions and engine performance compared to E10 blends [6,7]. The purpose of this study, which is a continuation of ongoing research on isobutanol, is to quantify particulate emissions from open-loop recreational marine engines and differentiate between ethanol and isobutanol extended fuels.

TEST ENGINES

Two outboard engines were selected for particulate and gaseous emissions testing which include a direct fuel injection two-stroke and electronic fuel injection four-stroke. The test engines were selected because they represent two very different engine technologies that are commonly used to propel recreational boats. Both engines are certified to the California Air Resources Board (CARB) ultra-low emissions standards (three-star) and meet the applicable EPA standards for engine model year 2014. The engines operate open-loop, meaning there are no combustion feed-back sensors to compensate for the change in air/fuel ratio required by the test fuel. The specifications for both engines are indicated in [Table 1](#).

No changes or modifications to the base engine calibration, spark timing or injection timing were made at any time during the testing process.

Table 1. Engine Specifications

Engine type	Mercury 90 Horsepower, 4 Stroke	Evinrude 90 Horsepower, 2 Stroke
Propeller power [HP/kW]	90/67	90/67
Maximum engine speed [RPM]	5000-6000	4500-5500
Cylinder/Configuration	In-line 4, 16-valve, direct acting dual, overhead cam (DOHC)	In-line 3 cylinder
Displacement [CID, cc]	105.7/1732	79 /1295 cc
Bore/Stroke [mm]	82/82	91/66
Cooling System	Water-cooled w/thermostat	Water-cooled w/thermostat
Ignition System	Inductive Coil on Plug	Inductive
Gear Ratio	2.33:1	2.00:1
Exhaust System	Through prop	Through prop
Lubrication System	Integrated dry sump	Integrated oil tank
Fuel Induction System	Computer controlled sequential multi-port Electronic Fuel	Spray-guided stratified direct fuel injection
Recommended fuel	87 octane/up to 10 vol% ethanol	87 octane/up to 10 vol% ethanol
Dry Weight [kg]	181	145

GENERAL TEST SET-UP

Measurement of particulate emissions from recreational marine outboard engines presents a number of challenges with respect to the handling of wet engine exhaust. As shown in [Figure 1](#), a complete outboard engine is mounted in a test tank with a direct connection from the engine propeller shaft to the engine dynamometer. The tank is filled with water to a predetermined level to keep the gear-case cool and provide appropriate back-pressure on the engine exhaust system. An outboard engine uses surrounding lake water for engine cooling, and

exhaust is routed through the center of the propeller hub for noise attenuation purposes. A certain percentage of engine cooling water is dumped into the midsection of the engine exhaust runner in an effort to lower exhaust temperature prior to exiting the engine through the propeller hub. Particulate samples must therefore be taken at the base of the power head, before water is mixed with the engine exhaust.

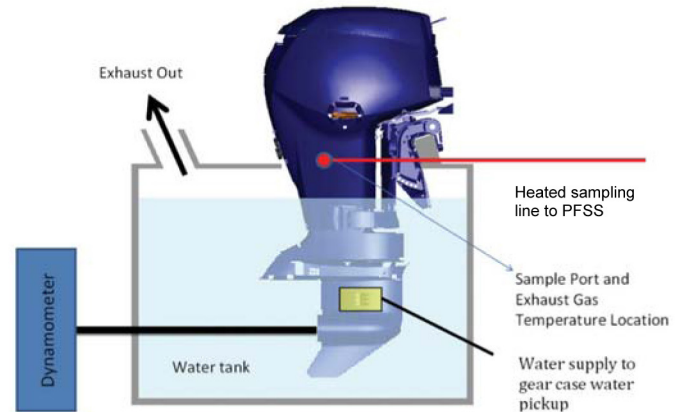


Figure 1. Typical outboard engine dynamometer test cell set-up schematic

Gaseous emissions (HC , NO_x , CO , CO_2 , O_2) were measured at the base of the power head using an AVL i60 five-gas emissions bench. The bench utilizes a heated flame ionization detector (FID) for total hydrocarbons, heated chemiluminescence detector (CLD) for oxides of nitrogen, non dispersive infrared (NDIR) for CO and CO_2 and a paramagnetic detector for O_2 . A heated sampling line connects the engine exhaust sampling probe to the emissions bench. The heated line is maintained at 185°C .

A Froude AG-150 eddy-current dynamometer is used to load the engine during the testing process. A Tescom water pressure controller is used to vary the engine cooling water pressure to what is typically expected at the gear case water pick-up location while the boat/engine is underway.

Engine fuel flow was measured with a Pierburg 60 LPH volumetric flow system using a density sensor to arrive at fuel consumption in grams per hour. An AVL Bobcat data acquisition system recorded test cell data at a frequency of 1 Hz. Test cell temperature and humidity are controlled to 23°C and $35\% \pm 5\%$, respectively.

