

Alternative Fuel Butanol: Preliminary Investigation on Performance and Emissions of a Marine Two-Stroke Direct Fuel Injection Engine

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ABSTRACT

In pursuit of reducing dependencies on foreign oil coupled with U.S. renewable fuel standards and an overall focus and interest in greenhouse gas emissions, investigations continue on feasibility of replacement biologically derived fuels such as ethanol and butanol. Majority of existing recreational products such as marine outboard engines, boats, personal watercraft, all terrain vehicles and snowmobiles are carbureted or operate open-loop, meaning the engine does not have the capability to sense air-fuel ratio. Ethanol has a specific energy content that is less than gasoline. Without means to compensate for air-fuel ratio requirements of specific fuels, open-loop engines may suffer from a condition known as enleanment, in which catastrophic engine failure may result.

On the contrary, butanol has specific energy content closer to that of gasoline, suggesting open-loop engines may be less prone to negative effects of increased biologically derived fuel concentrations in gasoline.

This is a preliminary investigation into the effects of butanol/gasoline mixtures on a two-stroke direct injection recreational marine outboard engine. Additionally, ethanol/gasoline mixtures are also tested as comparison. Engine performance, combustion characteristics and emission results including overall effects of various butanol/gasoline and ethanol/gasoline blends will be explored.

INTRODUCTION

Engines used in a marine environment to power recreational craft are subject to very different operating conditions, usage cycles and overall physical running conditions than automotive engines. Therefore, it is important to understand

these variations on how fuel blends primarily intended for automotive use may affect recreational marine engines and fuel systems.

Engine and drive weight is very critical for recreational marine products. Engine power to weight ratio has a direct effect on vessel performance and fuel economy. Additionally, it is not uncommon for recreational marine engines to be operated at wide open throttle (WOT) at rated speed for extended periods of time. During WOT, components are stressed more, not only from a mechanical standpoint, but also thermally. Subtle differences in combustion as a result of fuel properties can have a significant affect on performance, engine durability and emissions [1, 2].

According to the National Marine Manufacturers association (NMMA), as of 2007, 12,185,568 gasoline powered recreational boats are currently registered in the United States [3]. Of that, approximately 225,000 have been retired from the fleet, which is less than 2% of the total powerboat fleet. The recreational marine industry as a whole has one of the oldest fleets of the engine sector. This results in a particularly difficult challenge in development of alternative fuels that will minimize engine run-ability issues, fuel system component issues or potential engine failures considering the wide range and age of products currently still in use.

Several different materials are used for boat fuel tank construction including aluminum, polyethylene and fiberglass. Alternative fuel compatibility with different types of fuel tank materials needs to be considered and understood [4, 5].

Most boat fuel systems are vented directly to the atmosphere, which allows moisture to enter the fuel tank during daily diurnal temperature changes. This is further complicated by

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the marine environment itself - in which water or salt water is more likely to be inadvertently introduced into fuel systems. Moreover, typical usage of boats, especially in northern parts of the US, equates to longer periods of storage and subsequently potential for more fuel system related issues [6].

With respect to the aforementioned vented fuel system issue, as compared to ethanol, butanol is not hygroscopic and is much less susceptible to phase separation. [Figure 1](#) shows the difference between ethanol and butanol fuels when 10% H₂O is added to each fuel. A colorant was added to highlight differences between the two samples. As shown, the cylinder containing ethanol on left has phase separated, meaning water and ethanol have formed an aqueous mixture forcing the gasoline to the top of the cylinder. In the cylinder, on the right containing butanol, water has settled to the bottom of the cylinder, leaving butanol and gasoline for the most part unaffected. Phase separation with ethanol causes additional engine enleanment due to both the fact that gasoline is displaced and water is present in the fuel causing the engine to ingest an ethanol water mix. Lack of phase separation in presence of H₂O is a desirable basic property of butanol, not only for the recreational marine industry, but also for the overall fuel distribution network, as butanol could be successfully delivered in existing pipelines [7].

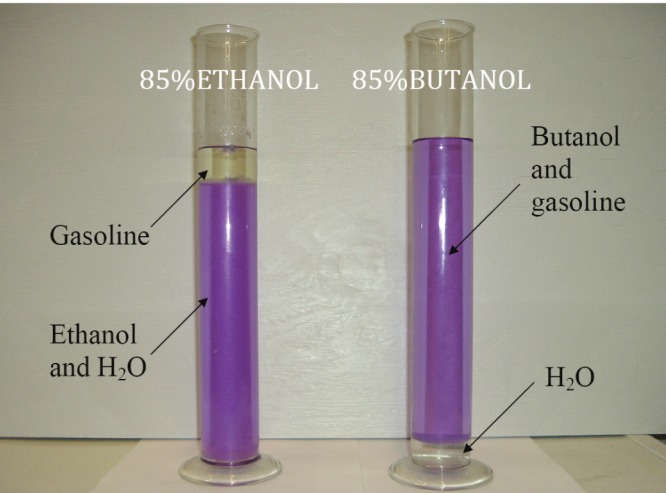


Figure 1. Effect of adding 10% water by volume to 85% ethanol and 10% water by volume to 85% butanol.

TEST SETUP

This section includes a description of the test engine, fuel flow system, test fuels, emissions analyzers, combustion analysis equipment, engine cooling water system, and overall test process. A schematic of engine test cell set-up is presented in [Figure 2](#).

TEST ENGINE

A three cylinder 90 horsepower (67.1 kW) spray-guided stratified charge direct injection two-stroke production outboard engine was used for testing. The engine operates open-loop and does not have any type of combustion feed back sensor. This particular engine was chosen as it tends to be slightly more knock and fuel sensitive. Moreover, it is a scalable design, as this configuration forms 150, 175 and 200 horsepower V-6 outboard engine models. Engine specifications are shown in [table 1](#).