The engine is tested according to the International Council of Marine Industry Associations (ICOMIA) / EPA CFR 40 part 1045 steady state test cycle as shown in [Table 2](#) [8]. All subsequent gaseous and particulate test results reflect a weighted total average based on specific output in grams per kiloWatt-hour (g/kW-hr).

The specifications for the fuels used throughout the testing program are indicated in [Table 3](#). Ethanol and butanol were blended with blendstock for oxygenate blending (BOB) rather than indolene to achieve fuel properties that are similar to fuels

currently used in the field. Isobutanol was blended to achieve equivalent oxygen content to a 10 vol% gasoline/ethanol blend (E10). The resulting blend level is 16 vol% isobutanol (iB16) at an oxygen content of 4 wt%. The oxygen content in the fuel also impacts the stoichiometric air demand, AFR_{ST}, which is approximately 13.8 for E10 and iB16 compared to 14.6 for indolene, as well as the energy content. The resulting lower heating value of the alcohol blends is approximately 29.5 MJ/L compared to 32 MJ/L for indolene. These changes in properties are particularly relevant since the test engines, like most recreational marine engines, do not employ a closed loop engine feedback control. Reid Vapor Pressure (RVP) of the E10 blend is almost as high as indolene compared to the lower RVP of iB16. These changes are attributable to the azeotropic behavior of ethanol blends, which are not exhibited with butanol [9]. Both neat ethanol and iso-butanol have octane ratings significantly higher than gasoline [10]. Research Octane Number (RON) and Motor Octane Number (MON) of the blends are slightly lower than indolene due to the low RON and MON of the BOB used for blending compared to indolene.

Table 2. 5-mode steady-state marine test cycle [8]

Mode	% RPM	% Torque	% Weight Factor
1	100	100	6
2	80	71.6	14
3	60	46.5	15
4	40	25	25
5	Idle	0	40

Table 3. Fuel Specifications

			indolene EEE	E10	iB16
Density	ASTM D4052	kg/L	0.743	0.7397	0.7489
RVP	ASTM D5191	psi	9.1	8.81	7.97
Carbon	ASTM E191	wt%	86.31	82.916	83
Hydrogen	ASTM E191	wt%	13.34	13.094	12.998
Oxygen		wt%	0	3.99	4.002
H/C ratio	ASTM E191	mole/mole	1.841	1.895	1.879
O/C ratio		mole/mole	0	0.036	0.036
AFR _{ST}			14.571	13.856	13.832
RON	ASTM D2699		96.6	94.0	94.7
MON	ASTM D2699		88.7	85.4	83.8
LHV	ASTM D240	MJ/kg	43.01	39.75	39.54
LHV		MJ/L	31.96	29.40	29.61

PARTICULATE MEASUREMENT

Total mass particulate matter was determined gravimetrically using a partial flow sampling system (PFSS) to collect an exhaust emissions sample from the base of the engine power head. The system consists of a 90mm dilution tunnel, heated and conditioned dilution air, vacuum pump, bellows meter, sample valves and sample timer. Based on previous test experiments, NO_x is used to determine dilution ratios of the sample system. A schematic of the dilution tunnel is shown in Figure 2, and the full system is further explained in detail in previous publications [11,12].

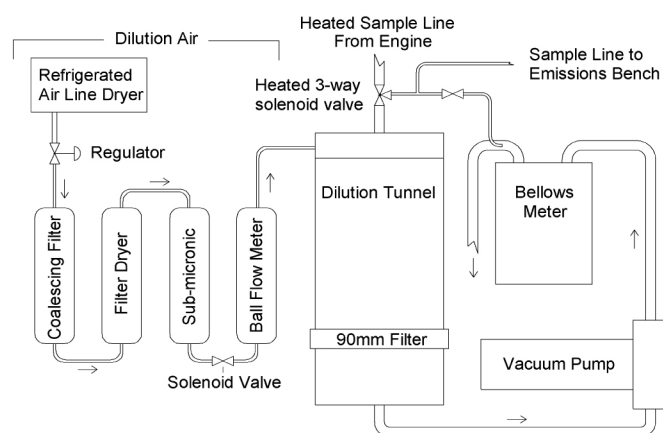


Figure 2. Partial flow dilution tunnel flow diagram



Figure 3. Constant temperature/constant humidity glove box - the scale sits atop a granite seismic mass table.

90mm Pall Emfab™ Teflon® glass fiber filters were stabilized in a constant temperature/ constant humidity glove box as shown in Figure 3 prior to initial weighing, and stabilized for two hours prior to final weighing. An Ainsworth M-220D scale with measurement resolution of 0.00001 gram was used to determine particulate filter mass. A weighted composite particulate sample (five modes on one filter) was collected by varying the sample time of the partial flow sampling system to match the five-mode ICOMIA weighted test cycle (EPA CFR 40 part 1045). Two filters were collected for each test fuel, and the average of the two