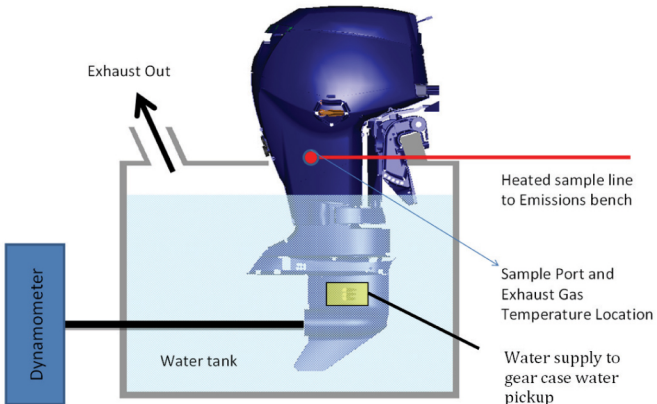


Figure 2. Engine test setup

Table 1. Test Engine Specifications

Model Year	2010
Fuel System	Gasoline Direct Fuel Injection (GDI)
Emissions Rating	California Three-Star Ultra-Low
Engine Cycles	2
Valves	Reed
Number of cylinders	3
Displacement	1296
Rated power HP (kW)	90 (67.1)
Full throttle operating range	4500 - 5500
Idle speed	650
Engine Hrs	175
Midsection length (inches)	20

FUEL AND FUEL FLOW INFORMATION

Fuel used for baseline emissions testing and as a base for blending is Indolene clear, which is a standardized gasoline test fuel that conforms to EPA CFR part 1065 requirements for certification testing [8]. Fuel flow is measured volumetrically using a Pierburg 60 lph fuel metering system along with a Calibron Densitrak DT625L density meter to arrive at fuel consumption in gram per hour. The fuel

specifications are shown in [Table 2](#). Calculated stoichiometric air/fuel ratios for various alternative fuel blends are shown in [Figure 3](#).

Various amounts of butanol or ethanol were blended with base indolene fuel to arrive at the desired concentrations of alternative fuel by volume:

- (B-10): 10% Butanol, 90% Indolene
- (B-15): 15% Butanol, 85% Indolene
- (B-20): 20% Butanol, 80% Indolene
- (E-10): 10% Ethanol, 90% Indolene
- (E-15): 15% Ethanol, 85% Indolene

Table 2. Test Fuel Specifications

Property	Gasoline	Ethanol (CH ₃ OH)	n-Butanol (C ₄ H ₉ OH)	Indolene
Specific gravity @60F	0.72-0.75	0.79	0.8133	0.74
Net Lower Heating Value (BTU/lbm)	18700	11600	14280	19500
Octane Number Research	91-100	111	96	96
Motor	82-92	92	80	88
Stoichiometric AFR	14.6	9	11.1	14.3
Self-ignition Temperature (C)	450	420	343	450

Calculated stoichiometric air/fuel ratio for various alternative fuel blends: gasoline, butanol, ethanol

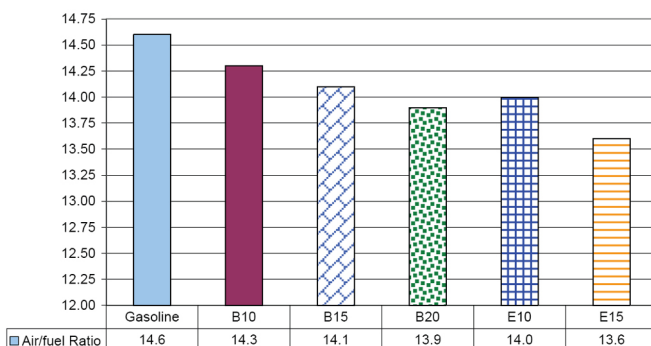


Figure 3. Calculated stoichiometric air/fuel ratio for various butanol and ethanol blends.

EMISSION ANALYZERS

A Pierburg AMA-2000 five-gas emissions bench was used for emissions analysis. A heated flame ionization detector (FID), heated chemoluminescence detector (CLD), non-dispersive infrared (NDIR) and paramagnetic analyzers were used for measurements of THC, NO_x, CO, CO₂ and O₂ respectively.

COMBUSTION ANALYSIS

An AVL Indicom 2 crank-based combustion analysis system was used to acquire 500 cycles of cylinder pressure on all three cylinders. Data was then processed to determine, burn rates, %COV of IMEP, misfire rate and to quantify knock characteristics.

WATER COOLING SYSTEM

Engine cooling water is supplied to the engine through the gear-case water pick up as shown in [Figure 2](#). Water pressures are regulated with a Tescom ER-3000 electronic pressure controller to provide pressures typically seen at the gear case of a boat while underway.

TEST PROCESS

For each test fuel, the engine was run according to the International Council of Marine Industry Associations (ICOMIA) five-mode steady state test cycle as shown in [Table 3](#) [9]. Two consecutive five mode emissions tests followed by two wide open throttle (WOT) power tests were conducted on each fuel blend. This was done in order to more accurately account for small deviations in test results. The average results from two tests on each fuel blend are reported. Five gas emissions HC, NO_x, CO and CO₂, exhaust gas temperature, fuel flow, and combustion characteristics were recorded for each test mode and test fuel. EGT and emissions were sampled in the midsection megaphone, just below the base of the engine powerhead as indicated in [Figure 2](#).

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